Summary of Thesis submitted for PhD degree

by Kurt Dowson

on

Towards Extracting Artistic Sketches and Maps from Digital Elevation Models

The main trend of computer graphics is the creation of photorealistic images however, there is increasing interest in the simulation of artistic and illustrative techniques. The techniques used in conventional cartography for the representation of terrain are organised into a new taxonomy. A class of techniques which represent terrain pictorially is identified. These include block diagrams, sketches and physiographic mapping methods. This thesis describes an original technique for automatically producing artistic sketches of DEMs.

A cartographic line simplification algorithm is used to rate each cell in the DEM, by application to terrain profiles. This detects perceptually important cells which are termed "core cells". Visvalingam's algorithm, with effective area and perpendicular distance as metrics, is compared with the Douglas-Peucker algorithm to determine which produces the best set of core cells for sketching. It is concluded that Visvalingam's algorithm, with either metric produces superior results for sketching. Effective area is used.

The pencil strokes made by an artist are simulated by connecting strings of core cells on the same profile. These strings of core cells are then extended along the profile lines to form "profile-" or "p-strokes". Strings of core cells may be extended to either the right, the left or both while the length of extension may also be varied.

To simulate the varied strokes made by an artist four individual types of p-stroke were identified ; +parallel, –parallel, +orthogonal and –orthogonal. Positive profile strokes describe convexities while negative profile strokes describe concavities. The symbolism, direction and length of extension can be set individually for each type of p-stroke while a user-specified tolerance controls the number of core cells selected.

Figures are presented using a vertical oblique projection which allows the profiles that p-strokes follow to be separated to produce a map-like effect.

THE UNIVERSITY OF HULL

Towards Extracting Artistic Sketches and Maps from Digital Elevation Models

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Abstract

The main trend of computer graphics is the creation of photorealistic images however, there is increasing interest in the simulation of artistic and illustrative techniques. This thesis investigates a profile based technique for automatically extracting artistic sketches from regular grid digital elevation models. The results resemble those drawn by skilled cartographers and artists.

The use of cartographic line simplification algorithms, which are usually applied to complex two–dimensional lines such as coastlines, allow a set of most important points on the terrain surface to be identified, these form the basis for sketching.

This thesis also contains a wide ranging review of terrain representation techniques and suggests a new taxonomy.

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Chapter 1

Introduction

1.1 THE AUTOMATED ARTIST

1.1.1 Drawing Machines

The surrounding landscape affects all of our lives, regardless of who we are or where we choose to live. Cosgrove (1993, p.1) writes "Landscapes provide a stage for human action, and, like a theatre set, their own part in the drama varies from that of an entirely discreet, unobserved presence to playing a highly visible role in the performance. Sometimes landscapes actually came so to resemble the form and design of a theatre that analogy becomes identity and we speak of dramatic landscape". Therefore it is not surprising, when we consider that making drawn and painted images has always been part of our nature, that the landscape has been a favourite subject of artists and the major concern of the field of cartography. Evidence of picture-making goes back to at least 15,000BC (Lansdown, 1990) and since that time millions of beautiful sketches, paintings and maps have depicted the landscape in a multiplicity of styles.

It is also not surprising in these modern times, this age of the digital computer, that the potential of this machine has been turned to the production of images. Drawing machines are not a new concept, Leonardo da Vinci showed a picture of a man using a drawing machine in his notebooks (Willats, 1990) while Albrecht Dürer devised several such machines to aid the artist in the production of faithful images or copies of reality. Many drawing machines enforce the accurate utilisation of the laws of linear perspective (see Cole, 1992). Arnheim (1956, p.234) describes the operation of one of Dürer's machines, which is shown in figure 1.1, "The draftsman stared with one eye

Figure 1.1: One of the drawing machines invented by Albrecht Dürer (reproduced from Arnheim, 1956).

through a peephole, which secured an unchangeable point of observation. A given view of the object at a given moment took the place of the totality of experiences, accumulated, sifted, judged, and organised during a lifetime, which were formerly the 'model' of the artist. And even this given view was not to be ordered, judged, and understood by the draftsman, but to be copied, detail by detail, as it projected itself on the glass." Later drawing machines included lenses and it was their development which culminated in the invention of photography (Willats, 1990). Like these drawing machines of centuries past, the goal of mainstream computer graphics has been to create exact copies of reality.

The creation of photorealistic images involves the emulation of the laws of physics and ad hoc rules of thumb to produce scenes of mathematical perfection. Such images possess the ability to mesmerise almost all who see them. Of all the tasks that a computer can perform it is the beautiful images it can produce which have the most power to amaze us, for they are far more easily amenable to visual creatures such as ourselves than abstract figures like the number of instructions which can be performed in a single second (it has been estimated that over fifty percent of the brain's neurons are concerned with vision (McCormick *et al.*, 1987)). Even the layman with no knowledge of computing can appreciate the entrancing images produced. "Why is all this work on synthetic imagery being carried out? Primarily, of course, because of the intellectual challenge it affords. But it has its practical uses too. Designers frequently need to simulate the appearance of objects before making them; aeroplane pilots need flight training simulators which show convincing scenes; the entertainment industry wants to create realistic images of scenes for which it would be difficult to make full-sized or scaled physical models - indeed, it is probably from the entertainment industry that the maximum demand is arising" Lansdown (1990, p.233).

We seldom pause to question whether such perfect emulation of reality is what is required to best communicate a message. Winkenbach and Salesin (1994, p.91) write "the computer's ability to display images of ever increasing complexity gives rise to a new problem: communicating this complex information in a comprehensible and effective manner. In order to communicate truly complex information effectively, some form of visual abstraction is required. This type of abstraction has been studied most comprehensibly in the fields of graphic design and traditional illustration". Unlike a photorealistic rendition of reality a sketch can select those elements which are deemed significant and these may be emphasised while superfluous detail may be omitted. An artist also brings to his sketches those subtle qualities of technique which add interest and life to what may otherwise be a prosaic matter (Lobeck, 1924). Other researchers have recently investigated the simulation of sketching and illustration techniques (Sasada, 1987; Leister, 1994; Dooley and Cohen, 1990; Saito and Takahashi, 1990; 5D Solutions, 1994; Hsu and Lee, 1994; Winkenbach and Salesin, 1994; Salisbury *et al.*, 1994).

This thesis proposes a technique for the production of minimalist sketches or caricatures of regular grid Digital Elevation Models (DEMs). A DEM is a computer model of an area of terrain, usually terrestrial though it could describe alien planets or the bottom of the ocean. There are similarities between art and cartography, both are concerned with abstracting from (usually) reality, important features or trends for portrayal. The profile based technique proposed in this thesis uses line simplification algorithms, which are used in digital cartography, to determine which lines should be drawn to produce a sketch. The resulting sketches resemble the landscape sketches drawn by artists and the field sketches made by geographers. When the separation between profiles is increased, overlap is reduced, and the result bears some relation to a map.

1.1.2 Generalisation

Maps portray a generalised version of reality. Cartographic generalisation is usually necessary as a result of reducing the scale of a map. As the scale gets smaller the physical space available also gets smaller and hence the amount of detail shown should be reduced. This is called "scale dependent generalisation". Generalisation may also be applied at a constant scale to produce a simplified representation the same size as the original. This is called "scale independent" generalisation.

Most research on automated generalisation has so far focussed on the generalisation of lines. Lang (1969, p.50) describes the need for line simplification, "If an irregular line such as a coastline is greatly reduced in scale, the irregularities in the line merge to produce a thickened line with dark smudges which looks rather as if the ink had run. Hence, the line must be generalised, keeping the salient features but discarding excessive detail, to produce what is essentially a caricature of the original." Line simplification reduces a string of coordinates which define a line, by eliminating all but a chosen few points which are deemed most important for maintaining the character of the line. The removal of unnecessary points from a line, such as points on a straight line, is termed "weeding".

The simplest line simplification algorithm is the *n*th point algorithm which simplifies a line by retaining only every *n*th point. The larger the value of *n*, the greater will be the degree of simplification. However, this algorithm takes no account of the character of the line. Many other more sophisticated line simplification algorithms have been proposed (*e.g.* Deveau, 1985; Dettori and Falcidieno, 1982; Roberge, 1985; Opheim, 1981). Two line simplification algorithms are used in this thesis. These are the Douglas-Peucker algorithm (Douglas and Peucker, 1973), which is the most widely used line simplification algorithm, and Visvalingam's algorithm (Visvalingam and Whyatt, 1993), which is a relatively new algorithm developed at Hull University.

Arnheim (1976) states that a similar generalisation process occurs spontaneously in all perception and that it is simplified images which we remember. To demonstrate this he asked students to draw the outline of the American continent and he observed that a highly generalised outline was produced.

1.1.2.1 The Douglas-Peucker Algorithm

The Douglas-Peucker algorithm (Douglas and Peucker, 1973) is the most widely used line simplification algorithm. The description below is based on that given by Whyatt and Wade (1988). The algorithm operates as follows:

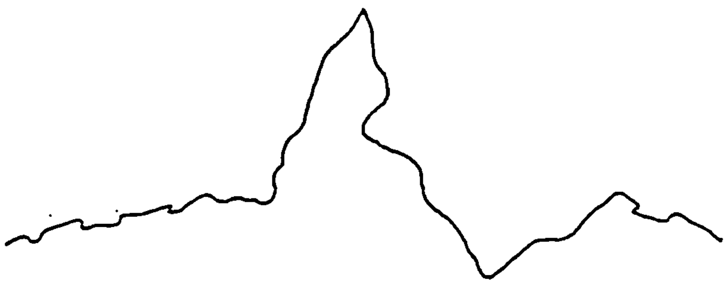
> Let the first point on the line be the "anchor" and the last point on the line be a "floater". Draw a straight line connecting the anchor and the floater. The perpendicular distance from a point to the anchor-floater line is termed its offset. An offset is calculated for each of the points between the anchor and the floater. If no offset exceeds a distance specified by the user, known as the "tolerance", then the anchor-floater line is deemed suitable as the simplified version of the line.
>
> If one or more offsets exceed the tolerance value, the current floater is stored on a stack and the point with the greatest offset is chosen to be the new floater. The process is then repeated. The anchor-floater line is now the straight line connecting the anchor and the new floater. Offsets are calculated perpendicular to this new anchor-floater line. The line is repeatedly subdivided in this way until no offset exceeds the tolerance value. When this happens the anchor is moved to the position of the current floater

and the previous floater (the one at the top of the stack) becomes the new floater.

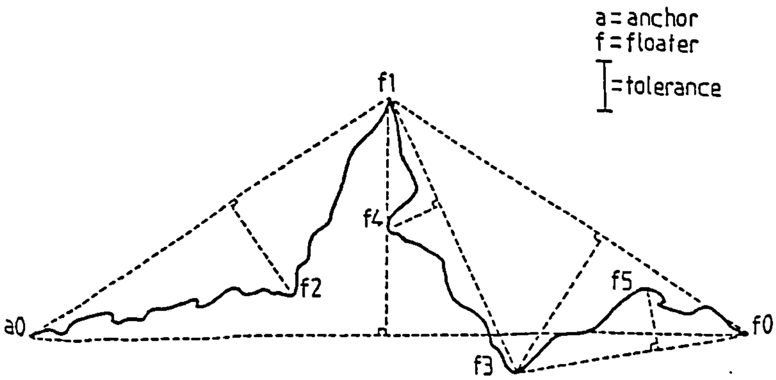
The process is repeated until the anchor reaches the last point on the line. When this occurs the simplification process is complete. The simplified line is the line produced by joining the points previously assigned as anchors.

Setting a low tolerance value means that the simplified line will closely resemble the original, while a high tolerance will result in a greater degree of simplification.

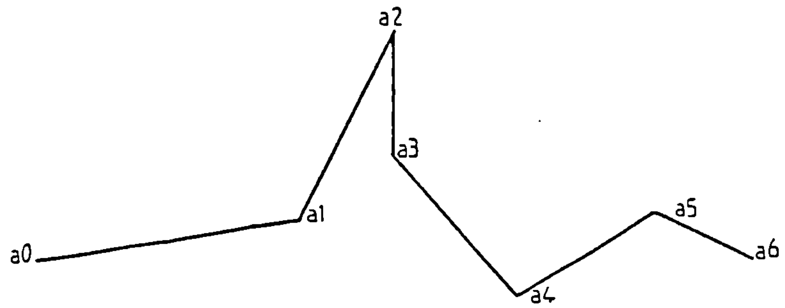
The following example, reproduced from Whyatt and Wade (1988), describes the simplification of the line shown in figure 1.2(a). Figure 1.2(b) shows how the points are selected while figure 1.2(c) depicts the simplified line. The following text describes the point selection procedure in detail.



(a) Original Line.



(b) Point Selection.



(c) Simplified Line.

Figure 1.2: The Douglas-Peucker algorithm (reproduced from Whyatt and Wade, 1988).

1. Straight line segment a0–f0. Max offset at point f1.
2. Straight line segment a0–f1. Max offset at point f2.
3. Straight line segment a0–f2. All intervening points within tolerance. Anchor moves to point f2 (a1).
4. Straight line segment a1–f1. All intervening points within tolerance. Anchor moves to point f1 (a2).
5. Straight line segment a2–f0. Max offset at point f3.
6. Straight line segment a2–f3. Max offset at point f4.
7. Straight line segment a2–f4. All intervening points within tolerance. Anchor moves to point f4 (a3).
8. Straight line segment a3–f3. All intervening points within tolerance. Anchor moves to point f3 (a4).
9. Straight line segment a4–f0. Max offset at point f5.
10. Straight line segment a4–f5. All intervening points within tolerance. Anchor moves to point f5 (a5).
11. Straight line segment a5–f0. All intervening points within tolerance. Anchor moves to point f0 (a6).
12. Simplification complete by joining the anchor points with straight line segments.

1.2 FOCUSSING ON THE RESEARCH TOPIC

Sketching the terrain was not the initial aim of the project. In fact it took two years to focus on this topic of research. At the outset the aim of the project was the generalisation of complex mapping and engineering features for integration with other Geographical Information Systems (GIS) information.

However, after the initial two month placement with the industrial sponsor, it emerged that Scott Wilson Kirkpatrick and Partners (SWK) considered the problem of landscape visualisation more important. When SWK embark upon a civil engineering project they want to show clients how the finished project will appear and how it will affect the landscape. Traditionally, an artist would be commissioned to produce artistic impressions but this is an expensive and time consuming process. Therefore, SWK desired to be able to use the computer as a quick, cheap alternative for producing still images and animated fly throughs. However, because of a lack of data describing objects in the landscape there is a need for simulation. The idea of simulating objects in the landscape appealed to me.

An initial analysis was carried out, based on the set of objects shown on maps, to determine which objects to simulate. Once a number of objects had been selected for simulation the next step was to consider the method of simulation. Various procedural models were considered. Procedural models create large amounts of data from a few parameters (Smith (1984) called this "database amplification"). Work had already been carried out by other researchers on the simulation of some landscape elements using procedural models such as fractals (mountains (Mandelbrot, 1982) and trees (Oppenheimer, 1986)), particle systems (clouds and fog (Reeves, 1983), trees and grass (Reeves and Blau (1985)) and grammar based models (trees (Smith, 1984), architecture (Stiny and Mitchell, 1978; Stiny and Mitchell, 1980) and landscapes (Friedell and Kochhar, 1991; Friedell and Schulmann, 1990)). Some experiments were carried out using grammar based models to simulate detail for towns and cities in my second year of research.

At this stage it was felt that the research could proceed in two ways:

1. Bring together existing strands of work. Here the originality comes from the combination of these elements in a single system. This path would require a great deal of system development.

2. Simplification of terrain for simulating landscape elements.

I decided to work on the second of these, hoping to add simulated cultural elements to the landscape after researching procedures for sketching the terrain. However, sketching proved to be a more involved task than originally anticipated and resulted in the original procedures described in this thesis. This novel idea of producing artistic sketches of DEMs was provided by my supervisor who was also closely involved in the development of the approach adopted.

1.3 ACHIEVEMENTS

The original contribution of this thesis consists of:

1. A wide ranging review of terrain representation techniques and the suggestion of a new taxonomy.
2. A novel technique for extracting artistic sketches from regular grid DEMs which is based on the identification of the features present in a DEM (*e.g.* ridges and valleys). The term "surface specific features" is used to describe such features.

1.4 OVERVIEW OF THESIS

Chapter 2 contains an extensive and wide ranging review of techniques used for terrain representation. The chapter begins by organising the techniques used in conventional cartography into a new taxonomy. These techniques and their variations are then described. This is followed by a description of techniques for computer visualisation of terrain. The conventional cartographic techniques which have been imitated are identified as well as those methods unique to the computer. This chapter also includes an analysis of techniques for the extraction of vector topological sketches from DEMs. Such sketches are quite different from our artistic sketches. The chapter concludes with a discussion of notable work which has chosen to diverge from the photorealistic trend of visualisation.

Chapter 3 describes an original technique for automatically extracting sketches from regular grid DEMs. These sketches resemble those drawn by an artist or geographer. A profile based approach is employed which uses Visvalingam's cartographic line simplification algorithm to extract perceptually important DEM cells from each row and column of a DEM. These important cells, termed "core cells", determine the position of the lines in the sketch. This chapter is based on Visvalingam's initial draft of a paper being co-authored by her and myself. This chapter presents an adaptation and extension of the material in that draft.

Chapter 4 compares three methods for core cell selection to determine which produces the best set of core cells for sketching. In chapter 3 Visvalingam's algorithm was used with the effective area metric. However, Visvalingam's algorithm can also be driven by other metrics. Core cells selected by Visvalingam's algorithm, using effective area and perpendicular distance metrics, and by the Douglas-Peucker algorithm are compared. Each method is evaluated in terms of one-dimensional terrain profile simplification, the two-dimensional distribution of core cells across the DEM and the resulting sketches.

In the previous two chapters a 1:10,000 Ordnance Survey DEM, covering the hilly area behind Port Talbot, was used for experimentation. Chapter 5 presents results and observations obtained from applying the sketching procedure described in Chapter 3 to a smaller scale DEM (1:24,000).

Chapter 6 is the conclusion.

Chapter 2

Background

2.1 INTRODUCTION

The problem of representing terrain, on a map or on a computer screen, is a difficult one. "Since the earliest days of map-making, the depiction of relief has been one of the major problems of cartographers, for it involves the representation of three dimensions upon a plane surface." (Monkhouse and Wilkinson, 1976, p.87). Winterbotham (1939, p.96) writes of this problem "Hills are of the greatest interest and importance to all of us; yet they are by far the most difficult features for the map to show. Somehow or other they must be made to stick up from the flat sheet of paper, at all the different gradients, and with all the minor features which characterise them." This chapter describes many techniques used for representing terrain. The methods used in conventional cartography are organised into a taxonomy and a class of "pictorial" techniques are identified. These valuable techniques have been virtually ignored when it comes to computer emulation. This is due to the artistic element required in their production. However, these techniques are of great value despite going against the main trend of computer graphics, which is to produce scenes of increasing realism. The aim of this thesis is identified as the automatic production of artistic sketches from regular grid DEMs. The production of such sketches is based on the extraction of perceptually important elements in the landscape and for this reason techniques used to extract vector topological sketches from DEMs are examined. It should be pointed out that vector topological sketches are quite different from artistic sketches.

2.2 TERRAIN VISUALISATION TAXONOMY

Cartography texts usually classify relief representation techniques according to whether they are qualitative or quantitative (Dickinson, 1969; Lawrence, 1971). Qualitative methods provide a visual impression of relief while quantitative methods provide precise values. Birch (1964) also uses this taxonomy but terms qualitative methods "pictorial" and quantitative methods "exact". Kraak (1988) proposes a different taxonomy but this is geared towards viewing methods (optical stereo, anaglyph, holographics, *etc.*) rather than representation techniques. The classification of Brandes (1983) is more useful. He classifies techniques, according to utility, into methods for morphometric analysis, point information portrayal, three-dimensional diagrams and continuous surface flat maps. However, for the purposes of this research, it was found more useful to classify the terrain representation techniques of conventional cartography into several categories, describing different methods of representation. Table 2.1 shows an original taxonomy consisting of six classes:

1. Surface specific features - Methods in this class portray only certain features of the terrain surface. These features may be points, usually having some significance, such as the summits of hills or may be lines describing features like valleys or ridges.

2. Slices - Techniques in this class chop the terrain surface into slices and represent each slice. The danger with such methods is that the form of the terrain between the slices is not described. The terrain may be sliced horizontally, vertically or at an angle. The automatic sketching approach described in this thesis uses profiles (vertical slices) as a basis.

3. Shading - Methods in this class shade the terrain surface. Shading may be performed using dots, lines or area tones. The intensity of shading is based upon either steepness of slope, illumination from an oblique light source or a combination of these two.

4. Pictorial - Pictorial techniques require some degree of artistic ability to produce. This is why these techniques have been virtually excluded from computer emulation. However, this thesis proposes a method of emulating such techniques.

5. Photographic - Highly realistic photographic methods are relatively new. Realism in this sense means to capture an image of the earth's surface

which coincides with how the scene would appear to a human observer. However, a high degree of realism may not mean a better end result because with realism comes complexity.

6. True 3D - Methods in this class are three-dimensional. While methods in the other classes give the impression of three-dimensions on a flat two-dimensional surface, which may be a piece of paper or a computer screen, and may make use of special techniques, stereopsis and anaglyphs for example, to provide a more convincing impression of depth they are not substantial. However, methods in this class are actually three-dimensional, being solid models of the real thing.

Section 2.3 describes the techniques in each class. Some techniques have many variations and these are also described. Section 2.4 describes techniques used to represent terrain on the computer screen. Some of these emulate the methods used in conventional cartography while others are unique to the computer. Often the representation of terrain will be a combination of two or more of the techniques described since each has its own strengths and weaknesses.

2.3 TECHNIQUES USED IN CONVENTIONAL CARTOGRAPHY

The review of Brandes (1983) and the texts by Monkhouse and Wilkinson (1971), Raisz (1938) and Imhof (1982) proved to be valuable sources during the compilation of this review while the classic text on block diagrams by Lobeck (1924) also deserves to be mentioned. Monkhouse and Wilkinson (1971) describe many types of map and diagram while Raisz (1938) covers many aspects of cartography and provides excellent coverage of pictorial techniques. Imhof (1982) outlines the historical development of relief representation and describes several methods in unparalleled depth.

2.3.1 Surface Specific Features

2.3.1.1 Spot Heights

Spot heights record height at discrete points on the terrain surface. The position of a spot height is shown by a symbol, such as a dot, while the

Terrain Visualisation Taxonomy	
Surface Specific Features	Spot Heights Skeletal Lines
Slices	Profiles Contours Layer Shading
Shading	Stippled Relief Hachures Hill Shading
Pictorial	Physiographic Oblique Regional View Block Diagram Sketches
Photographic	Photomaps
True 3D	3D Models Globes

Table 2.1: Taxonomy of terrain representation techniques used in conventional cartography.

altitude is given as a numeric value. Spot heights can also be used to record depth on maritime charts. The advantage of spot heights is they provide precise information. The disadvantage is that alone they fail to give a general idea of relief (Birch, 1964, p.82). However, when they are combined with other methods they provide an exactness which is otherwise often lacking (Monkhouse and Wilkinson, 1976, p.88). The placement of spot heights is important. Monkhouse and Wilkinson (1976, p.88) make the following recommendations, "Prominent summits should have their heights marked, even on a small-scale map, and there should be a few heights in lowland areas and valley bottoms, so often ignored."

2.3.1.2 Skeletal Lines

Imhof (1982, p.105) describes skeletal lines as "the ground plan of watersheds, drainage networks and lines of all types which divide up the terrain. To this group belong 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.*" Skeletal lines are often used as a constructional aid for other methods of terrain representation. However, they may also appear in a finished map combined with some other technique; an example is kantography where skeletal lines are combined with contour lines. Skeletal lines may also appear as an independent form of terrain representation (Imhof, 1982, p.108). Skeletal lines depicting convexities are usually differentiated from those depicting concavities.

2.3.2 Slices

2.3.2.1 Profiles

A profile is a cross-sectional outline of the earth's surface. The drawing of an individual profile may be of great assistance in visualising relief and in the description and explanation of the land-forms. Such profiles are quantitative since a scale can be included. In most cases it is necessary to vertically exaggerate profiles to make them look correct, otherwise if they are drawn with no vertical exaggeration they tend to look too flat and the undulations along the profile will not be noticeable. A profile is differentiated from a section because a section is used in volume visualisation to show the underlying geological structure. A single profile is not regarded as a map but a map may be created by producing a series of closely spaced profiles (Brandes, 1983). When using a series of profile lines to describe the landscape those features that are parallel to the profile lines are not represented. This becomes evident when the direction of the parallel lines is changed, resulting in a very different portrayal.

The mesh/fishnet/crossed profile method consists of using two sets of profiles which are usually parallel to the map axes and usually based at 90^o to each other. The relief is portrayed by the network of squares that are distorted to reflect undulations of the landforms. This method is often used to illustrate statistical surfaces where the idea is "to make quantitative data analagous to terrain," (Brandes, 1983, p.91).

A variation on the profile technique is to draw oblique traces. Here the profiles are drawn at a slant so that they are perpendicular to the direction of viewing. This has the consequence of lengthening the front surface. Tanaka (1932) used this technique to represent terrain, labelling his technique the "orthogonal relief method". He used the term inclined instead of oblique to describe the profile lines drawn. These lines were also referred to as inclined contour lines, inclined traces or traces of parallel inclined planes and were constructed from ordinary contour lines. He intended the profiles to be perpendicular to the angle of the sun's illumination so that it could be used as a technique for shading. He writes (p.214) "inclined contours will appear as a sort of light and shade, since in accordance with the undulations of the ground surface the lines will be closer together in some places than in others." He goes on to say (p.214) "the inclined contours suggest the perspective appearance of the outline of the hills, and that the continuous lines of these contours running close together and nearly parallel to one another give life to the map," but he notes that one disadvantage of his method is the resulting maps are generally too dark. Variations of Tanaka's method were developed. Figure 2.1 was produced using one such variation.

2.3.2.2 Contours

Contour lines are the most widely used method for representing relief on maps (Raisz, 1938, p.129). They are imaginary lines which are not visible on the earth's surface. They connect all points at the same altitude and may be labelled with a numeric height value. Contouring is one use of isolines however, they are also used to depict a number of other phenomena such as isobars for pressure, isohyets for rainfall and isotherms for temperature. Contour lines usually occur at regular vertical intervals, though the

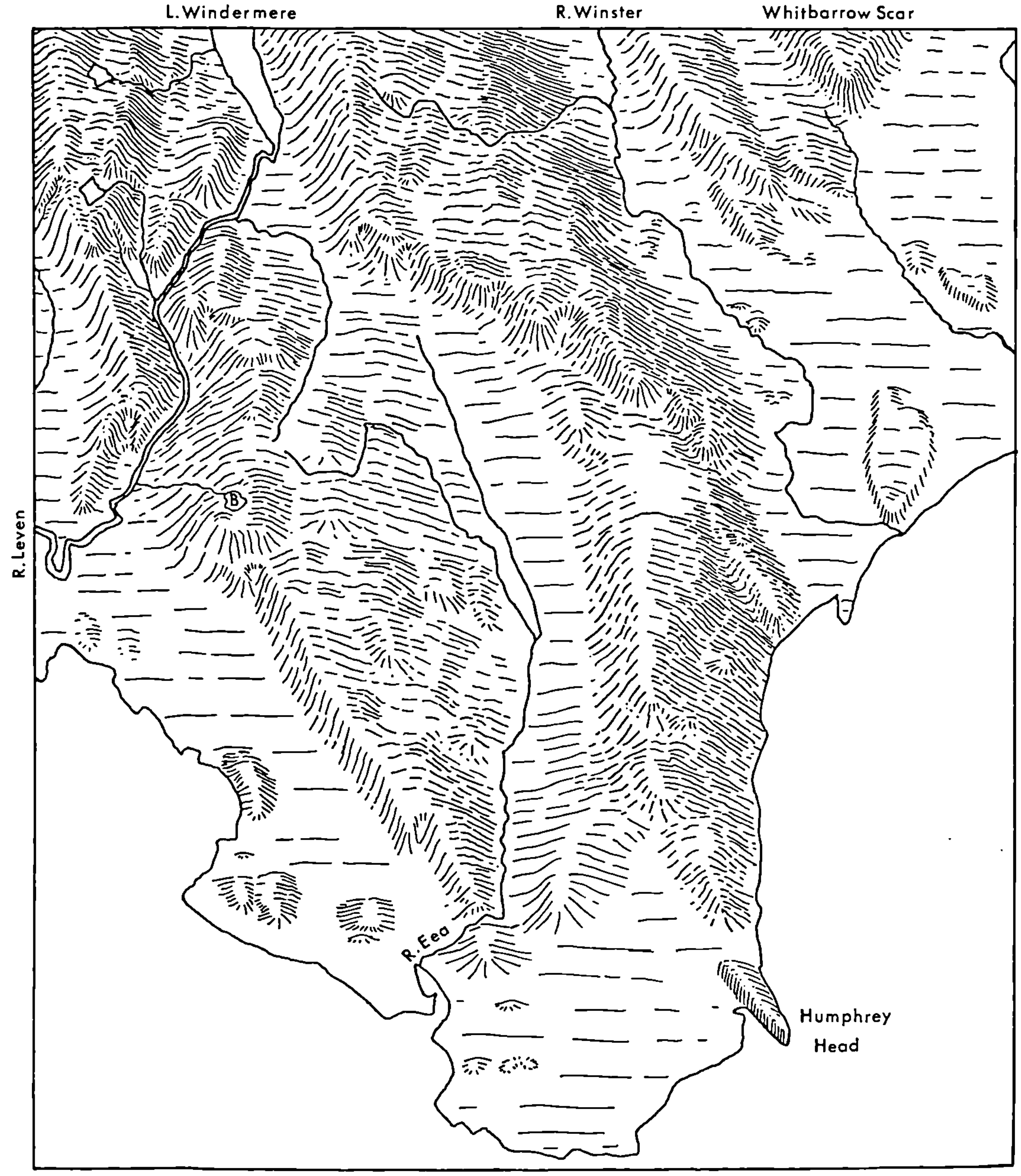


Figure 2.1: Modified version of Tanaka's inclined profile method (reproduced from Dickinson, 1969).

appropriate spacing varies according to the terrain. “In low lying areas a frequent contour interval is clearly necessary whereas in hilly areas this could lead to confusion,” (Lawrence, 1971, p.17). To facilitate the reading of contour maps every *n*th contour is emphasised. The emphasised contours are termed index contours and Imhof (1982, p.137) recommends that every fifth contour should be an index contour. Robinson *et al.* (1984, p.377) states that contouring is the most metrical system yet devised. However, Dickinson (1969, p.63) comments that intricate patterns of contours do not necessarily present an easily assimilated impression of the overall relief of an area. Extremely accurate contour maps can rapidly be produced from air photographs using modern photogrammetric methods. Not surprisingly, there have been numerous variations devised with the aim of making contour maps more expressive.

Contours may be accompanied by intermediate local contours. This is the addition of detail in the lower relief areas of a map by drawing occasional and partial contours at mid and sometimes quarter heights between the regular contour interval. These lines are shown in a different thickness or style (Lawrence, 1971, p.19).

“At times contours are drawn in by eye when a surveyor has few or no fixed heights to control the work. Such lines are meant to show the form of the land, and are called form lines,” (Birch, 1964, p.84). Dickinson (1969, p.63) describes form lines as lines which behave like contours but are not tied to any specific altitude - they show the shape of features but not their vertical extent. Lawrence (1971, p.16) uses the term form line to refer to a contour line derived by interpolation and therefore having less precision. Robinson *et al.* (1984, p.378) call these approximate contours. Bryant and Hughes (1918, p.82) state of form lines “Such lines are generally broken, and so cannot be mistaken for contour lines. They are not figured, as they merely show the general conformation of the ground and not actual heights.”

Kantography was introduced to make the contour maps of small regions more expressive. The contour lines are combined with break lines drawn where there is an edge or break in the topography. Breaks may be convex as in ridges, or concave as in valleys. Kantographic representation is of greatest significance in mountainous and glaciated countries while in smooth hilly regions, relatively few edges can be drawn (Raisz, 1938, p.149).

Variations exist which assume an oblique illumination source. Illuminated contour lines were developed to give a contour map the appearance of detailed relief while preserving the essential character of the contours. Normal contour lines are given a shaded effect by printing the contour lines relatively lighter or darker than a grey background depending on position toward or away from the light source (Tanaka, 1950). Other techniques for simulating oblique illumination but without the use of area tones are described by Imhof (1982, p.149) and consist of strengthening the parts of a contour line hidden from the light source.

Imhof (1982) describes other variations on contouring. On page 148 he describes a technique where contour line thickness is increased as the elevation increases and on page 143 he describes how the colour of the contour line can be varied based on elevation in a similar fashion to layer shading. However, he states that both of these techniques are not very successful.

Another variation of the contour line map is the three-dimensional step diagram. Here the spaces between contour lines appear as flat steps while the contour lines themselves appear as vertical rises.

Brandes (1983, p.91) describes a method of displacing standard contour lines to produce the effect of "an obliquely viewed three-dimensional surface". This is done by displacing the contour lines towards the top of the page. This variation is termed oblique contours. A good example can be found in Carter (1984, p.51).

"Where the ground is so steep and broken that contours become impracticable, recourse must be had to rock-drawing," (Hinks, 1933, p.27). Rock or cliff drawing is a means of showing the presence of such features from above and may be used in conjunction with methods other than contouring. Imhof (1982, p.235) describes techniques for rock drawing in great depth. However, he states (p.279) that "there is no satisfactory means of portraying steep cliffs and finely detailed rock areas in a cartographic plan view", the difficulty of which is obvious.

2.3.2.3 Layer Shading

Layer shading is also known by a number of other names. The word "layer" may be replaced by "altitude" or "hypsometric" and the word "shading" may be replaced by "colouring" or "tints". Here the area between certain arbitrary contour intervals is coloured depending on elevation. Care must be taken when selecting the range of colours to be used. One alternative is to use a sequence of greens, yellows and browns in ascending altitude, possibly culminating in red, purple and even white in high country (Monkhouse and

Wilkinson, 1976, p.96; see Imhof (1982, p.299-311) for a discussion of other colour schemes). Layer shading is a simple technique which has been widely used. It is commonly used on wall maps and atlases (Lawrence, 1971, p.24). This method is not ideal because heights between discrete contour intervals are uniformly coloured. The method can also be misleading as there is a tendency to equate the colour of areas with physical phenomena, green is often mistaken for vegetation and white for snow. Monochrome may be used instead of different colours.

This method may be combined with contour lines. Here the contours are shown regularly within the area of each layer. This method may also be combined with hachuring (Imhof, 1982, p.229) which is described in section 2.3.3.2. Unit shading, described by Carmichael (1969), is a method of combining layer shading and hill shading where the layers of colour are overprinted on a hill shaded base to give information about absolute altitude. Reverse layer tinting is another variation described by Carmichael (1969) for the combination of layer shading and hill shading. Reverse layer tinting aims to maximise the contrast between each layer step by overprinting two colour plates on which the darkness representing each layer is exactly opposite (reverse). By using complimentary colours for printing the effect given is of one solid colour at either end of the scale diminishing and merging with the complimentary colour from the opposite end.

2.3.3 Shading

2.3.3.1 Stippled Relief

Stippled relief attempts to describe terrain by using many small dots. This is similar to the pointillist painting technique of the impressionists though the dots used to depict relief are all the same colour. The level of shading is controlled by varying dot density which may be done to simulate either vertical or oblique illumination. In the case of vertical illumination the density of the dots indicate steepness of slope using the principle of "the steeper the slope, the darker the shading". When simulating oblique illumination dot density is determined according to light and shade. Brandes (1983, p.93) states that the dots may be "systematically aligned to indicate direction of slope." However, Alpha and Winter (1971) believe the use of dots is limited because they are less expressive than lines.

Traditionally, the effects of stippled relief were quickly obtained by using a thick, rough textured paper called stipple board. When chalk or charcoal is rubbed over the rough paper the density of shading is determined by the amount of pressure applied (Brandes, 1983).

2.3.3.2 Hachures

Lines have been used as a means of shading in art for many centuries and hachuring is one cartographic version of this technique. Hachures are short lines, drawn down the direction of slope (figure 2.2). The most common technique is to vary the hachures to indicate the steepness of slopes. Steep slopes are dark, grading into white for flat areas. Hachure variation is introduced by altering either "the thickness, shape, density, or length of the markings," Brandes (1983, p.93). Hachures are usually narrower on one end than the other with the narrow end pointing down hill. Hachures based on the principle of "the steeper the slope the darker the shading" can be thought of as being vertically illuminated. Another method of hachuring theorises an oblique source of illumination. Here the hachures are varied according to their position in relation to the light source. This method of hachuring is known as shaded (Lawrence, 1971, p.23) or shadow (Imhof, 1982, p.224) hachuring. "Hachures can pick out quite small relief features and very rugged or broken terrain usually comes out well; conversely gently undulating or flattish areas are much less easily represented. The vividness of well-drawn hachuring made it a popular method for showing relief, but it was slow to execute and expensive and consequently has largely been replaced by later devices" Dickinson (1969, p.58). A problem with hachures is that they do not provide absolute information and it is in some cases difficult to determine whether a blank area is a flat upland or lowland. On modern maps they are printed in colour, usually brown, purple or grey, since black hachures tend to have an obliterating effect in hilly areas, preventing the depiction of other detail. A problem with the use of hachures on small scale maps is that they can degenerate into rows of fuzzy looking marks referred to as hairy caterpillars or woolly worms.

Contoured hachures is a variation where the placement of the hachures are controlled by constantly spaced contour intervals. Hachures may also be combined with layer shading. Imhof (1982, p.230) describes a method of horizontal hachuring. In such a method the hachures resemble contour lines but are free to follow the shape of the terrain instead of being constrained to a single altitude. The thickness of the hachures may be varied to give an effect of either oblique or vertical illumination.

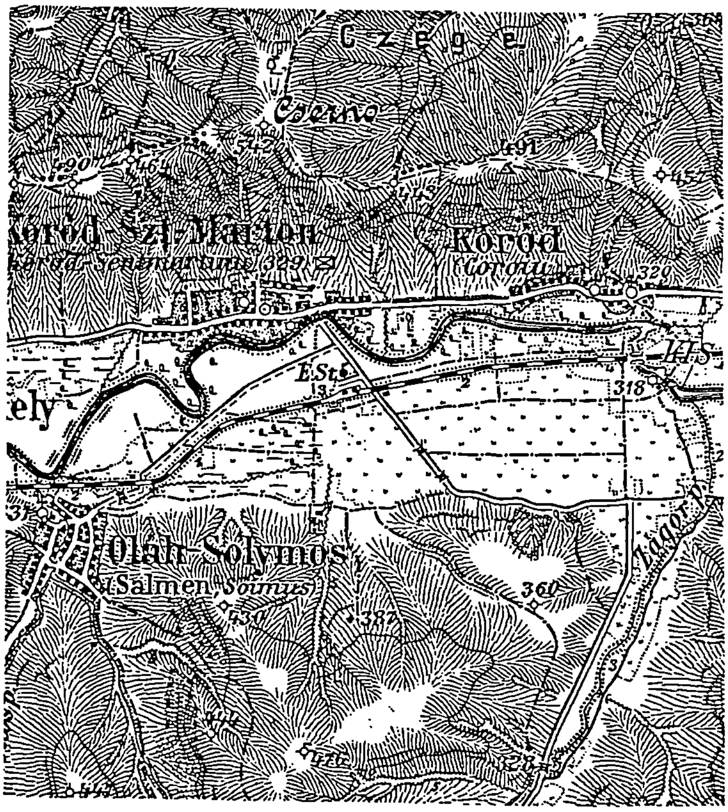


Figure 2.2: Hachuring (reproduced from Robinson *et al.*, 1984).

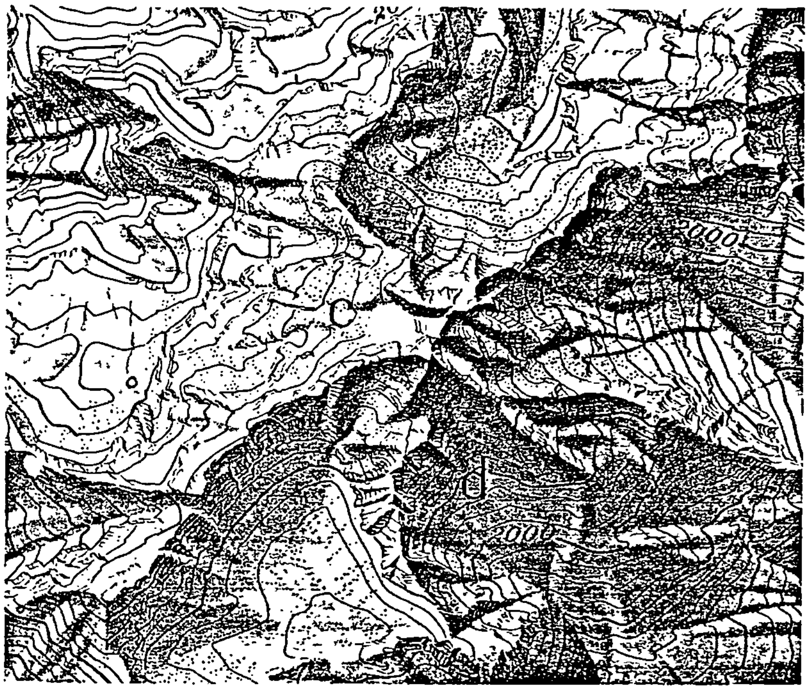


Figure 2.3: Hill Shading (reproduced from Imhof, 1982).

2.3.3.3 Hill-shading / Relief Shading

Burrough (1986, p.52) writes that hill shading "has roots in chiaroscuro, the technique developed by Renaissance artists for using light and shade to portray three-dimensional objects." Hill shading is also known as "plastic shading" or just "shading". The term "plastic" refers to a modelled three dimensional appearance and comes from the German word "plastik". Hill-shading attempts to simulate the effect of light and shade produced by illuminating a relief model, to produce a highly realistic representation (figure 2.3). The source of illumination is positioned either vertically above or obliquely. When lit from above ridge crests, plateaux, valley bottoms and plains are light. Grades of grey are used for shading slopes depending upon their steepness with the steeper slopes being darker. With oblique lighting the light source is usually positioned to the north-west, those slopes facing west and north-west are unshaded while slopes facing east and south-east are in the shade. In manual cartography the direction of the light may be varied slightly to better describe the features of the landscape. Sometimes the two positions of illumination are combined, one tone being used for vertical hill shading and another for oblique hill shading.

Hill shading may be produced manually by a skilled cartographer or by photographing a three dimensional relief model or automatically by computer. Imhof (1982, p.209) discusses work in the field of automated hill shading. The term "analytical hill shading" is usually used to distinguish automated hill shading from the other types.

The disadvantages of hill shading are similar to those of hachuring. There is a lack of specific information, confusion about which is uphill or downhill, spur or valley, plateau or plain, plus confusion about the relative steepness of slopes. However, hill shading describes the form of the terrain very well and can be used to good effect in conjunction with contours, hachures or both on topographical maps. Imhof (1982, p.166) favours oblique illumination. He emphasizes that vertical illumination has little or nothing to do with real illumination or shadow effects existing in nature (p.164) and writes that providing they have been skillfully constructed, maps which make use of oblique hill shading are easy to comprehend and bear a great resemblance to natural relief (p.166). Colour may be used instead of shades of grey.

The stereographic method is deceptively titled. It is not a method which requires two images and a stereoscope for viewing. Instead it is a combination of several techniques and so named because it is said to provide such a good three-dimensional impression of relief. It is a combination of oblique hill shading and layer shading. The hill shading is violet while the layer shading ranges from a greenish grey in the valleys to a bright orange-brown at high altitudes. Rock drawing is the final ingredient making the stereographic method excellent for use in mountainous countries while in lowlands it has little advantage (Raisz, 1938, p.145).

2.3.4 Pictorial/Artistic

2.3.4.1 Physiographic

Hill or mountain drawing is a primitive form of the physiographic technique. Standard symbols showing hills from the side are placed onto a vertically viewed map to show the location of such features. An example of this technique is shown in figure 2.4. "This method is usually found in very old or primitive maps and may be the first method ever used to portray terrain," Brandes (1983, p.91). Imhof (1982, p.1) says of the symbols used "the most common form of early mountain illustration remained the 'molehill': the simple, uniform, side view of a regularly rounded dome." The arrangement of these 'molehill' symbols to show a mountainous region unfortunately often

Figure 2.4: Hill or mountain drawing (reproduced from Lawrence, 1971).

results in an impression resembling fish scales. However, the hill symbols evolved over time to incorporate variations in size and shape as well as being shaded to give the impression of illumination.

Raisz (1938, p.155) comments that it has been suggested that the physiographic method should be called "the landscape method". This method may also be known as "morphographic" or "morphologic". Using this technique landforms are realistically portrayed and easily identifiable. Monkhouse and Wilkinson (1976, p.104) state that the physiographic method "has much of the nature and quality of landscape drawing", they go on to state (p.102) that it "gives a good broad impression of the country". Raisz (1931, p.303) writes of this technique "the map appeals immediately to the average man. It suggests actual country and enables him to see the land instead of reading an abstract location diagram. It works on the imagination. What this means can be best appreciated by teachers." A problem with the physiographic approach is that the side view of a landform has a vertical dimension which takes up space, traditionally used for planimetric position, possibly hiding other features.

Raisz (1931) provides an expert system in the form of a set of physiographic symbols which can be systematically applied to produce a small scale physiographic map. Raisz's table of symbols is shown in figure 2.5. Raisz (1931, p.299) writes that his table represents an effort to "classify the earth's surface into types and, from Davis, Lobeck, Morris, Cotton, de Martonne, and other masters of this art, to select the best symbols for the types, keeping in mind that the good symbol is that which can be read without an explanation."

Robinson and Thrower (1957) propose a variation on the physiographic method which attempts to remove the problem of planimetric displacement. They give the following example of the problem (p.507) "if a single mountain is drawn on a map as seen from the side or in perspective, the peak or base and most or all of the profile will be in the wrong place planimetrically." Robinson and Thrower (1957, p.507) go on to state that deviations from correct planimetric position on small scale maps might amount to "tens or scores of miles". Their method is based on inclined profiles as described by Tanaka (1932). The inclined profiles are produced from a contour map and serve as a guide for the drawing of the landforms. Figure 2.6(a) shows a set of inclined profiles and drainage features while figure 2.6(b) shows the finished rendering of the terrain. This method is appropriate for use at any scale. A critical appraisal of this technique is carried out by Oberlander, 1968; Oberlander, 1969 and Robinson and Thrower, 1969.

The physiographic method is a qualitative approach which means that it is not possible to measure heights or distances. The trachographic method (Raisz, 1938, p.274) is only intended for use at small scales and represents the ruggedness of the terrain by drawing many tiny hill shaped curves. The height of each curve is proportional to relative relief while its width is proportional to average slope. The curves may also be shaded to simulate illumination. Raisz (1938, p.274) states the purpose of this technique as the combination of a measurable representation with "a pictorial effect which can easily be perceived and remembered". This technique is illustrated in figure 2.7. Raisz (1938, p.276) goes on to say that this type of map does not require a great deal of artistic ability. The proportional relief landform map (Ridd, 1963) also attempts to introduce a quantitative element by making the height of landforms on the map directly proportional to their actual relief. This method was developed for the production of medium-scale maps.

Alpha and Winter (1971) proposed a variation termed the "quantitative physiographic method". This is another variation which introduces a quantitative element. Accurate height data is provided by adding planimetrically adjusted contour lines to a qualitative physiographic diagram. The adjusted contours which may be obliquely illuminated are produced by a special device called an isometrograph (shown in figure 2.8(a)). This is similar to the device used to create Dufour diagrams, which are described in section 2.3.4.3. The quantitative physiographic method is intended for

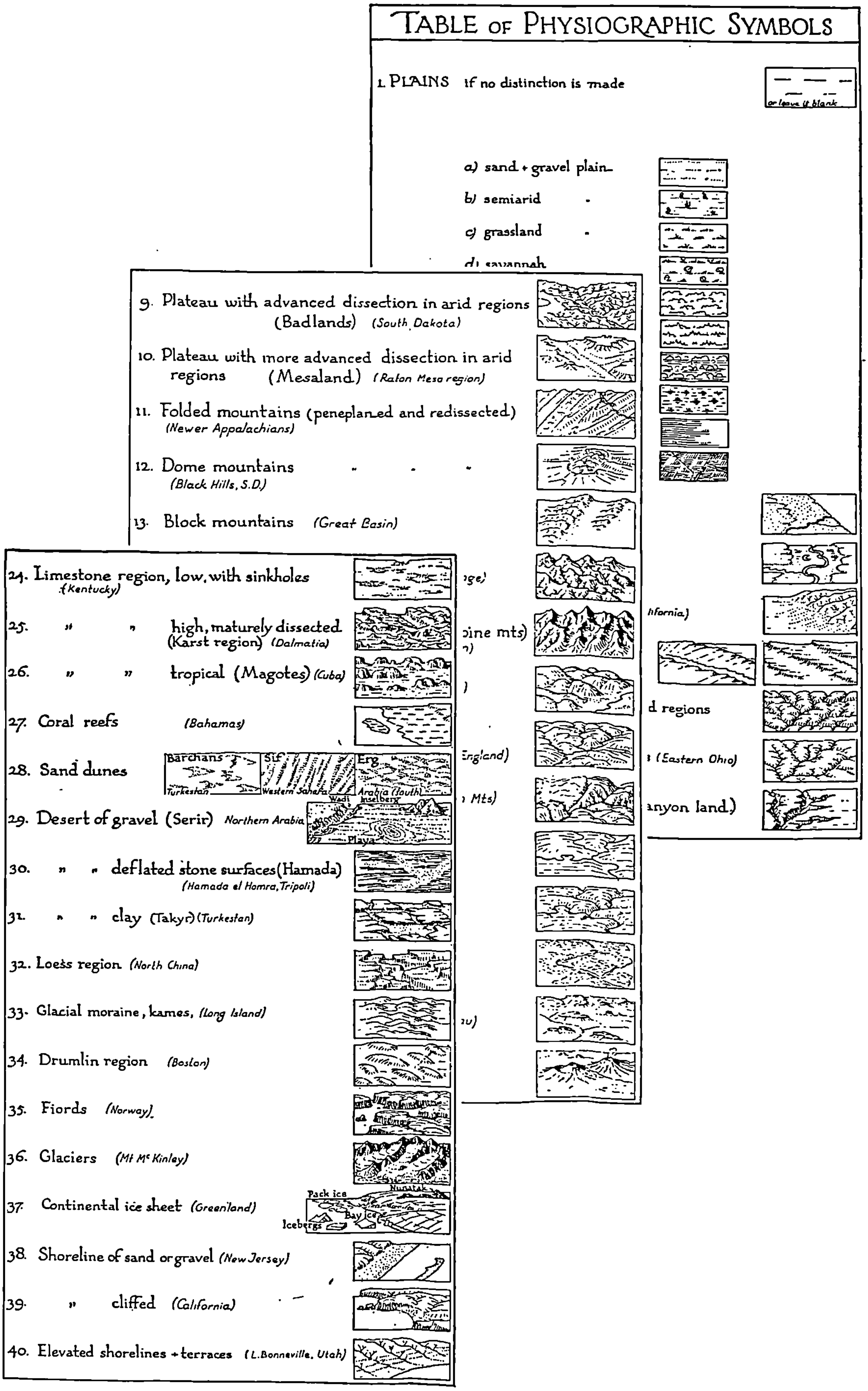
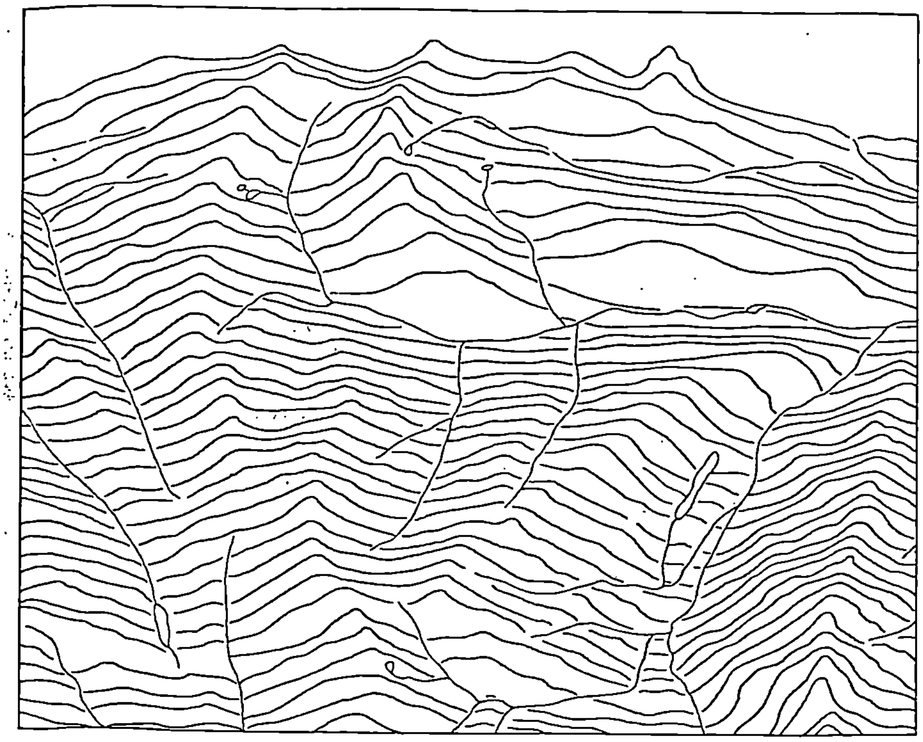
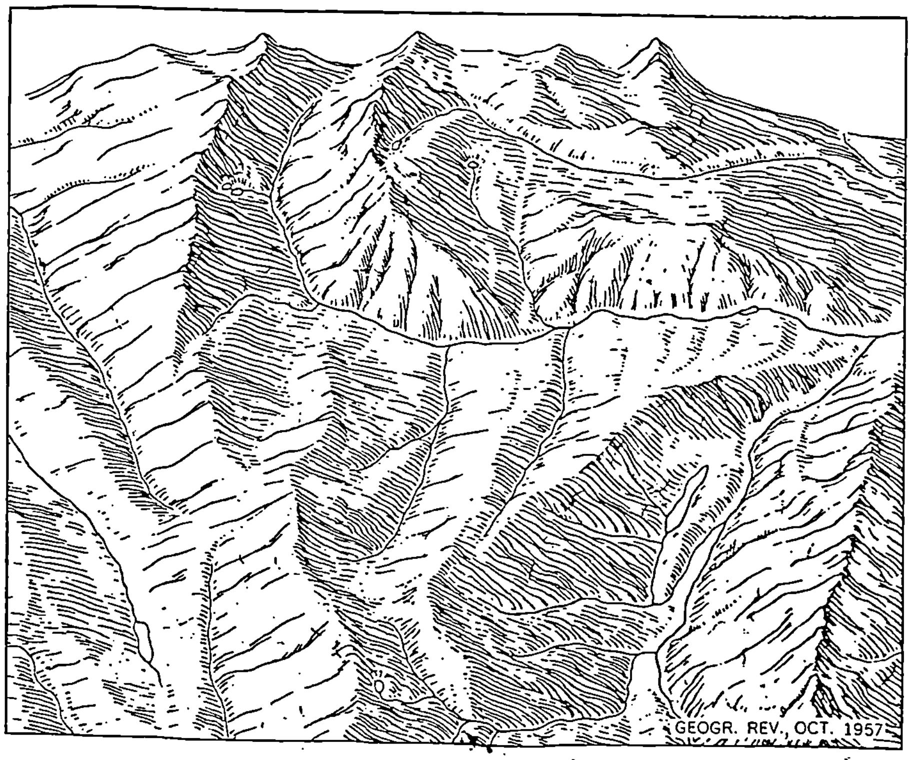


Figure 2.5: Raisz's physiographic symbols (reproduced from Raisz, 1931).

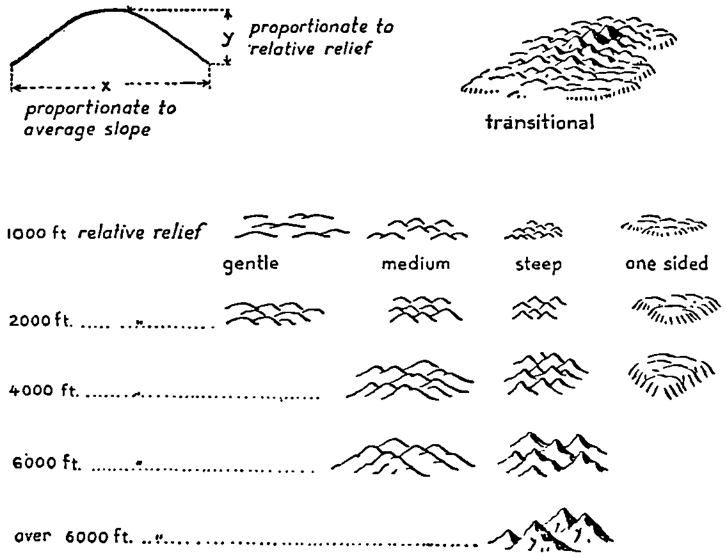


(a) Inclined profiles and drainage features (reproduced from Robinson and Thrower, 1957).

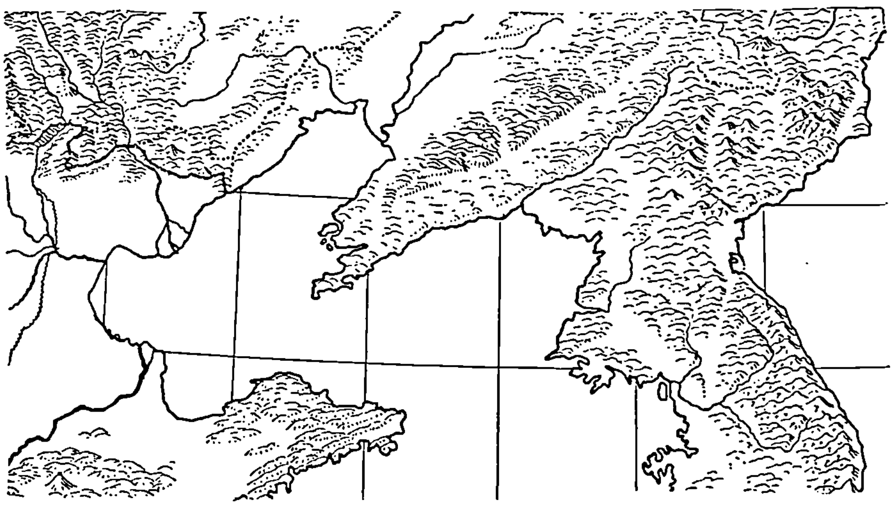


(b) Completed rendering of terrain (reproduced from Robinson and Thrower, 1957).

Figure 2.6: Robinson and Thrower's method.



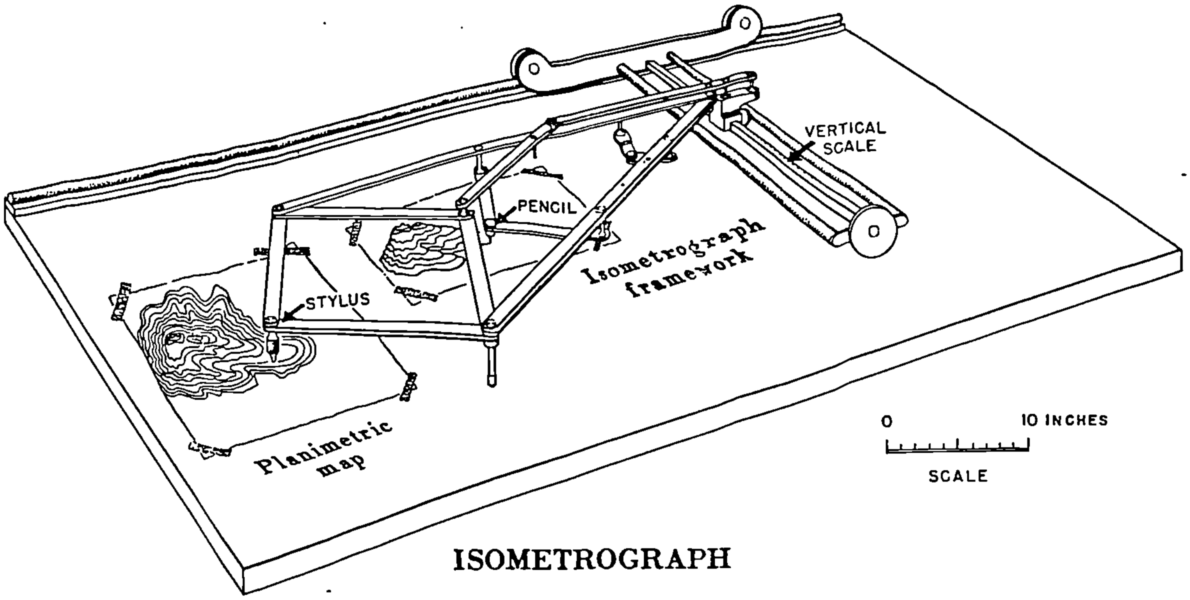
(a) Trachographic symbols (reproduced from Raisz, 1938).



(b) A trachographic map (reproduced from Raisz, 1938).

Figure 2.7: The trachographic method.

large-scales and the oblique landforms may be shaded using a method similar to hachuring in that lines are varied in direction, length, width and spacing, depending upon the slope they depict. Figure 2.8(b) shows an example of this technique.



(a) An isometrograph (reproduced from Alpha and Winter, 1971).

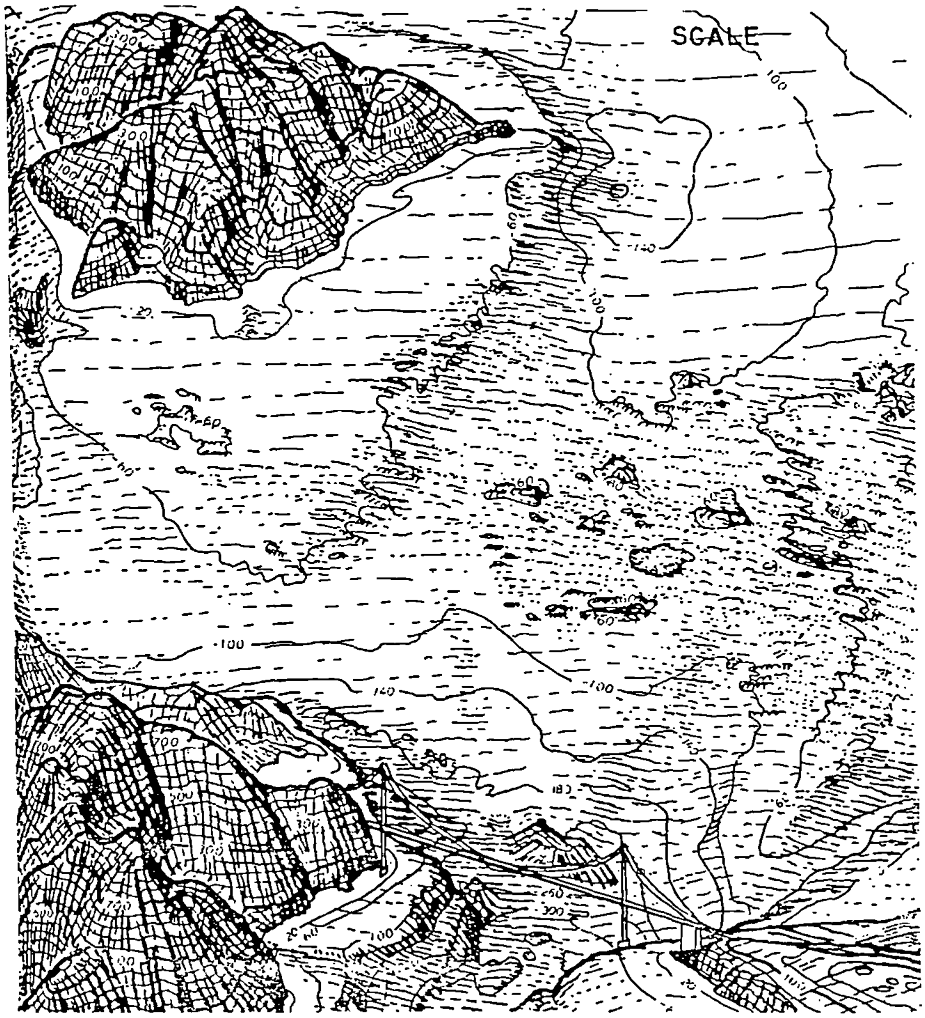
Figure 2.8: Alpha and Winter's method.

2.3.4.2 Oblique Regional View

An oblique regional view shows a section of a globe. It is usually constructed on either an orthographic projection or on a photograph of an actual globe. The portrayal of the terrain is pictorial. The very small scale involved means that a great deal of simplification is required and it is necessary to use a high degree of vertical exaggeration to make mountains visible. Oblique regional views are excellent at showing national viewpoints and strategic concepts. See Robinson *et al.* (1984, p.374).

2.3.4.3 Block Diagram

In his classic text Lobeck (1924, p.1) gives the following description, "A block diagram presents the relationship between the surface of the ground and the



(b) The quantitative physiographic method (reproduced from Alpha and Winter, 1971).

Figure 2.8: Alpha and Winter's method.

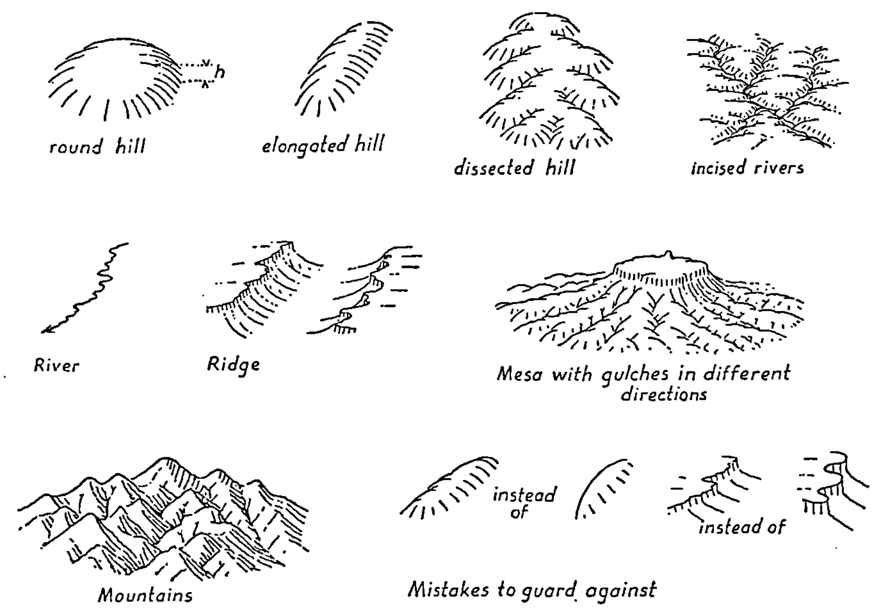
underground structure by representing an imaginary block cut out from the Earth's crust. The top of the block gives a bird's-eye view of the region, and the sides of the block its underlying geological structure". As can be seen in figure 2.9(b) the surface of a block diagram is represented pictorially and therefore requires some artistic ability to produce. Raisz (1938, p.294) attempts to aid the draughtsman by providing a catalogue of basic graphic forms which can be put together to describe most landforms. Raisz's catalogue is reproduced in figure 2.9(a). Sometimes it is only the top of the block which is of interest and in such cases the sides of the block are either shaded or left blank. The advantages of block diagrams are expressed by Birch (1964, p.139), "Block diagrams require very little skill in their interpretation, they render long verbal description unnecessary, and are fairly easy to remember and reproduce. They illustrate land forms better than photographs do, and when applied to fairly extensive areas, they illustrate topography in a way which maps alone fail to do." The construction of block diagrams is described by Lobeck (1924), Monkhouse and Wilkinson (1976), Stacy (1958) and Birch (1964).

A variation of the block diagram is the panoramic section. These are extremely elongated from left to right and narrow from top to bottom (Brandes, 1983). Raisz (1938, p.287) refers to these as block or animated profiles and describes their purpose as enhancing the expressiveness of a profile by adding a narrow strip of landscape in the fashion of a block diagram.

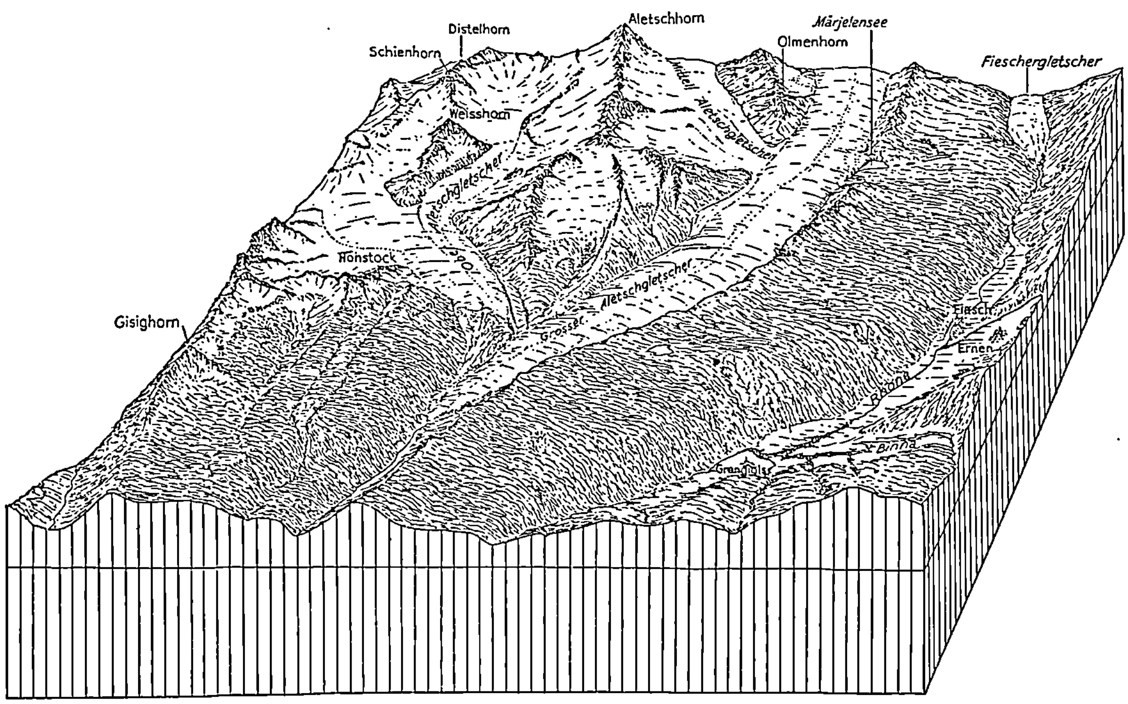
Dufour diagrams are isometric block diagrams created from contour maps by the use of a mechanical drawing device invented by the French student M. Pierre-Th. Dufour. The lines of the contour map are followed by the draughtsman and the mechanical device creates the corresponding block diagram. The device also allows the size of the resulting illustration to be controlled. The pictorial surface of the block diagram may then be drawn using the contour lines as an aid. See Lobeck (1924, p.142) for a detailed description of how such a machine works.

2.3.4.4 Landscape Sketching

Artistic sketching or landscape drawing is the application of an individual's artistic ability to produce an impression of a landscape. The resulting sketch is highly individual, style varying from one artist to another. Unfortunately landscape drawing seems to have lost much of its former importance due to the advent of photography. However, it possesses many advantages. Sketches



(a) Basic forms which make up the landscape (reproduced from Raisz, 1938).



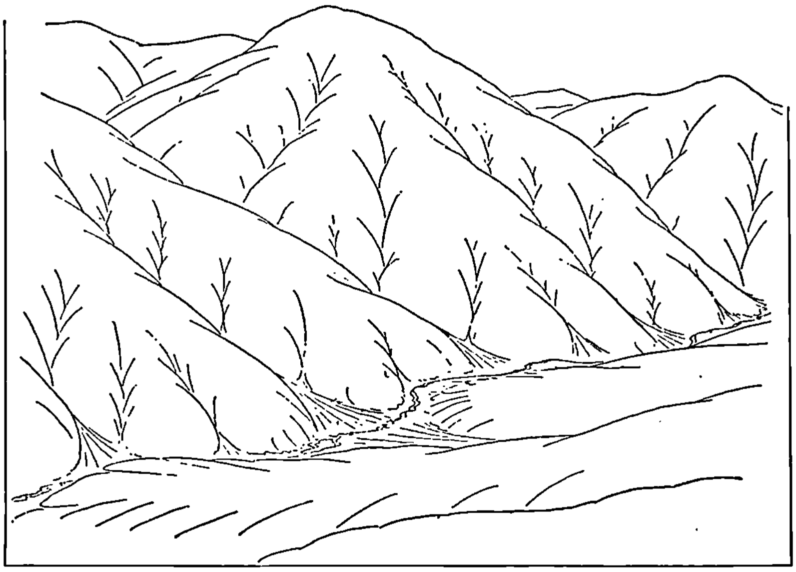
(b) A block diagram (reproduced from Lobeck, 1924).

Figure 2.9: Block Diagrams.

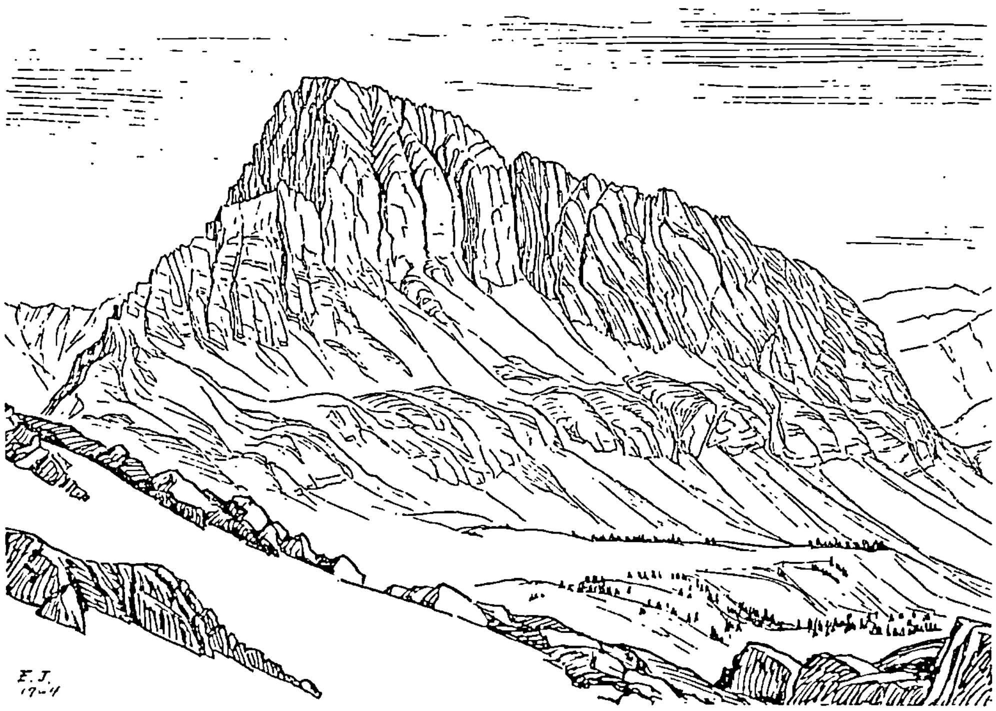
are interpretations of the landscape by skilled individuals rather than mechanical copies. A sketch allows the important elements of the landscape to be extracted and emphasised while irrelevant detail can be omitted. Figure 2.10 shows examples of landscape sketches.

Jones (1974, p.25) explains how landscape sketching was taught to military cadets in the last century. He writes "the human figure was studied in an attempt to measure the coordinates of known lines and curves as an aid to interpreting the curves of the landscape." Sketching was also taught by drawing three-dimensional models or the cheaper alternative of a pile of stones. Later sketching was done from three-dimensional geometrical solids in a similar fashion to that recommended by Lobeck (1924, p.3) who writes "the numerous topographic details which make up a drawing can be better represented if they likewise are related to geometrical solids to which the rules of perspective can be applied. Thus, rectangular and triangular blocks, pyramids, cones, hemispheres, and cylinders are easily drawn in perspective, and when deprived of their angular or severe character by a few judicious strokes, are made to represent mesas, and buttes, ridges, mountain peaks, volcanoes, and other features. Indeed there is no topographic form which cannot be related to a simple solid and as a consequence more easily drawn." Lobeck (1924, p.173 and p.174) reproduces tables of delineations showing how to sketch objects commonly found in the landscape, such as trees and buildings, as a further aid to the student of sketching.

While landscape sketches are a pictorial means of representation in their own right, they are often used in the preparation of block diagrams. Landscape sketching is of great relevance to this thesis and is discussed throughout. Sketches usually show an oblique view but Brandes (1983) points out that a vertical viewpoint may be used. Imhof (1982) described how he produced a landscape painting in plan view. Such paintings are impressionist in nature and do not slavishly show every detail. They employ light and shade as well as cast shadows which are removed for the cartographic technique of hill shading (see section 2.3.3.3). Aerial perspective provides a cue to the height of the relief. While such paintings provide beautiful impressions they are unable to provide the "topographic, conceptual and metric information" (Imhof, 1982, p. 337) which one expects from a map.



(a) A sketch by W. M. Davis (reproduced from Lobeck, 1924).



(b) A sketch by E. Imhof (reproduced from Imhof, 1982).

Figure 2.10: Landscape Sketches.

2.3.5 Realistic

2.3.5.1 Photomaps

A photomap is the combination of photography and map detail, for example the addition of contour lines to an air photograph. An air photograph makes it possible to obtain a picture of the landscape in a very short time (Van Zuylen, 1969). However, air photographs are subject to a number of possible distortions and must be rectified to remove these. When distortion has been removed to the point that an orthogonal projection of the ground is shown the result is an orthophotograph and map detail can then be added to produce an orthophotomap. A collection of air photographs may be joined together to give an overall picture of the ground, termed a mosaic. Imhof (1982, p.51) writes that photomaps which are well executed combine "the natural appearance and the richness of detail contained in the aerial photo with the metric and other properties of the map," but he goes on to state that "as a rule, such a mixture of graphically alien material provides little satisfaction,". Scott (1969) comments that photomaps can be difficult to interpret.

"Within the limits of photographic resolution capabilities and under suitable conditions of good lighting, *etc.*, aerial photographs (especially in colour) are realistic, instantaneous pictures of the earth's surface, albeit only its superficial aspects. However such pictures are often full of deceptive features and obscuring conditions. Similar things may frequently appear to be different. Important objects may not be visible while incidental or unimportant things may stand out clearly. The topographic map on the other hand, is a generalised image, conditioned by its scale, by its purpose, by conventions and by the artifice of its maker, and portraying significant and, more or less, permanent conditions and objects. Similar things appear the same. Important things are emphasized; unimportant things suppressed. Even if the map is made to resemble nature as closely as possible, it remains, in essence, abstract and more or less subjective; i.e. dependent on its maker." (Imhof, 1982, p.51). Photographs of landscapes may be atmospheric and beautiful, for example the wonderful pictures in Wainwright and Brabbs (1991) or Aerofilms Ltd. (1991). We are all familiar with such photographs on postcards, in travel brochures and in our own holiday snaps. However, the differences between aerial photographs and maps described by Imhof also apply to the differences between such landscape photographs and artistic sketches.

2.3.6 True 3D

The ultimate representation of terrain is the terrain itself. However, also counted in this category are three-dimensional models and globes.

A relief or terrain model affords a three-dimensional reproduction of the landscape, with length and breadth to scale, though it is necessary to introduce vertical exaggeration. Raisz (1938, p.331) writes that many geographic relationships are made surprisingly clear on a model. Models have been used for a wide variety of purposes. Raisz (1938, p.331) lists engineering problems, landscape architecture and the demonstration of interesting geological structures while Jones (1974) mentions the use of models for teaching students to sketch and for the planning of military operations. Models may be made from plaster, potter's clay, superimposed layers of paper, card, hardboard or plywood or from various plastics. These models may be prepared from topographical maps and/or air photographs (Monkhouse and Wilkinson, 1976, p.83). Robinson *et al.* (1984, p.388) states that the production of a three-dimensional model is not an easy task.

Globes have been made ever since the ancient Greeks recognised that the Earth was round. A globe is the most correct representation of the Earth and the only representation in which the scale can be made correct for all parts of the Earth's surface. Worldwide relationships in geology, geography and other Earth sciences can often best be understood from globes. This gives them great educational value. Most globes are political in emphasis and show the various countries in vivid colours. A better representation of the form of the Earth is given on physical globes which use layer shading, sometimes combined with hachuring (Raisz, 1938, p.328).

2.4 COMPUTERISED VISUALISATION

Haber and McNabb (1990, p.75) defined visualisation as "a series of transformations that convert raw simulation data into a displayable image. The goal of the transformations is to convert the information into a format amenable to understanding by the human perceptual system". They divided the process of visualisation into three stages:

1. Data enrichment/enhancement transformations. These convert raw data into derived data.

2. Visualisation mapping. The derived data is transformed into an Abstract Visualisation Object (AVO).

3. Rendering. This transforms the AVO into a displayable image.

In order to be able to render a piece of terrain it is necessary to first create a model of the terrain inside the computer. The AVO is such a model. Different types of terrain models can be used, each of which can be rendered in a number of different ways. Thiemann (1989, p.177) mistakingly refer to rendering as visualisation when they write "Visualisation is the process of using the computer model of the terrain or scene to create a picture. The final output is assumed to be a bitmap of pixels. Visualisation can be thought of as the process of taking 3D-information ... (the model) ... and making a 2D image from it". The first stage is preprocessing and is not always necessary. For example, preprocessing may be the selection of every second height, if the resolution of the raw data is very high, or the generation of artificial terrain.

The methods used for rendering AVOs/terrain models are restricted by several factors:

1. terrain model type. While a model can be rendered using different techniques, both two- and three-dimensional, the type of model influences which rendering techniques can be used. The type of terrain model is itself influenced by data collection techniques. The types of digital elevation model available have also influenced which methods from conventional cartography have been emulated.

2. the computer's capabilities. The methods of rendering supported are ones which rely on skills matching the aptitudes of the computer, the calculation of mathematical formulae and the following of deterministic steps. Very seldom is an attempt made to provide other methods which require skills of which the modern computer is found wanting, such as the artistic ability necessary to produce a landscape sketch.

3. ease of implementation. The regular grid is the most popular terrain model because it is easy to implement. Similarly, the chosen method of rendering is often influenced by ease of implementation.

Because of the influence of the AVO/terrain model on the rendering technique, terrain modelling is briefly described below. The problems of rendering triangular irregular networks are also described.

2.4.1 Terrain Modelling

"Any digital representation of the continuous variation of relief over space is known as a digital elevation model (DEM). The term digital terrain model (DTM) is also commonly used. Because the term 'terrain' often implies attributes of a landscape other than the altitude of the landsurface, the term DEM is preferred for models containing only elevation data. Although DEMs were originally developed for modelling relief, they can of course be used to model the continuous variation of any other attribute Z over a two-dimensional surface," (Burrough, 1986, p.39). Milne (1992) uses the alternative term 'Digital Ground Model' (DGM). The term DEM will be used in this thesis. The two most widely used types of DEM, namely the regular grid and the triangulated irregular network, are described below. When choosing which of these to use the purpose of the application must be considered. Each model has its strengths and weaknesses which may make one more suitable than the other for certain applications.

Extracts from the initial draft of a paper by Visvalingam (personal communication), being co-authored by her and myself, have been extended and used in sections 2.4.1.2 and 2.4.1.3.

2.4.1.1 The Regular Grid

The most common form of computer model is a grid of heights. Here the data comprising the terrain model is measured or collected in the form of a regular grid. It is only necessary to store the height values (attribute Z) because the coordinates of each point (X,Y) can be determined from the position of the point in the grid. The disadvantage of this method is that the grid size is constant and must be determined in advance rather than being related to the characteristics of the terrain. However, it must be small enough to capture the detail in complex areas which leads to over representation (data redundancy) in areas which are less complex. "While the square grid is the most common form, rectangular, hexagonal and triangular-based grids are also encountered," (Petrie and Kennie, 1987, p.172). This is the simplest model to implement and to store on a computer. Its main advantage is the ease and efficiency of processing.

2.4.1.2 Detection of Surface Specific Features

The extraction of primal sketches and cartoons from images seeks to emulate the manual tracing of outlines in images, such as photographs. This is a key area in the field of computer vision where the system has to "understand" an image (Haralick *et al.*, 1983). Pearson and Robinson (1985) and Pearson *et al.* (1990) seek to extract cartoons of people's heads and hands to achieve data reduction in order to transmit the images over a telephone line for the purpose of teleconferencing and deaf communication. The recognition of objects in an image is constrained to a single view, in much the same way that the field sketch is just the view from one vantage point. The DEM, on the other hand being a three-dimensional model, facilitates the production of sketches of multiple views. It is clearly advantageous to derive these from a topological model. Developments in three-dimensional computer graphics and visualisation are already being exploited to simulate flight around DEMs (Cohen and Gotsman, 1994). As noted earlier, application builder visualisation systems, such as AVS (Upson *et al.*, 1989) and Iris Explorer (Edwards, 1992) offer a range of tools and techniques for visualisation and rich human-computer interaction within a data flow model for visual programming (Brodlie *et al.*, 1992; Visvalingam, 1994). Such systems provide a high degree of realism in the visualisations they produce. Visvalingam (1991) pointed out that mental visualisation is better served by graphic visualisation of abstractions, as undertaken within cartography, than by rendering of all data. Recently, British Aerospace (1993a; 1993b) attempted to omit some of the map detail when laying it on the three-dimensional surface of terrain but did not address the problem of generalising the terrain itself.

Sasada (1987) produced artistic sketches of distant mountain ranges. Although this must have involved caricatural generalisation of the terrain the paper did not describe the algorithms. Moreover, the sketches are of distant mountains where a vague impression is sufficient; the figures only show the major relief features and the detail on nearer views is obscured by simulated vegetation. Sasada experimented with several techniques to produce his mountain ranges. One method consisted of drawing all of the ridges visible from a specified viewpoint. The ridge lines are detected by checking points in order of distance from the viewpoint to see if they are visible. In this way boundaries can be located where the next point is no longer visible and these boundaries are the ridge lines. Other techniques involved showing only the upper ridges giving the outline of the mountain range or using the natural waterflow lines. Sasada also experimented with the use of shading.

While Sasada (1987) was concerned with producing artistic sketches of the landscape other researchers have been more concerned with deriving topological sketches. The ideas of Peucker and co-workers are relevant to our long term programme of study. This group addressed two problems, the abstraction of significant relief elements (Peucker and Douglas, 1975) and the approximation of the terrain surface by Triangular Irregular Networks (Peucker *et al.*, 1978).

Peucker and Douglas (1975) used local operators, similar to those used in low level image processing, to filter, connect and infer a variety of surface specific features, such as ridges, channels, peaks, pits and passes from regular grid DEMs. As explained by Fowler and Little (1979), the redundant cells within the linear features could be weeded out using line simplifiction algorithms, such as the Douglas-Peucker algorithm. There is continuing research to identify features in regular grid DEMs. Features, such as drainage networks (for example Mark, 1984, Haralick *et al.*, 1985, Tribe, 1990 and McCormack *et al.*, 1993), drainage basins (for example Jenson and Trautwein, 1987 and Jenson and Domingue, 1988) and ridge lines (for example Douglas, 1986 and Skidmore, 1990), as well as others have been detected.

Douglas (1986) described a new type of DEM based on valley, ridge and other information-rich lines. He termed this the RICHLINE digital elevation model. Important points detected using low level filtering methods are connected into information rich lines. While the identification of ridge and channel lines has a host of other uses, Douglas describes its main utility as the capacity to generate the model from a regular grid DEM and then to recompose the grid from the RICHLINE model. In this sense it is primarily a storage saving structure.

Heller (1990) stated that it would be a difficult and needless detour to try to algorithmically extract structures from a DEM when they were ignored in the sampling process and that the reconstruction of structures leads to plausible, yet quite arbitrary, results. However, in general, published results show that bottom-up tracking of features has some value in identifying the network of drainage channels and well-defined watersheds. In other types of geomorphic regions such as rolling hills, the results are noisy and are not as useful especially for delineating uplands. Peucker and Douglas (1975) conjectured that the discretisation of data in all three dimensions (x, y and z) impeded the recognition of intrinsically continuous features and that their algorithms were sensitive to encoding noise. Fowler and Little (1979) and Heller (1990) have observed that the abstracted surface specific features do not necessarily follow significant relief features in all cases.

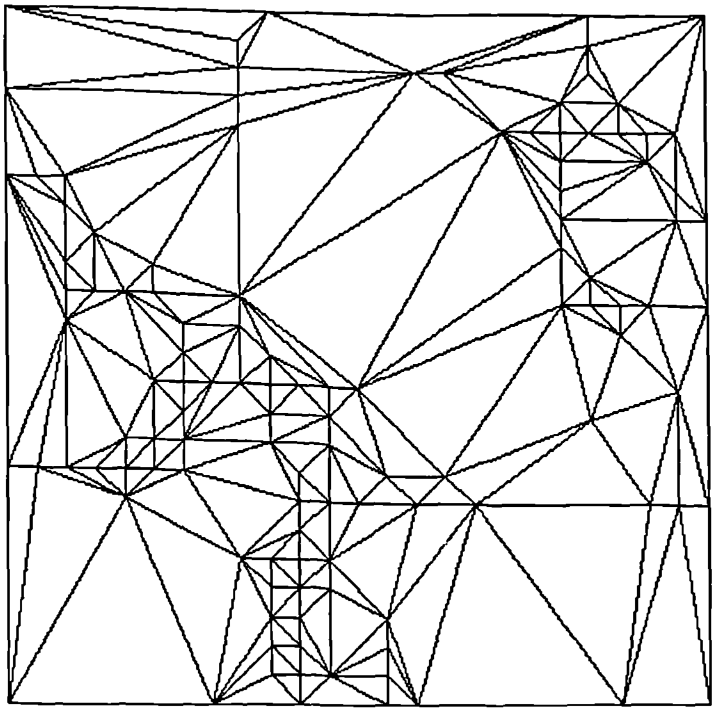


Figure 2.11: A triangulated irregular network (TIN).

The automatic recognition of surface specific structures continues to form a part of the long term research strategy of the Cartographic Information Systems Research Group (CISRG) but the procedures for sketching, described in this thesis, are not dependent upon the presence of such explicit high level knowledge.

2.4.1.3 Triangulated Irregular Networks

The second model consists of irregularly spaced data samples. These samples are collected at points of interest such as the summits of hills and can follow important topological features such as ridges and streams. It allows digitising to the accuracy required, eliminating the redundancy of the regular grid. However, it is necessary to determine how to connect the data points into a set of triangles.

Peucker *et al.* (1978) considered how terrain could be represented by a mosaic of contiguous, non-overlapping and irregularly sized and shaped triangular facets, called a Triangulated Irregular Network (TIN) (figure 2.11). This vector representation of terrain is similar in essence to the data structures developed by Peucker and Chrisman (1975) for modelling areal entities. TINs have since become standard concepts within proprietary Geographical Information Systems (GIS). For example the widely used Arc/Info GIS provides the "TIN" package to construct and manipulate TINs (ESRI, 1991). Delauney triangulation, which is the most widely used method of creating a TIN (DeFloriani, 1987), is used to connect the irregularly spaced heights into a network of triangles. Research on TINs is continuing, addressing problems of statistical and structural fidelity as well as the improvement of computational efficiency.

While the irregular set of points used to construct a TIN may result from the sampling strategy which is used, methods have been devised to extract an irregularly spaced set of points from a regular grid - Lee (1991) reviews such methods. To obtain the best results the most important, information rich points in the regular grid must be selected for inclusion in the TIN. Fowler and Little (1979) began by detecting surface specific features using the method devised by Peucker and Douglas (1975) - see section 2.4.1.2. A subset of the points defining linear features were selected using a three-dimensional extension of a line filtering algorithm devised by Douglas and Peucker (1973). These points were then connected to form an initial triangulation. Additional support points were included to reduce the maximum error below a specified tolerance to achieve statistical fidelity. The selection of a support point consists of computing an error for each unused point as the difference between its elevation and the interpolated elevation at that position on the surface of the TIN. The point which causes the maximum error is then inserted into the triangulation. This process is repeated until the maximum error is within the desired tolerance. "An error measure based on the vertical distance only is by now the most extensively used one in data compression methods for surface approximations" (De Floriani, 1987, p.43). Chen and Guevara (1987) used an image processing technique, in the form of a modified spatial differential high-pass filter, to extract the set of important points for triangulation. Here the importance of each point is based upon the difference between its actual elevation and an estimated elevation computed from its neighbours. A third method is the drop heuristic method (Lee, 1991) which starts by including every point in the regular grid as a point in the TIN. The point which is deemed least important, using a vertical distance measure, is dropped and the process continues until a point set of the desired size is produced or the desired tolerance has been reached. The concept of repeated elimination is similar to that used by Visvalingam and Whyatt (1993) in a two-dimensional context for their cartographic line simplification algorithm which is used in the process of sketching as described in chapter 3. De Floriani *et al.* (1983) used a vertical distance error measure to construct TINs within the required tolerance using a subset of points from an irregular data set.

Peucker (1975) and Ballard (1981) suggested that a line can be modelled in terms of a hierarchy of significant points and their strip trees respectively. A strip tree consists of a binary tree structure where the lower levels of the tree correspond to finer resolutions. Peucker used the term "bands" rather than strips. De Floriani *et al.* (1984) extended this idea to the three-dimensional domain to produce a hierarchical approximation of a surface using a TIN. The terrain surface is segmented into a hierarchy of (nested) triangular facets with each successive level of the hierarchy recording finer levels of detail. Their prime concern was with representation and compression of spatial data while maintaining statistical fidelity at a variable accuracy, providing a crude form of surface generalization. However, Visvalingam and Whyatt (1990; 1991) and Visvalingam and Williamson (1994) have shown quite conclusively that the Douglas-Peucker method of selecting maxima and minima is unsuitable for caricatural generalisation. Visvalingam and Whyatt (1990) also demonstrated why the current approaches for mathematical judgement of the success of generalisation may be objective but are nevertheless "inappropriate, misleading and questionable" (Visvalingam and Whyatt, 1990, p.213). They instead recommend evaluation through visualisation. The idea of a nested triangulation is similar to the quadtree data structure (Samet, 1984; Gargantini, 1982) which has been applied to representing grid DEMs (Chen and Tobler, 1986).

The TIN model is becoming increasingly popular for its storage efficiency and its ability to represent irregular data points. However, when a large number of data points are available a TIN can be highly inefficient in storage and for search and retrieval operations (De Floriani, 1987). Jones *et al.* (1994) state that while TINs typically use many fewer points than a regular grid they do not usually occupy much less data storage, due to the topological data which records how the points are connected into a network. However, Jones *et al.* (1994) try to remedy this with their implicit TIN which instead of storing topological information regenerates the TIN each time it is required.

Work has also been carried out to extract surface specific features from TINs. Palmer (1984) and Frank *et al.* (1986) describe the extraction of features such as peaks, pits, ridges and valleys using Prolog rules from a TIN structure coded as a series of Prolog facts. More recently Falcidieno and Spagnuolo (1990a, 1990b and 1991) devised an alternative method of extracting topographic features from TINs. Their technique works by considering the type of adjacency between triangles in order to divide the terrain surface into characteristic regions with concave, convex or planar shape. Linear features such as ridges, ravines and breaks of slope can be identified as can salient points such as pits and peaks. They then construct a graph-like data structure termed a "characteristic region configuration graph". This is an effective and concise representation of the surface similar to Douglas' RICHLINE model.

Current proponents of TIN argue that the required surface specific information are all implied by the TIN model and that it is possible to produce a variety of displays, including profiles, shaded relief maps, horizons and block diagrams from TINs. However, as Burrough (1986, p.43) has already pointed out, the final images retain the imprint of the Delauney triangulation. The results look unnatural. Douglas (1986) also commented on the problems associated with TINs. "A major difficulty with models based on triangles is that almost every graphic produced from them, such as a contour map, or perspective view, is beset with evidence of the method of construction in the form of distracting graphic artifacts. In some cases the artifacts totally dominate the structure being portrayed. A second, more severe, limitation of the triangular irregular grid digital elevation model is that it has limits of adaptability that are almost as severe as those of any regular partitioning. The rate of transition in density of the distribution of triangles over a surface is severely constrained," Douglas (1986, p.31). At the current stage of know-how, Heller (1990) felt that we have to be content with terrain models which may exhibit interpolation artifacts although the work by Falcidieno and Pienovi (1990) using their constrained stochastic interpolation technique, assumed that the appearance of TIN-based images could be enhanced by the application of fractal techniques to add minor surface detail and roughness. It is well known that artificial terrains generated by the midpoint subdivision of triangles contain artifacts caused by the way in which the triangles are subdivided (Dixon, 1994a; Voss, 1985). However, it is suggested here that such artifacts may be a fundamental feature of the TIN model which become amplified by the algorithm currently used for simulation. Heller (1990) attempted to improve the structural fidelity of TINs, which are now beginning to acquire the symptoms of baroque ill-fitting theories with piecemeal elaborations. There are landscapes, for example around Locarno and Ticino in Switzerland, which seem to be distinctly triangulated. However, the TIN model is inappropriate for other types of physiographic regions.

2.4.1.4 Filtering and Interpolation

Filtering and interpolation are preprocessing operations. The "most important" points may be extracted from a regularly spaced grid of heights by the process of filtering thus producing an irregularly spaced set of data suitable for triangulation (Lee, 1991). Similarly, an irregularly spaced set of data can be turned into a regularly spaced grid through the process of interpolation of heights at the grid positions (based upon the available data) (Petrie and Kennie, 1987). "Interpolation techniques can also be used to generate a finer grid from a coarser one," (Burrough, 1986, p.41).

2.4.1.5 Artificial Terrain

Lang (1993) describes three types of terrain data; real-terrain data recorded from the earth's surface, edited real-terrain data (*e.g.* increasing mountain height for aesthetic purposes) and computer generated artificial terrain data. A great deal of work has been conducted towards the generation of artificial terrain for purposes of simulation. Such methods usually utilise fractal techniques introduced by Benoit Mandelbrot (Mandelbrot, 1982). It was Mandelbrot who perceived an analogy between a record of Brownian motion over time and the skyline of jagged mountain peaks. He extended the idea to two-dimensions and used fractional Brownian motion (fBm) to create "fake landscapes". However, since such reliefs are "... based on involved algorithms", p.263, "approximations or shortcuts are needed," (Mandelbrot, 1982). This led to simpler methods of approximating fBm. The most common of which is midpoint subdivision (Fournier *et al.*, 1982); for examples of artificial terrain produced in this manner see Mandelbrot (1982), Peitgen and Saupe (1988) and Brivio and Marini (1993). Another method of generating artificial terrain is by the simulation of natural processes. This is the modelling of the geomorphological processes which shape the terrain. Kelley *et al.* (1988) used a model of stream erosion to accomplish this while Musgrave *et al.* (1989) simulated hydraulic and thermal erosion processes or more simply rainfall. The result of the preprocessing step which generates the terrain is an AVO/terrain model, which is either a regular grid or a TIN, which can then be rendered.

Work has been carried out here, in the computer science department at the University of Hull, to generate artificial terrain using the midpoint subdivision technique (see Dixon, 1994a). This work resulted in an improved data structure for artificial terrain generation (see Dixon *et al.*, 1994b), investigated fractal interpolation (see Dixon *et al.*, 1994c) and considered the generation of terrain on a planetary scale (see Dixon, 1994a).

2.4.2 Methods of Rendering

The great advantage of computer visualisation of terrain data is that of producing images very quickly and effortlessly. This is especially the case with three-dimensional diagrams which are of great value but can be time consuming and tedious to produce using conventional cartography.

There are many methods for visualising terrain in three-dimensions however, each method positions the terrain in one of two ways:

1. It is common to show the terrain using profiles, fishnet, *etc.* on top of a three-dimensional base, as in a block diagram. It is a pity that many texts (such as Burrough, 1986) have started to label such diagrams as block diagrams since these data displays involve neither generalisation nor artistic skill.

2. The alternative method of three-dimensional visualisation is to present a scene. In this case the terrain occupies the field of view and the edges of the DEM are not visible.

2.4.2.1 Raw Data

The simplest method of visualisation, which does not require any computer graphics, is to display the raw data - the heights themselves. Each height is similar to a spot height in conventional cartography and shares the same advantages and disadvantages. The heights are precise yet give no general idea of relief. A regular grid model can be conveniently displayed as a two-dimensional table. However, this method is only really useful for looking at very small DEMs or small subsets of larger DEMs for purposes of verification or analysis.

2.4.2.2 Mosaic

A common and very simple method of visualizing a regular grid model is by pseudo-colouring the cells of the grid. Laflin (1987, p.74) used the rather apt term "mosaic" to describe this method. The results produced are similar to conventional layer shading. Here, instead of colouring between contour lines, a colour is determined independently for each cell of the grid according to its altitude. The height values are split into a discrete number of ranges through the use of a simple mathematical formula and a colour is associated with each range. All elevations which fall into a range are coloured using the associated colour. The same colour scheme as conventional layer shading may be used, beginning with green for low altitudes, moving through brown to finish with white for high altitudes. Shades of grey may be used instead of different colours.

With a large grid the size of each cell is small and may even be represented by a single pixel. As the grid cells become smaller the jagged border between different colours, which results from the shape of the cells, becomes less noticeable and may even be eliminated. For such grids the results are similar to layer-shading. This method works because terrain is a continuous surface and despite determining the colour of each cell independently of any other, adjacent cells tend to fall into either the same range or the next one above or below. Because of the "contour" effect between different colours Burrough (1986, p.46) refers to this as a quick method of producing rough contour maps.

The visualisation may be improved by determining the ranges in such a way that each range represents an equal number of elevation data. This is accomplished using an image processing technique and requires that a histogram is computed from the elevation data. Thiemann (1989) described this technique called "median cut".

The method of pseudo-colouring based on altitude can also be used with irregularly spaced data - as in the Unimap system. Cells which data points fall in are coloured as for regular grid data while the remaining empty cells are assigned an arbitrary height such as zero.

A three-dimensional version of the mosaic method can be used. It consists of projecting each cell of the grid vertically to form a block or prism (see figure A.1). The altitude of each cell is used to determine the height and/or colour of the corresponding block. This gives the effect of a three-dimensional histogram. This method is seldom used for three-dimensional representation of terrain. Douglas (1993) writes that it is obviously folly to use this method for generating perspective views of terrain because of the unnatural stepped appearance which is produced. It is more commonly used for statistical mapping purposes where the colour of the block may be derived from a fourth variable, *e.g.* population density. This variable could also be used to determine the height of the blocks if colour was not used. This method is most appropriate to a small or medium sized grid. It is supported by Unimap and the early computer program produced by Brooks and Pinzke (1971).

2.4.2.3 Profiles

Sets of profiles are a very simple method of creating an effective three-dimensional portrayal of a regular grid model while individual profiles are useful for terrain analysis. This method consists of turning each row or column of the grid, depending upon direction of view, into a line with the regularly spaced heights as Z coordinates. However, a problem with this method is that features parallel to the profile lines can be missed. Another problem is that the impression of the terrain produced using rows as profiles may be very different from the one produced when using columns as profiles. Using a mesh or fishnet gets around these problems to some extent. A mesh/fishnet can be viewed from any position while this is obviously not so for profiles. Both profiles and meshes/fishnets can benefit from hidden line removal which is described below.

Profiles were one of the first cartographic methods to be programmed (Robinson *et al.*, 1984, p.329). Brooks and Pinzke (1971) describe an early computer program that uses crossed profiles.

2.4.2.4 Contouring

While contouring is the most popular method of relief depiction in conventional cartography it is also well represented in computer cartography. This is due to its popularity and widespread acceptance. Practically everyone is familiar with contour maps. Two- and three-dimensional contour plots can be produced. The three-dimensional variety usually have the hidden lines removed. While this is the most convenient form of visualisation for contour based DEMs it is not as easy to implement for regular grid DEMs or TINs as other methods. However, algorithms do exist to perform this task for both of these (Petrie and Kennie, 1987; Milne, 1992).

Algorithms for producing contours from regular grid data work by threading contours through the grid cells. Linear interpolation is carried out along the four sides of each cell, based on the values at the nodes. When a contour line enters a cell there must be a corresponding exit point. The entry and exit points are connected by straight line vectors. However, if the cells are large this results in long straight line vectors with abrupt changes in direction at cell boundaries. The situation can be improved by generating a sub-grid in each cell and using the interpolation method with this finer grid. More pleasing contours can be produced by using splines between entry and exit points. This may cause problems in steep areas where the splines could possibly cross which is obviously an impossible situation for contour lines.

Algorithms for producing contours from irregularly spaced data connected to form a TIN work in the same way by threading contours through the triangles using linear interpolation. Generating a series of sub-triangles can solve the problem of long straight vectors which occur with large triangles. Straight line vectors can again be replaced by using splines but as before these may cross in steep areas.

An alternative to linear interpolation which can enhance final results is to base the interpolation of the contour on more sophisticated mathematical techniques (Petrie and Kennie, 1987; Evans, 1987). Methods also exist for creating TINs and subsequently regular grid DEMs from contour data digitised from an existing map *i.e.* contour DEMs (Burrough, 1986).

Some systems implement solid altitude based colouring between contour lines - equivalent to layer shading in conventional cartography - when a contour plot is requested. This is the case with the Unimap system where a conventional contour plot is termed a "line map".

2.4.2.5 Vertices

A very simple method of producing a three-dimensional image is to plot each data point in three-dimensional space. This method is applicable to both regular grid data and irregularly spaced data. It has the advantage that it can be used with irregularly spaced data without the necessity of first creating a TIN. This method can produce results which give a reasonable idea of the form of the terrain if enough data points are present (figure 2.12).

2.4.2.6 Wiremesh

A wiremesh representation shows the skeletal form of the underlying model. It consists of drawing lines connecting the elevation data in order to approximate the original terrain surface (figure 2.13). For a regular grid, lines

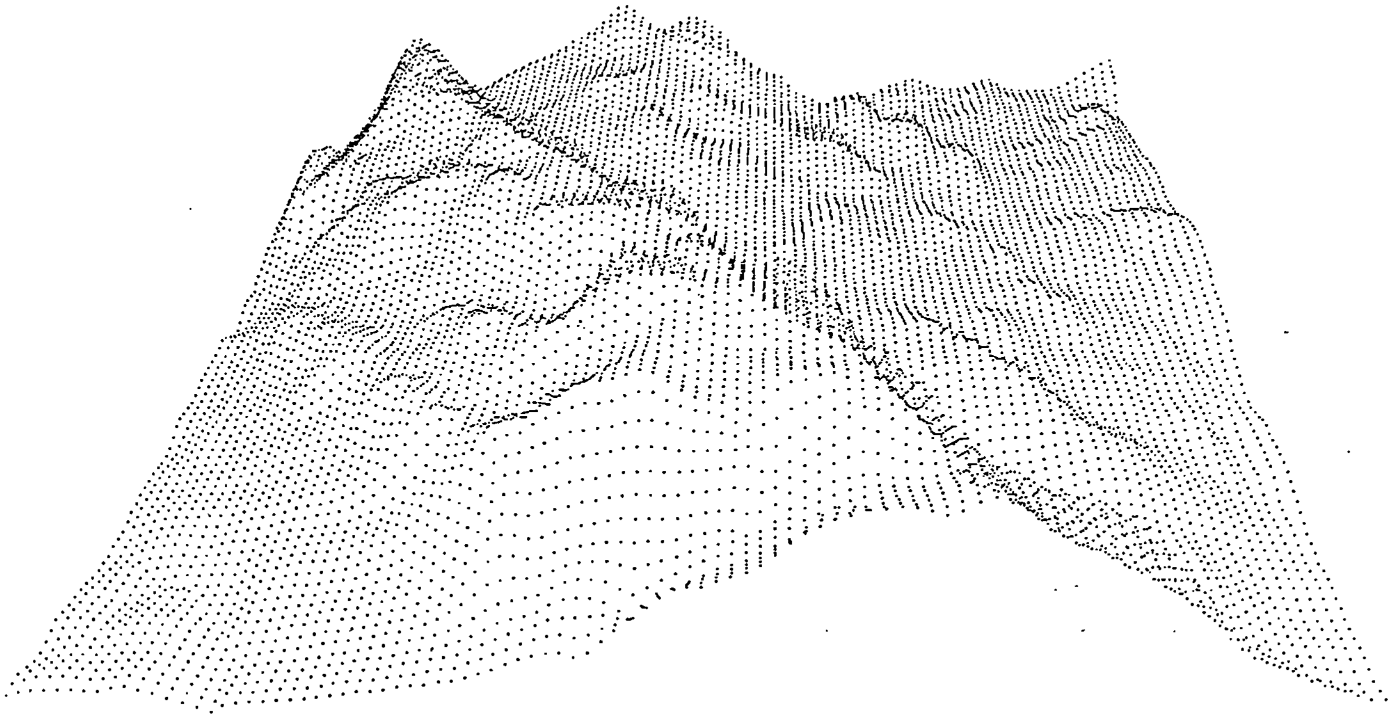


Figure 2.12: Terrain representation by vertices.

are drawn to connect each point in the grid to its neighbours. For irregularly spaced data which has been connected into a TIN the lines forming the network are drawn (these are the edges of the triangular facets). The problem with viewing a wiremesh is that there will be an element of confusion present. This arises because of the "transparency" of the surface which allows us to see lines that would normally be hidden from us by the intervening terrain. Algorithms exist in computer graphics for the purpose of hidden line removal. Such techniques greatly aid the interpretation of a wiremesh.

This method better describes the form of the terrain than the previous method of displaying only vertices. "Although images formed by wire-frame models with hidden edge removal are primitive images with no pretence at being realistic, they still portray form and geometric fidelity and provide an inexpensive technique for visualisation. Major advantages are the low overheads in their production and their ability to be output on standard vector-plotting devices. The visualisation of terrain models in wire-frame form is not limited to the direct output of the grid or triangular network; ridge lines and other visual forces, derived from the DTM, may be used discreetly

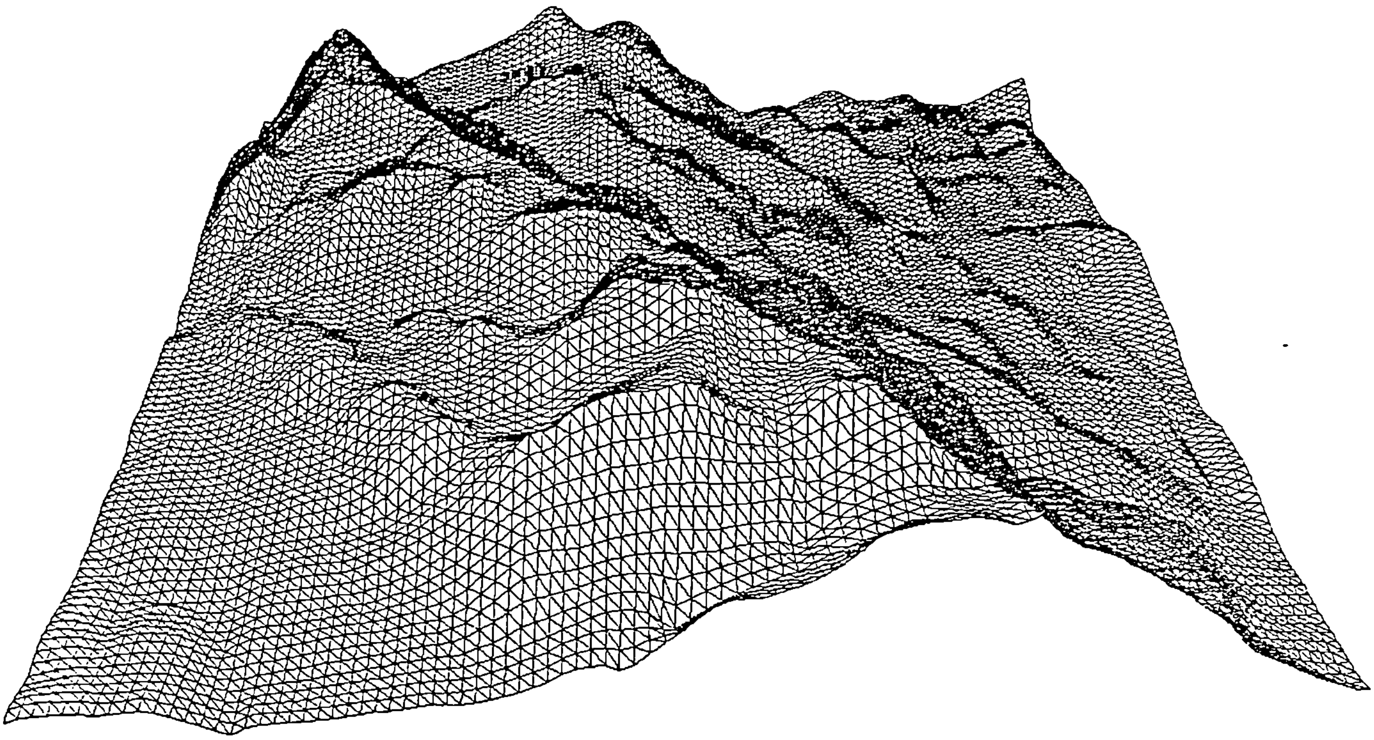


Figure 2.13: Terrain representation by wiremesh.

or in combination with the DTM structure lines," (McLaren and Kennie, 1989, p.89).

2.4.2.7 Polygon Model

The next step towards realism, after the wiremesh, is the polygon model. To produce a wiremesh it was necessary to connect the elevation data with vectors. By looking at the wiremesh it can be seen that, using the same connectivity, several elevation data and the vectors connecting them form polygons. These polygons can be filled with colour to produce a solid model.

The polygon model does not have the problem of transparency observed with the wiremesh but to prevent confusion it is necessary to show only those polygons which are not hidden behind other polygons i.e. to show only what could be seen if it was a real landscape being viewed. To perform this task many hidden surface removal algorithms have been developed each with their own advantages and disadvantages (see Foley *et al.*, 1990). One of the simplest hidden surface removal algorithms is the painter's algorithm. This algorithm is so named because of the way an artist paints a picture -

starting with the background, then the middle ground and finally the foreground (Kingslake, 1986). This method consists of drawing all of the polygons but by beginning with those which are most distant from the viewer and working forwards the drawing of nearer polygons overwrite/hide surfaces which are further away. The painter's algorithm is used in the research presented in this thesis.

2.4.2.8 Photorealism

There is a trend in the computer representation of terrain towards photorealism. See for example Cohen and Gotsman (1994), Cohen and Shaked (1993), Foley *et al.* (1990), McLaren and Kennie (1989), Lang (1993), Thiemann (1989) and Wolff and Yaeger (1993). This is the production of computer images which attempt to achieve the quality one might expect from a photograph. High powered three-dimensional graphics systems, previously unaffordable by many, are dropping in price. The ability to produce realistic terrain models is now widely available for applications from environmental to commercial to entertainment (Lang, 1993).

While the geometric modelling approach of computer graphics is better suited to the Euclidean shapes of man made objects, some stunning images of natural phenomena, including terrain, have been produced using advanced modelling techniques (see Foley *et al.*, 1990). "Raster scan displays have become the de facto technology for visualisation applications. Such devices are typically a 19 inch diagonal CRT screen with a typical resolution of 1024 x 1280 pixels and a capability of displaying up to 16.8 million colours," (McLaren and Kennie, 1989, p.84). While these displays are widespread the availability of the necessary devices to produce high quality, hardcopy has lagged behind and is only now beginning to catch up as the price falls. Techniques used to give the impression of realism include: removing lines and surfaces which are hidden from the viewer, the simulation of illumination, shadows and atmospheric effects, texture mapping and ray-tracing. Some of these are described below. For an in depth description of these techniques see Foley *et al.* (1990). Figure 2.14 shows the use of some of these techniques to render the same DEM as in the previous two figures. The Silicon Graphics machine used to produce figure 2.14 makes use of graphics routines coded in hardware to reduce rendering time.

Shading "Computer drawn pictures, even with hidden surfaces removed, usually look very crude and cartoon-like unless some form of shading system

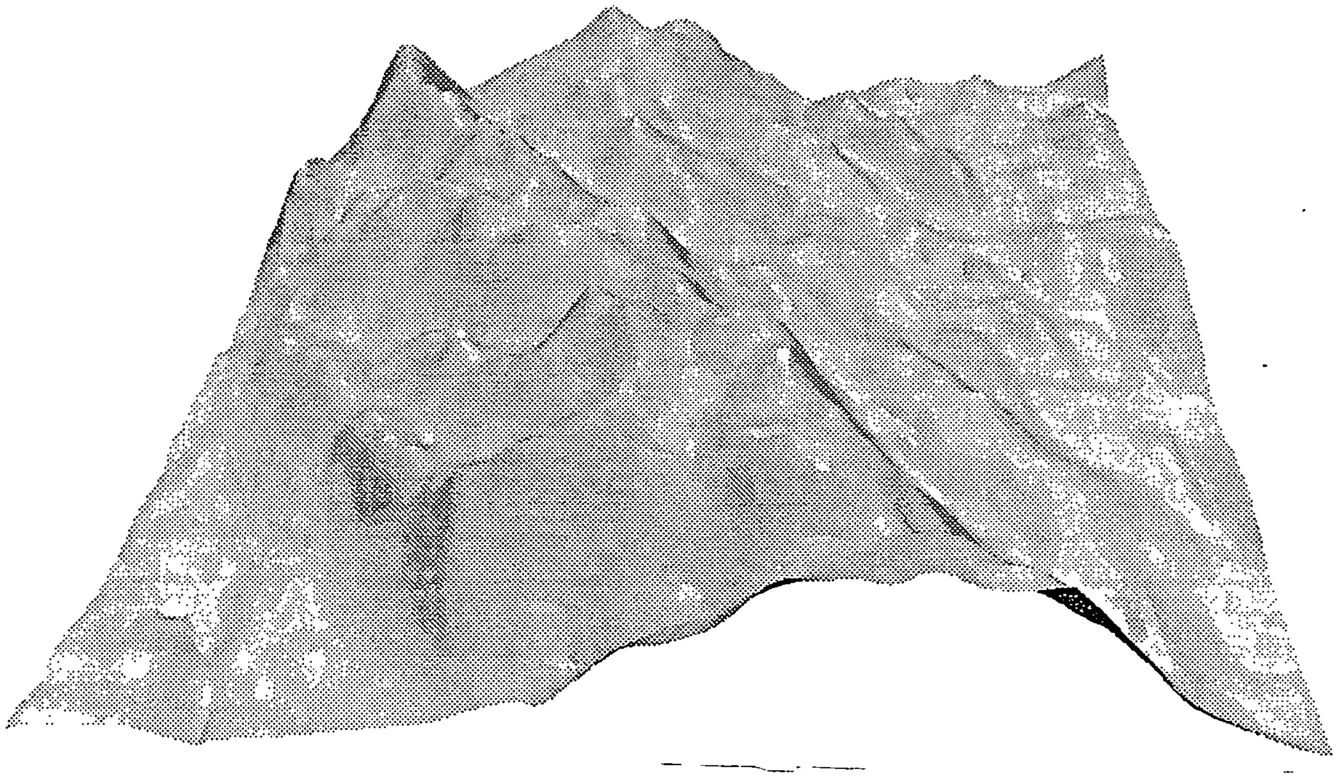


Figure 2.14: "Realistic" terrain representation.

is employed. Clearly this is expensive in computer time, but the improvement achieved with even only elementary shading systems is very great," (Kingslake, 1986, p.103).

Computer graphics shading algorithms are based on principles from physics. The objects in the world around us are visible because they reflect light which in turn reaches us. "The light reflected off a surface can be broken down into two components: diffuse and specular. When light hits an ideal diffuse surface, it is reradiated equally in all directions. Examples of real surfaces that radiate mostly diffuse light are chalk and flat paints. Ideal specular surfaces reradiate light in only one direction, the reflected light direction. Examples of specular surfaces are mirrors and shiny surfaces on which highlights are visible. Physically, the difference between these two components is that specular light bounces off the surface of an object while diffuse light penetrates the surface and is scattered internally before emerging again. The light reflected from real objects contains both diffuse and specular components, and both must be modelled to create realistic images," (Amanatides, 1987, p.45). A third type of light used in computer graphics is ambient light. This models the light reaching a surface from multiple reflections off other surfaces or the sky. Since modelling this ambient component accurately would be computationally prohibitive, it is usually approximated with a constant (compare with ray-tracing). A scene illuminated by ambient lighting alone contains no shading and has no external light source "each object is displayed with an intensity intrinsic to it," (Foley *et al.*, 1990, p.722). Use of ambient light means that surfaces lying in shadow are not completely black. Figure 2.15 illustrates the three components of lighting.

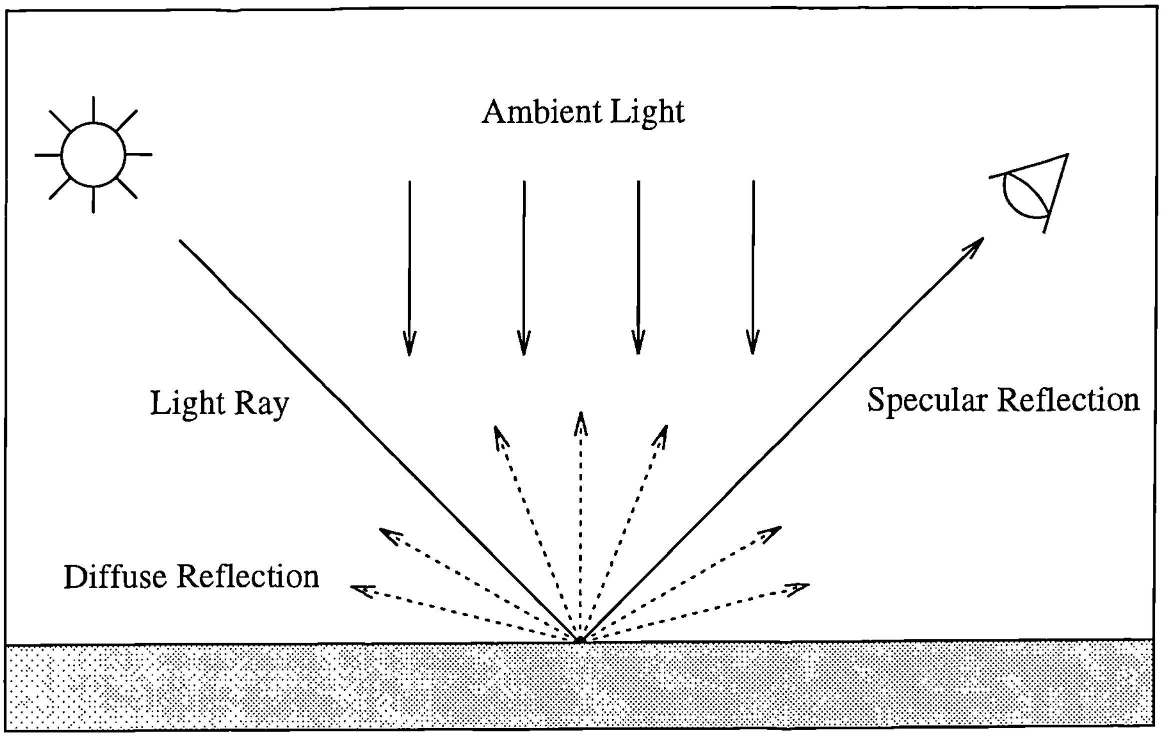


Figure 2.15: The 3 components of lighting.

Lambert shading is simple and reasonably fast. A single intensity is calculated for each polygon based upon its position relative to the light source. The polygon is then filled uniformly using this intensity. The disadvantage of this method is that it can produce a faceted unrealistic effect, revealing the underlying polygonal approximation of objects. For this reason the method is also known as faceted or flat shading. Lambert shading does not consider specular reflection. Diffuse reflection is strongest when a surface is perpendicular to the light source.

The following shading methods disguise the underlying polygonal approximation of objects by varying the intensity within individual polygons. These methods can produce far more realistic images of curved surfaces modelled using a polygonal mesh though they cannot disguise the silhouette of the edge of the mesh which will still clearly be polygonal. Objects which are supposed to be polyhedral can also benefit from these methods.

Gouraud shading (Gouraud, 1971) computes the intensity at the vertices of each polygon and linearly interpolates across the polygon to obtain the brightness at each point inside the polygon. Gouraud shading is also known as smooth shading because all faceting disappears. However, this can be a problem as the algorithm can not distinguish between real edges and artificial ones present because of polygonal approximation. Another disadvantage is the poor highlights and the possible occurrence of Mach bands. Gouraud shading does not consider specular reflection.

Phong shading (Phong, 1973 and 1975) interpolates the vertex normals and uses an interpolated normal to calculate the brightness at each spot on the surface using the actual light vector for that point. Phong shading is more computationally expensive but produces a more faithful rendering. The "glossiness" of the surface can be varied with ease to produce either crisp highlights or ill-defined ones. The highlights are strongest when viewing position and light source are coincident. The problem with Phong shading is its inability to cope with certain awkward shapes. Note that the viewing direction need only be known for this shading method as it is only needed for calculation of specular reflection.

Lambert shading is used by Thiemann (1989) and Yoeli (1967) to simulate the conventional cartographic technique of hill shading. This automated version is sometimes referred to as analytical hill shading. Imhof (1982, p.209) considers the application of the computer to hill shading. Both Gouraud and Phong shading have a smoothing effect which hides the underlying polygonal approximation. However, while this is highly desirable for the curved surface of a sphere or vase it is undesirable for rugged terrain where it would disguise the character of the terrain. Since terrain is not glossy and does not exhibit specular highlights Phong shading is less appropriate than Gouraud shading.

Shadows Computer graphics shadow algorithms produce two shadow effects. Firstly, part of each object will be in shadow where it is hidden from the light source (this effect is also produced by conventional shading methods). Secondly each object casts (or projects) a shadow that may fall on other objects in the scene. Shadow algorithms work in a similar way to hidden surface determination algorithms. Surfaces visible from the viewpoint which could not be "seen" from the position of the light source are in shadow. This means that no shadows are visible if the viewpoint and light source are coincident. Shadow algorithms are view independent. This means that different views may be computed without recomputing shadows as long as the light source remains in the same position.

The complexity of a shadow algorithm depends upon the number, position and type of the light sources. McLaren and Kennie (1989, p.91) state that computer graphics shadowing techniques can now handle a large number of light sources which can be inside or outside the field of view, use a variety of wavelengths of light and possess complex geometries which include point, linear, area, polyhedra and sky light. Shadowing techniques can also produce umbra and penumbra effects.

While conventional shadow algorithms exact a high computational price, ray-tracing and radiosity algorithms have been used to generate some of the most impressive pictures of shadows in complex environments but at a much greater computational cost (Foley *et al.*, 1990). Alternatively Blinn (1988) proposes a less expensive method of producing "fake" or approximate shadows.

Shadows provide one of the strongest visual cues. "Early computer images suffered from lack of gravity. Objects seemed to be floating above the ground plane. One way to solve this is to make the objects cast shadows. The shadows seem to 'tie the object down'. They also help to separate the object from the background," (Blinn, 1988). "Shadows contribute considerably to the realism of the scene by increasing depth perception" (Rogers, 1988, p.345). "A scene that appears 'flat' suddenly comes to life when shadows are included in the scene, allowing the comprehension of spatial relationships amongst objects," (McLaren and Kennie, 1989, p.91). The cartographic technique of hill shading does not show projected shadows.

Texture To provide the illusion of reality, we must be able to display complex scenes. For example, if we are modelling a room, we should be able to include portraits on the wall or Persian rugs on the floor. These objects could be modelled by many individual polygons, but as the number of polygons increase by several orders of magnitude, they can easily swamp the modelling and display programs. Texture mapping is basically a method of "wall papering" the existing polygons (Amanatides, 1987). Texture or pattern mapping is the mapping of a digitised or synthesised image onto a surface. The image being mapped is called a "texture map" and the elements in the texture map are referred to as "texels". Several texels may map to a single pixel and it is necessary to consider all of them in order to prevent aliasing. A texture map is usually quite small and is repeated to cover large polygons. Instead of being explicitly defined texture maps may be generated by procedures.

It is also possible to design three-dimensional or "solid" textures (Peachey, 1985; Perlin, 1985). Such a texture can be thought of as representing a solid block of material. Applying a solid texture to an object will produce a surface texture as if we had "sculpted" the object from the material. This method works well when the texture is being used to model the material that an object is made from such as marble or wood. Many solid textures can be generated by procedures and have the advantage that the texture need not be "fit" onto the surface of an object. An extension to this method is "hypertexture" (Perlin and Hoffert, 1989) which can model objects without well defined surfaces such as hair, fur, fire, glass, fluid flow and erosion effects.

Shading models produce smooth, uniform surfaces and while texture mapping adds detail surfaces continue to appear geometrically smooth. Bump mapping (Blinn, 1978) provides the appearance of a rough surface by perturbing surface normals. A bump map is an array of displacements each of which can be used to simulate displacing a point on a surface a little above or below that points actual position. This technique is effective but does not affect the silhouette edge of polygons.

A common method of adding texture to a landscape is to "drape" a two-dimensional satellite image or aerial photograph of the corresponding area over the three-dimensional terrain data. This technique is most appropriate for regular grid DEMs (see Wolff and Yaeger (1993), Moellering (1990), Kaneda *et al.* (1989), McLaren and Kennie (1989), Gelberg and Stephenson (1987) for examples). Lang (1993) and Cohen and Gotsman (1994) refer to this technique as "phototexturing". Alternatively a suitable texture map could be draped over the model. Textures are often modelled by mathematical functions. Gardner (1984) describes a method of natural scene simulation where a mathematical function is used to model surface texture.

Depth Cueing When looking at a real landscape, or one captured in a photograph, distant parts of the landscape appear faint and tinted blue. Artists term this phenomena "aerial perspective" while scientists use the term "atmospheric attenuation". This effect is caused by the passage of light through the atmosphere. The more distant an object, the more atmosphere the light must travel through and hence the greater the effect. The colours in the light attenuate or decay by varying amounts. Blue is least affected which explains the blueness of distant objects.

The computer graphics approach is to render objects with decreasing intensity as the distance from the viewer (depth) increases. This technique can be used with vector visualisation techniques, such as a wiremesh, as well as with solid models. In colour graphics systems this technique is usually implemented using a depth-cue colour which is typically the colour of the background. The intensity of the depth-cue colour varies according to distance from the viewer. Its intensity is greatest when far away and decreases linearly as it nears the viewer. The colour of each object in the scene is obtained by combining the colour of the object with the depth-cue colour whose intensity is determined by the distance of the object from the viewer. Depth cueing is implemented in this way by PHIGS PLUS. Depth cueing can be used to provide a valuable cue when visualising terrain. However, Foley *et al.* (1990) state that depth cueing is only useful for differentiating large differences in depth because the eye's intensity resolution is lower than its spatial resolution. Nevertheless, this can still be very effective since views of hilly terrain tend to consist of distant hills rising "above" those which are nearer to us.

Aerial perspective has been used in conventional cartography. However, other atmospheric phenomena, not used in traditional cartography, have been simulated in order to add realism to computer generated scenes. For example the beautiful clouds of Gardner (1984 and 1985), fog and mist, as well as mirages.

Ray-Tracing and Radiosity The conventional shading methods previously described (Lambert, Gouraud and Phong) only consider local information concerning light source and surface orientation, while ignoring the overall setting in which the surface is placed. An alternative method is ray-tracing (Glassner, 1989) which takes the whole scene into consideration, for this reason it is termed a global illumination model. Ray-tracing, which was introduced by Whitted (1980), can produce a high degree of realism. It can simulate transparency, the reflection of one surface in another, refraction, shadow effects, atmospheric attenuation.

Objects can be seen because rays of light from a source strike them and then somehow reach the viewer. "Ray-tracing follows rays of light one by one obeying the fundamental laws of physics and so calculates the colour and intensity of each individual pixel," (Rogers, 1988). Each time a ray of light hits an object the ray splits into an infinite number of diffuse rays, a specularly reflected ray and possibly a refracted ray (figure 2.16). Usually only the specularly reflected ray and the refracted ray are traced because it would be prohibitive to trace the many diffuse rays. A refracted ray is produced when a ray of light hits a transparent or semi-transparent object such as glass or water. Such a ray is refracted or bent as it enters the object and again when it exits. Shadows are produced by firing additional rays called "illumination rays" towards the light source(s) each time a ray hits an object. Illumination rays are also used to approximate diffuse reflection.

The rays of light are traced backwards from the viewer through the pixels of the screen and for each one a tree of rays is created. This tree extends from the viewer to the first surface encountered and from there to other surfaces and finally to the light sources. The depth of the tree is usually limited in some way to reduce processing. The intensity of light received by the viewer is determined by traversing the tree. Beginning at the bottom an equation is used to calculate the intensity at each node with the result being input to the calculation of the intensity of the parent.

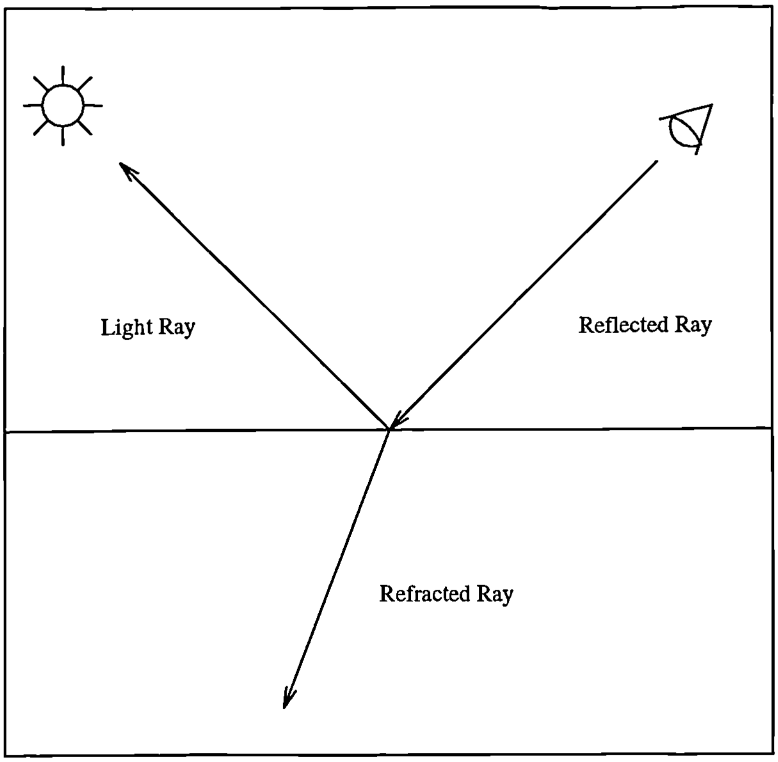


Figure 2.16: The principle of ray-tracing.

Ray-tracing is both conceptually and algorithmically simple yet it has been used to create some of the most beautiful and highly realistic images ever produced by computer graphics. The price of this realism is the very high computational expense. The algorithm which is recursive may be implemented in parallel to improve performance.

Thiemann (1989) uses ray-tracing to render DEMs while Miller (1986) believes that ray-tracing should be used for the calculation of shadows and reflections of the terrain in water.

Ray-tracing models specular reflection while diffuse reflection is approximated. An alternative technique is the radiosity approach. Radiosity methods model the intensity of light diffusely reflected within an environment using principles from thermal engineering and add specular highlights afterwards. An advantage of this method is that it is view independent - the interaction of the environment with the light sources is first computed and it is then possible to compute multiple views from different positions. Because of the focus of this method on diffusely reflected light this method may prove more useful than ray-tracing for photorealistic terrain visualisation. In some cases radiosity methods have been merged with ray-tracing (Glassner, 1989).

2.4.3 Alternatives to Photorealism

As noted earlier, the art or science of producing photorealistic images is highly advanced. It is possible at this stage to produce images which possess such a high degree of perfection that one cannot be sure whether it is a computer generated image which is being viewed or a photograph of a real scene. Computer graphics systems have been developed to produce, both scenes of man made objects, such as interiors of buildings or space ships fighting in a future which exists only on our cinema screens, and stunning images of natural phenomena including trees and vegetation, mountain ranges, clouds and water (see Foley *et al.*, 1990). Research continues to improve the speed at which photorealistic images can be produced and the power of workstations is increasing rapidly. The ability to produce photorealistic images will soon be on everyone's desktop. Few problems remain to be solved in the quest for photorealism; an example of one such problem is the difficulty of convincingly depicting people. A few notable divergences from the mainstream trend of photorealism are described below. Most of these are not directly related to terrain but show a new direction for computer graphics. This new direction comprises methods of emulating the art of drawing, painting and engraving rather than the art of photography.

Winkenbach and Salesin (1994) implemented a number of the principles of traditional pen and ink illustration as part of a largely automated rendering system. Their system can produce pen and ink illustrations from three-dimensional scene geometry and a list of "stroke textures". Stroke textures consist of a collection of strokes and are used to convey both texture and tone while individual strokes are made to look more natural by making them wavy and varying line thickness along their length. However, a good pen and ink illustration "requires putting just enough detail in just the right places, and also fading the detail out into the unornamented parts of the surface in a subtle and unobtrusive way" (p.95). To achieve this a human operator roughly indicates where the stroke texture should appear (see figure 2.17(a)). Another interesting aspect of their work is that stroke textures allow "resolution dependent rendering, in which the choice of strokes used in an illustration is appropriately tied to the resolution of the target medium" (p.91). A related project is described by Salisbury *et al.* (1994) who developed an interactive system for creating pen and ink illustrations. "The user 'paints' with a desired stroke texture to achieve a desired tone, and the computer draws all of the individual strokes" (p.101). Figure 2.17(b) shows a scene drawn in a variety of styles.

Saito and Takahashi (1990) imitated techniques commonly used in hand drawn illustration to make images more comprehensible. "Techniques for the comprehensible drawing of three-dimensional shapes are indispensable for various applications such as industrial design or medical imaging. Their importance in computer graphics is not at all inferior to that of photorealistic rendering techniques. Comprehensibility is mainly created through suitable enhancement rather than by accurately simulating optical phenomena. For shape comprehension, line drawings are effectively used as an addition to or substitute for surface colouring and shading. For example, profiles and edges can be enhanced with black or white border lines. Curved surfaces can be made comprehensible by hatching with curved lines. These techniques are commonly used in hand drawn illustrations. However, they have not been adequately developed for computer graphics compared to photorealistic rendering techniques" (Saito and Takahashi, 1990, p.197). Their technique is based on two-dimensional image processing operations. Examples are described for edge enhancement, line drawing illustrations, topographical maps, medical imaging and surface analysis.

The graphics company 5D Solutions Ltd. have produced software for "illustrative" rendering. Its purpose is to filter the raw information in the three-dimensional model of a scene to make it more informative or appealing. The software draws meaningful lines which are extracted from the three-dimensional data, silhouette lines which surround objects and profile lines which are drawn at surface creases are examples. Shading styles are comprised of dots, dashes and lines. Light source and viewing position can be manipulated and many of the features found in conventional two-dimensional paint box systems are available. The system uses an extension of photorealistic rendering methods to perform its task. It has primarily been used for product marketing and documentation. Figure 2.17(c) shows an example of the kind of illustrative rendering produced by 5D solutions.

Dooley and Cohen (1990) recommend that computer graphics focus on what is drawn and how it is drawn. They advocate an enriched vocabulary of lines which convey greater meaning. For example, where a line passes behind an object its end is thickened to illustrate this. Different types of lines are distinguished; boundaries, silhouettes, discontinuities and lines to help convey the curvature of a surface. Unlike conventional polylines the attributes of each line may vary along its length. Other researchers have also suggested the use of more expressive strokes. Hsu and Lee (1994) and Strassman (1986) simulated the varied strokes made by an artist's paintbrush.

Leister (1994) produced images which simulated the appearance of copper plate prints. This old fashioned printing technique dates back to the middle ages and was formerly used to produce book illustrations. The technique has also been used by many famous artists. Such prints consist of lines of varying thickness and style as wells as single points. Objects are bordered by lines and shading is performed by means of regular hatching. Such illustrations possess "a special aesthetical flair and have the power to present facts more tersely than raster reproductions of photographs, as some details can be emphasized in a special manner," (Leister, 1994, p.69). Leister's method is based on ray-tracing. He recommends its use for illustrations and for generating icons for user interfaces. Figure 2.17(d) shows an example of Leister's work.

Sasada (1987) was concerned with the "realism of drawing". He described methods of simulating hand drawing for buildings, trees, water and (most important in the context of this thesis) mountain ranges.

Ervin (1992 and 1993) developed Emaps, a raster based, object-oriented GIS, which provides an interactive environment for visualising landscapes and exploring geographic information. The cells in the raster can be visualised in many ways in both two and three dimensions. For example a three-dimensional version of the mosaic method is shown where each cell of the terrain surface is divided into two pseudo-coloured triangles. Land use symbols depicting different kinds of building and vegetation are then placed on the landscape. The aim is not photorealism. Instead Ervin is interested in how abstractions and representational conventions can be used to gauge

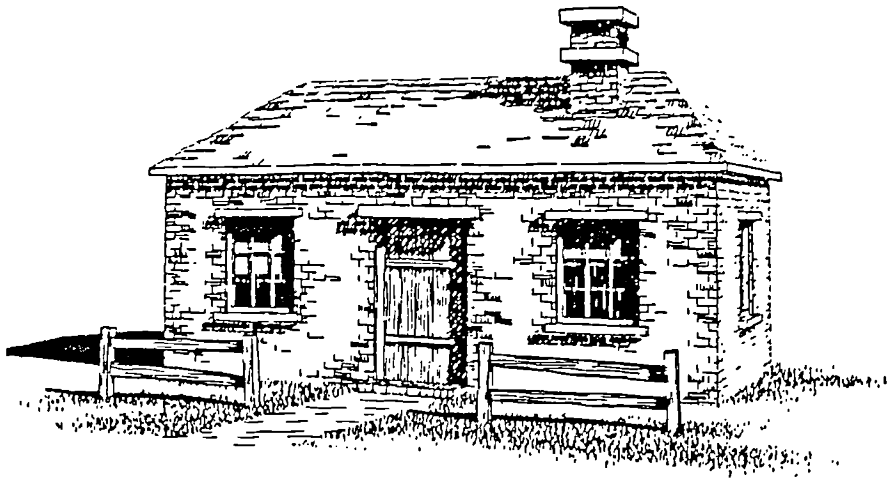


Figure 2.17(a): Simulated pen and ink illustration (reproduced from Winkenbach and Salesin, 1994).

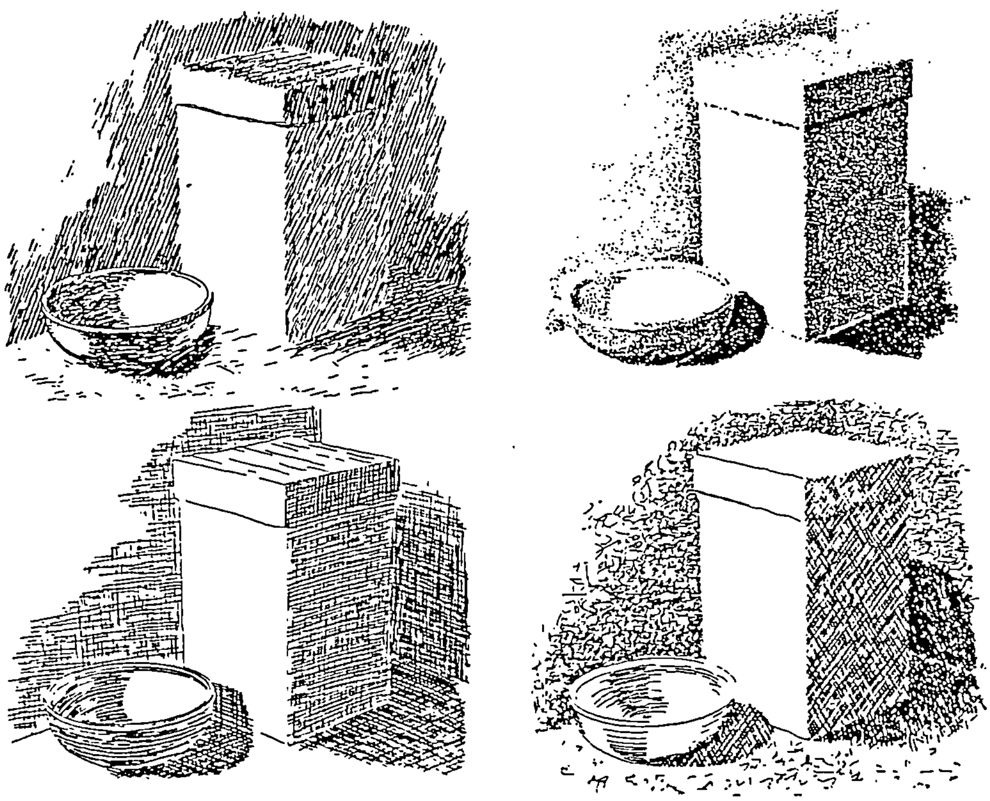


Figure 2.17(b): Interactive pen and ink illustration (reproduced from Salisbury *et al.*, 1994).

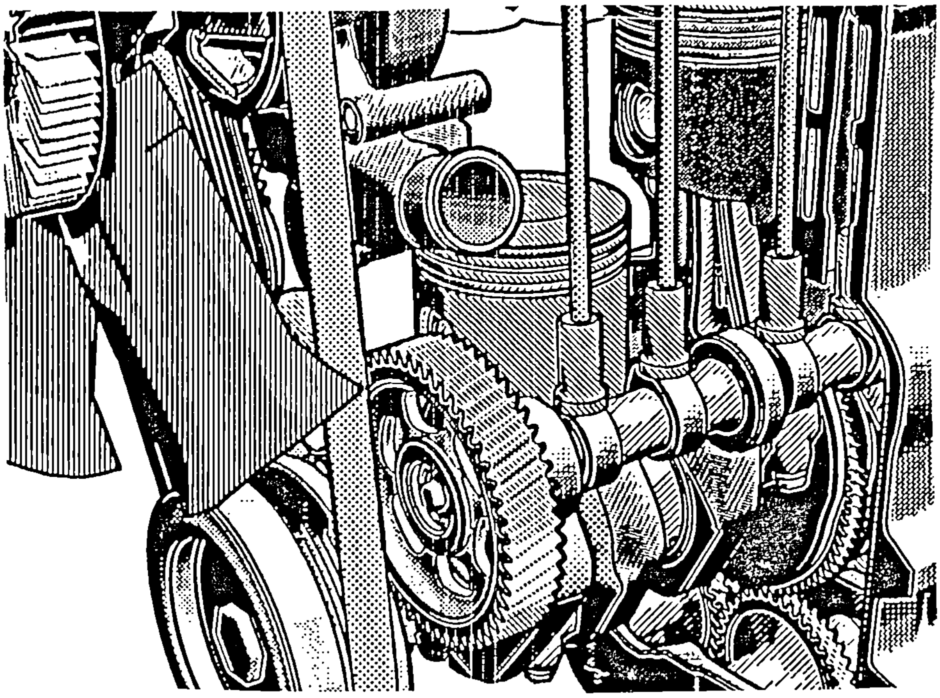


Figure 2.17(c): Sample of "illustrative" rendering (reproduced from 5D Solutions, 1994).

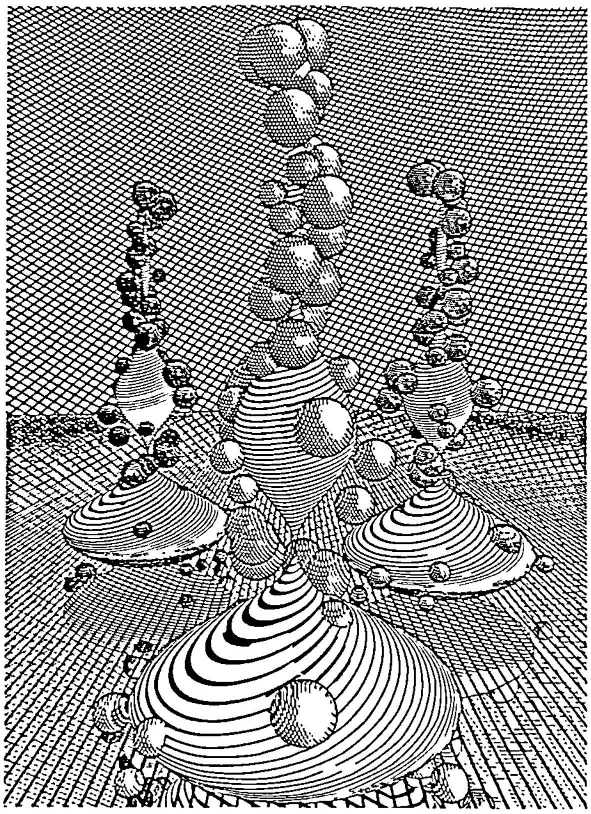


Figure 2.17(d): Simulated copper plate printing (reproduced from Leister, 1994).

visual and environmental impacts of proposals for landscape change. The displays produced are the equivalent of "a designer's thumbnail sketch," (Ervin, 1993, p.33). Ervin (1993) goes on to state the importance of representational conventions such as abstraction, simplification, false colouring and others for purposes of design, education and communication. Figure 2.17(e) shows a scene composed of pseudo-three-dimensional objects.

Haeberli (1990) states that in many cases the designer must balance realism and effectiveness. A stylised image may be more effective than a realistic photographic one. Haeberli's goal is to produce effective, interesting images that communicate. He describes several techniques for turning a synthetic or natural scene into an abstract impressionistic image. The majority of the techniques are based upon the simulation of impressionistic brush strokes. Most of the two-dimensional images are created by paint box techniques but he describes one method which is applicable to three-dimensional scenes. Here, surface normals control the directions of the brush strokes. Interactive processing of an image allows the selection and manipulation of visual information to eliminate distracting detail and influence the viewer's perception of the subject. Figure 2.17(f) shows a "painted" representation of a pyramid, sphere, cone and cylinder produced from a three-dimensional model.

All of the work described in this section recognises the benefits of abstraction over photorealism. Visvalingam and Whyatt (1990) state that relatively basic computer graphics are sufficient for purposes of visualisation, to stimulate insight and understanding. Parslow (1987) expressed concern over the adequacy and the necessity of the usual depth cues to produce a correct picture of reality. This caused him to state (p.25) that "the enormous cost of producing accurate but sterile pictures is wasted".

2.4.4 New Technology

Two relatively new technologies which will have an impact on the visualisation of terrain are multimedia and virtual reality.

Multimedia systems facilitate the use of various types of media, such as text, graphics, photographs, video and audio. Multimedia Geographical Information Systems (GIS) are starting to appear. A multimedia system or multimedia GIS could include still photographs of an area as well as video sequences of flying over the terrain. This could be coupled with more conventional data such as a textual description of the area, numeric data describing for example

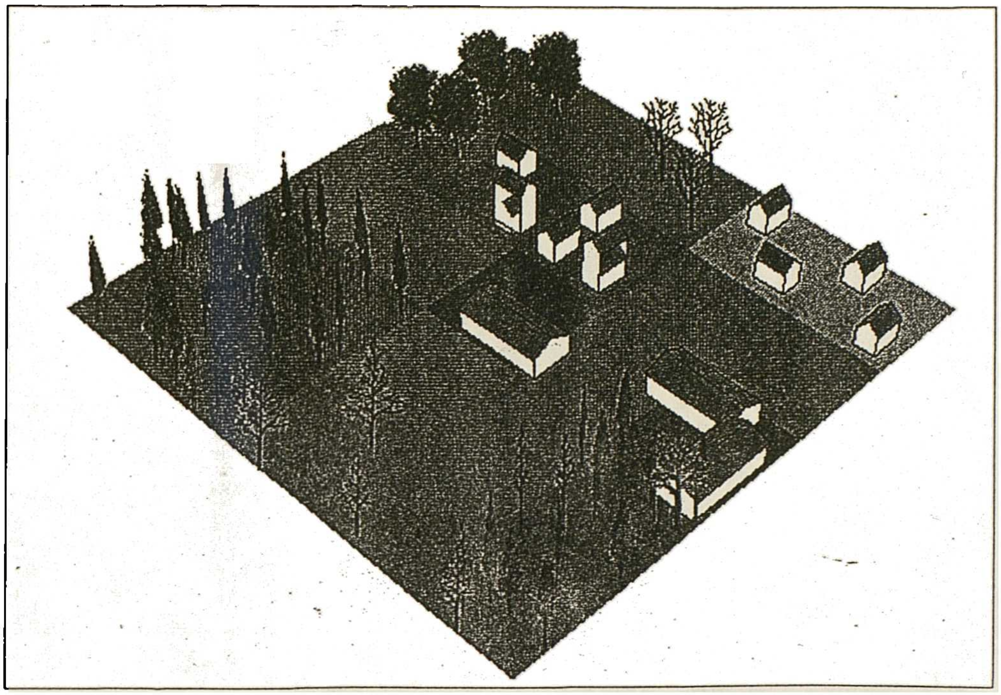


Figure 2.17(e): Scene composed from pseudo-three-dimensional objects (reproduced from Ervin, 1993).

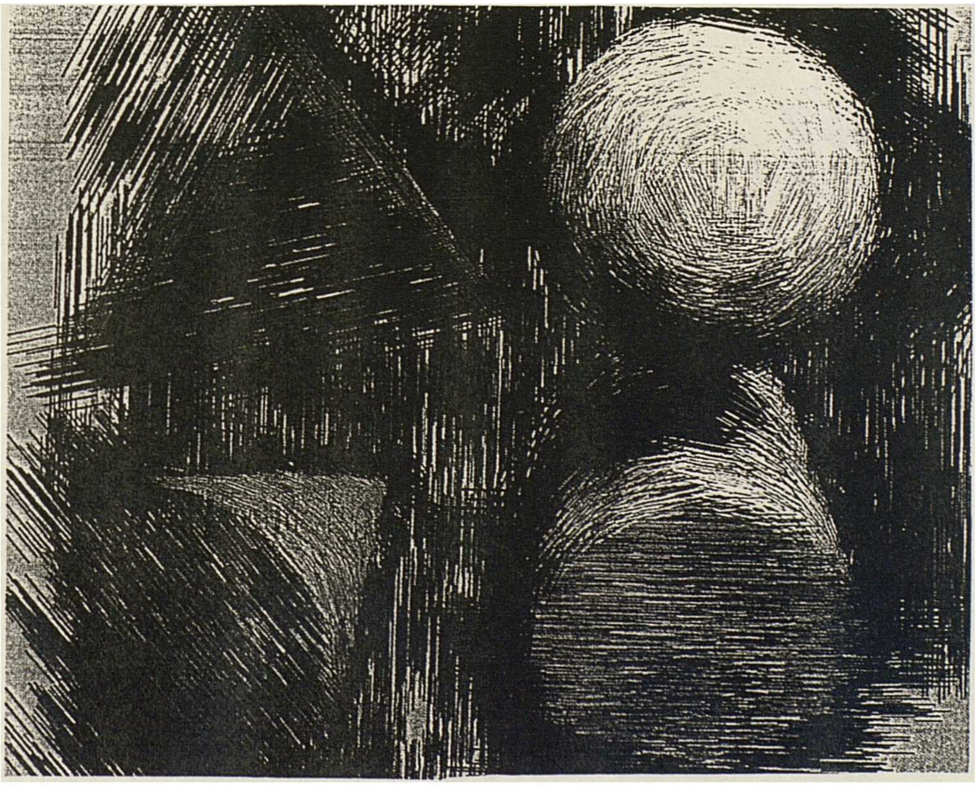


Figure 2.17(f): Painted representation of a pyramid, sphere, cone and cylinder produced from a three-dimensional model (reproduced from Haeberli, 1990).

the amount of rainfall and computer graphics to produce maps or the types of visualisation described in this chapter. One of the problems with multimedia is the massive amount of data which typically needs to be stored on CD, video tape or laser disk. Also Groom and Kemp (1994) write "multimedia data is very much more complex than standard data, and therefore requires much more work to be able to perform sensible, useful queries, and display the results in a structured way." Some multimedia systems incorporate principles from hypertext, these are called "hypermedia" systems. Hall and Simmons (1992) describe the application of hypermedia to GIS while Fisher *et al.* (1993) mentions the application of multimedia and hypermedia to maps and visualisation.

Virtual reality is an emerging technology. "Very few new technologies have captured the imagination of people in all walks of life as much as virtual reality (VR). It seems that not a week goes by without some mention in the newspapers and on the television of new breakthroughs in entertainment, medicine and defence," (Stone, 1993). In fully immersive VR a helmet is worn which contains a screen for each eye. Each screen displays a slightly different image, using the principle of stereopsis to provide an appearance of depth. The wearer of the helmet can see only the virtual world displayed inside his helmet. If the wearer moves his head the scene before him changes as it would if he moved his head in the real world. The wearer can navigate through the virtual world and can interact with it possibly using new interaction devices. Sophisticated systems provide a glove containing position sensors for the hand or even a suit that extends to include whole limbs or the entire body (Arthur, 1992). "Ultimately, that sense of being there is the defining characteristic of virtual reality," (Quinnell, 1993). In VR it would be possible to walk or fly across terrain. Such virtual terrain has been used in flight simulation and various military applications while NASA Ames and the European Space Agency (ESA) have created virtual worlds, using the data sent back from space, to explore the oceans of this world as well as the surface of other, distant planets such as Mars (Bagiana, 1993). VR is still in its infancy and dramatic advances in technology need to be made for it to become convincing. Quinnell (1993) writes that virtual reality today would disappoint most potential users. Also no-one yet knows what the short-, medium- and long-term effects of immersion in a virtual world actually are. One research problem in VR concerns the generalisation of data representing virtual worlds. The detail in a scene should be varied with distance from the viewer. Near objects should be highly detailed while objects which are far away contain little or no detail.

2.5 SUMMARY

This chapter described the methods used in conventional cartography for the representation of terrain and organised them into a new taxonomy. This was followed by a description of terrain modelling and representation using a computer. Many of the techniques described are either imitations of those found in conventional cartography or for photorealism but others are unique. The trend of mainstream computer graphics was identified as increased photorealism though some notable work which goes against this trend was mentioned. Exact copies of reality are not always required and there are many advantages to using abstraction. The techniques of conventional cartography classed as "pictorial" in the taxonomy require artistic ability to produce. Such techniques often produce results of great value, possessing simplicity and beauty. However, the computer emulation of pictorial techniques has sadly been virtually ignored. This chapter presented a review of techniques to extract vector topological sketches from DEMs. Such sketches are quite different from artistic sketches.

Since the underlying Delauney triangulations of TINs results in visible artifacts the next chapter describes an original approach to sketching terrain which seeks to inject more "art" into computer cartography.

Chapter 3

Computer-drawn sketches of DEMs

3.1 INTRODUCTION

This chapter describes an original method for producing artistic sketches of Digital Elevation Models (DEMs). The regular grid of height values, which is the most widespread form of DEM, is the type used. The resulting landscape sketches resemble those produced by cartographers, geographers and artists. This chapter explains why this novel problem was investigated and describes the research strategy and algorithms. Promising sketches, extracted from a quarter of the 1:10,000 sample dataset released by the Ordnance Survey of Great Britain, are presented. These show the hilly area behind Port Talbot in Wales. In conclusion, some wider implications of this research are considered along with some suggestions for future work.

3.2 SKETCHING THE TERRAIN

This section explains the reasons for posing the novel problem investigated in this thesis, namely the extraction of artistic sketches from digital elevation models (DEMs). The abstraction of perceptually important elements in the landscape is identified as a specific concern.

As has been described in the previous chapter, the continuous surface of the terrain has been modelled and visualised in numerous ways by artists, cartographers and the computer graphics fraternity. Section 2.3 described most of the techniques used in conventional cartography for representing terrain on a plane surface in a manner which suits different geographic applications while section 2.4 described the methods used in computer visualisation. The most common technique used in conventional cartography, which has also been widely implemented on computer, is the contour map (Raisz, 1938, p.129). In traditional maps, this symbolic representation was supplemented by other terrain related information such as spot heights, hachures and textures to portray embankments, quarries, rocky outcrops, vertical faces and scree slopes (see for example, Harley, 1975). Elements of realism were thus incorporated within an otherwise abstract model of the earth's surface. An appreciation of the real world was urged through pictorial representations, which use artistic conventions to depict the landscape in an easily recognised manner corresponding to the way it would appear to an observer. Such methods include block diagrams (Lobeck, 1924), physiographic methods (Raisz, 1931) and field sketching (Raisz, 1938).

The skilled drawing of block diagrams and physiographic maps was appreciated as a scientific art; the classic text by Lobeck (1924) contains several splendid examples. Cartographers, skilled in the application of scientific mapping principles to artistic depictions of landscape, were in high demand in many spheres of activity, including education, surveying, engineering and the military. Eminent cartographers, like Raisz (1931), designed expert systems, in the form of a set of pre-designed graphic conventions for depicting different types of physiographic regions at medium-scale (figure 2.5), so that artistically less gifted draftsmen and geographers could copy and adapt them.

In comparison, the products of mainstream digital cartography have been somewhat limited to the conventional cliches which can be output using standard graphic output primitives, partly because of the types of digital terrain model used. For example mapping agencies, like the Ordnance Survey of Great Britain, have started to replace traditional hachures with area fill symbolism for slopes and polyline styles for the top breaks of slopes. Even manual cartographers could not always master the art of drawing hachures which tended to degenerate at small scales into "hairy caterpillars and woolly worms" (Brandes, 1983; Raisz, 1938). Data diagrams, ranging from wireframe profiles, contours and fishnet plots to photorealistic scenes in perspective, have become the standard cliches for visualising terrain while the alarming trend of mainstream computer graphics is an increase in the degree of photorealism. Cartographers, as ancient as Ptolemy in the second century AD, and historians of art, such as Arnheim (1956) and Gombrich (1960), have recognised the value of departing from the eyewitness approach of depicting realism.

Developments in Human-Computer Interaction and Graphical User Interfaces are enabling a new breed of cartographic consultants to take advantage of the growing repertoire of graphic techniques and images on the flexible medium of raster-refreshed displays. This new breed of cartographers are beginning to articulate their own individualistic styles based on the principles of traditional cartography. Alan Collinson, 1993 winner of the British Cartographic Society's John Bartholomew Award and of a BCS Design Award Highly Commended Class, is finding that interactive computer graphics offers immense potential for the creation of "impressionist maps in the digital age" (Collinson, 1993). Command-driven mapping had removed the art from cartography and Collinson, spoke for many others, when he argued that cartography, without art, is no longer cartography but an impoverished discipline, cography. Although, there are a multiplicity of trends and concerns within cartography (Visvalingam, 1990), the advent of direct manipulation has indeed been a boon to the freelance cartographic consultant.

The research reported in this thesis forms part of a longer term programme of research which seeks to innovate new techniques and tools for accelerating the revival of the art forms of cartography. This initial study was made possible by a UK SERC CASE Award with Scott Wilson Kirkpatrick and Partners, a consulting firm of civil engineers, as collaborators. Consultants in civil engineering still employ artists to portray the environmental impact of proposed developments.

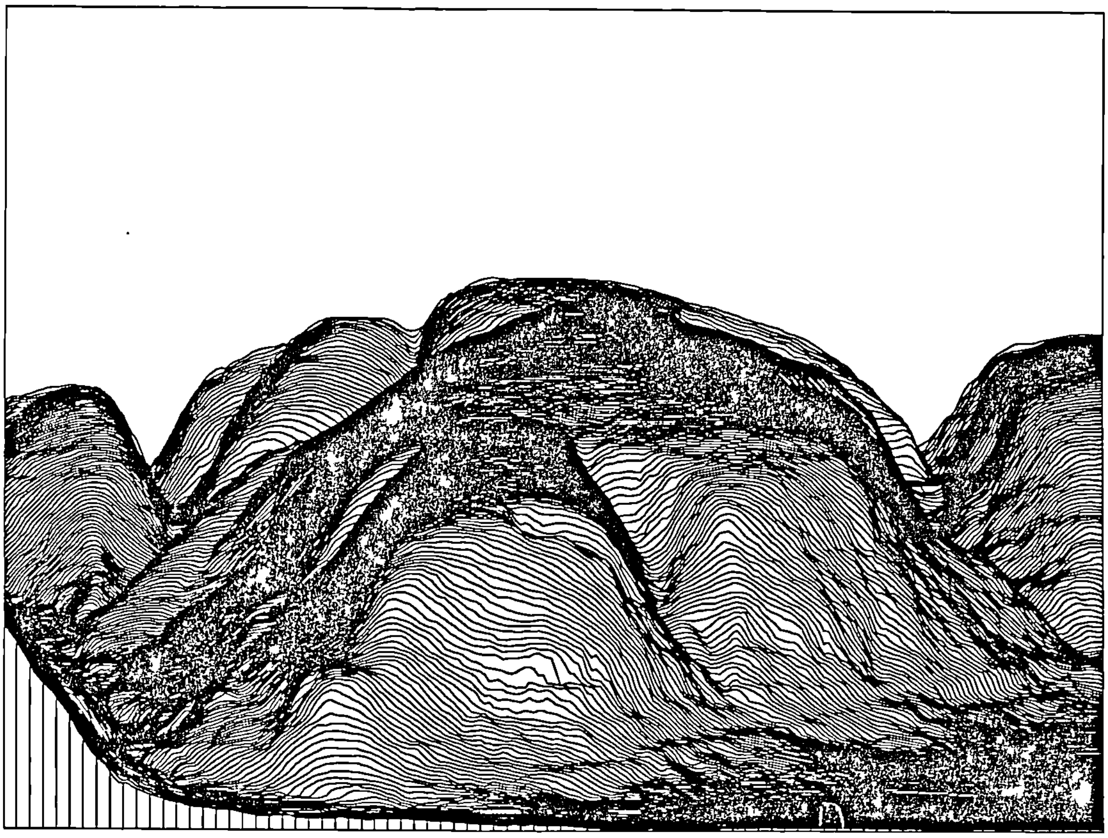
DEMs are being used within a variety of applications of Geographical Information Systems (HMSO, 1987). A number of applications are described by Burrough (1986) and Catlow (1986). The regular grid has become the most available form of DEM. These are available for the whole of Britain and the United States of America and they are becoming increasingly accessible. Field sketching was an essential preparatory activity in the construction of block diagrams and physiographic maps though this sadly became less so with the introduction of photography. However, field sketching has many advantages over photography and photorealistic representation. Lobeck (1924, p.165) writes that photographs "usually lack the simple, direct appeal which a sketch carries with it, because, unlike sketches, photographs can not select out of the landscape just those elements which may be deemed significant. They lack, too, the personal touch which the artist brings to his aid and those subtle qualities of technique which add interest and life to what may be otherwise a prosaic matter." If algorithms could be innovated to automate the sketching of DEMs, then the cartographer could take over the artistic rendering of the display using paint box systems.

This exploratory study addresses only one aspect of sketching. Visvalingam (personal communication) explained that the process of producing a field sketch consists of two primary activities. The first involves the simultaneous abstraction of the objects in the scene and how they are related in space. The second concerns decisions relating to the choice of graphic signs and conventions, also called delineations, and the choice of drawing system, which portrays the spatial relationships between objects (Willats, 1990). The second set of concerns may be considered later when the final drawing is made. Computer emulation of field sketching can also separate the two primary activities so as to experiment with different parameters. Visvalingam also pointed out that the primary concerns of this study would be the abstraction of the perceptually important elements in the landscape and the investigation of a novel way of turning this information into a sketch. Field sketches rely on the use of conceptual devices, such as vanishing points, and special equipment (such as sketching screens) to aid in the realistic portrayal of depth and perspective. This study is not concerned with this aspect of sketching which has been addressed by mainstream computer graphics. Instead, it addresses the task of summarising and clarifying the scene with a few strokes which reveal the major relief elements in the landscape.

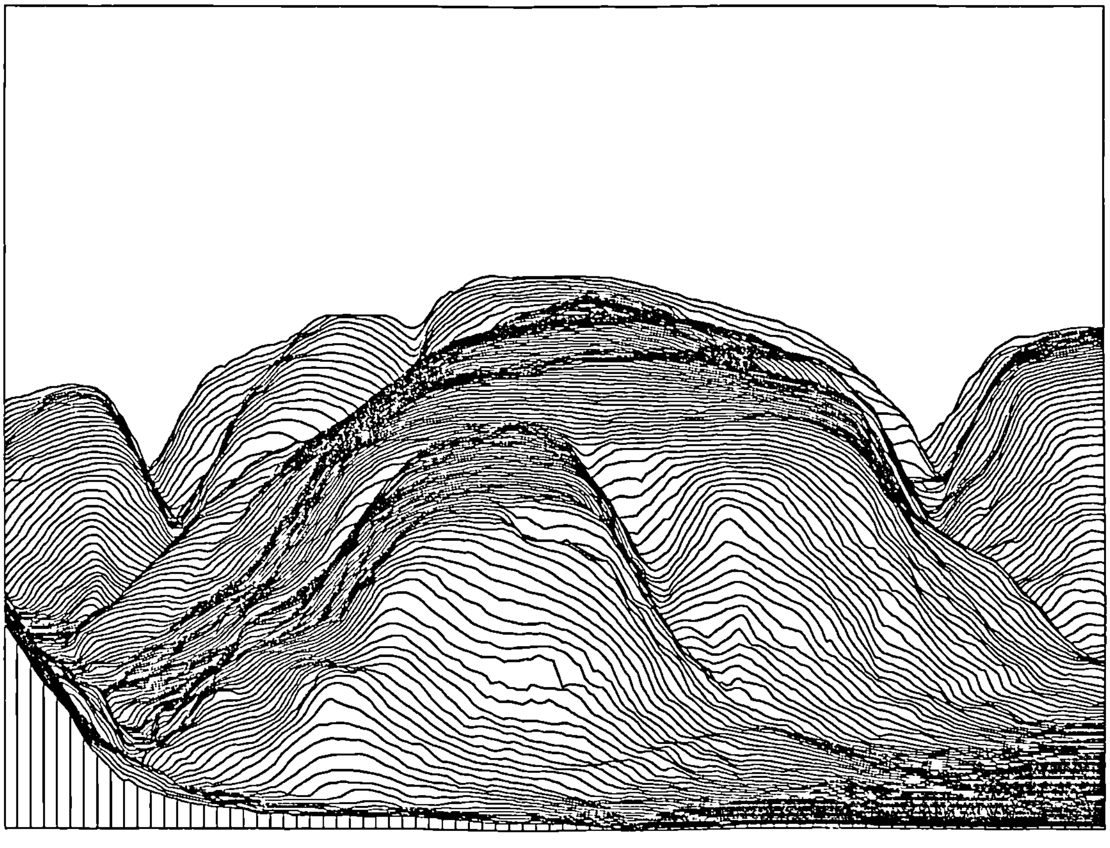
The DEM portrayed in figure 3.1(a) represents only a quarter of the small 1:10,000 sample dataset released by the Ordnance Survey of Great Britain (10m grid spacing). It is visualised by a series of profiles. This quarter of the data set consists of 250 profiles each containing 250 points. Even so, the display of all data results in illegibility in places and a loss of information. Some of the clutter may be eliminated by suppressing data, for example, by plotting only alternate lines (figure 3.1(b)). As the resolution and coverage of DEMs continue to increase there will be a growing need to generalise and map them particularly for viewing at small scales. This is especially necessary in applications which use the DEM as a base against which they wish to project foreground information (Visvalingam, 1990).

3.3 SKETCHING WITHOUT KNOWLEDGE

Jenks (1981) classified representations into four categories. The first of these concerns applications, such as contour mapping, which require minimal simplification. The second is thematic maps which can stand higher levels of simplification, but the maps must be recognisable, even if they are seen to



(a) Drawing all of the profile lines.



(b) Drawing alternate profile lines.

Figure 3.1: Port Talbot DEM represented by profile lines. Viewed from the west. Data supplied by the Ordnance Survey.

depart from the original. Thirdly is caricatural maps, cartograms (Cuff and Mattson, 1982) and newsmaps which can be subjected to even further generalisation; cartograms often preserve only the topological relationships, an example is the well known map of the London Underground system. The fourth category concerns maps which have been generalised beyond recognition and which are not usable.

Symbolic representations of physiographic regions (Raisz, 1931) tend to typify and caricature the landscape. The mind has to recall implied forms by association. Block diagrams simplify by a process of selection, they rely on the mind's capacity to project and imagine the relevant form given only the essential information. Lobeck (1924, p.165) advised that the field sketch "should be left unfinished, with just enough detail suggested here and there to make it possible to complete the drawing" later; the aim is "to select from the landscape those critical and important lines which give it its character, that is, to lay out its major elements" and then only "to put in some details, not too accurately, but in such a way as to explain better the larger features". Sketches, like maps, are graphic precis of reality. The cartographer brings to field sketching his skills in cartographic generalisation which includes the processes of selection, simplification, classification, symbolism, displacement and exaggeration (Robinson *et al.*, 1984).

In the context of line generalisation, Visvalingam and Whyatt (1993) and Visvalingam and Williamson (1994) demonstrated that it was possible to automatically caricature coastlines and roads by a process of elimination of geometric features within features without semantic knowledge, for example, of geomorphology. Visvalingam and Williamson suggested that the algorithm's propensity to generalise made it a valuable tool for segmenting and structuring a line into hierarchies of constituent parts, particularly in the case of man-made objects like roads.

The studies of terrain described in the previous chapter seek to infer features from regular grid DEMs and TINs as well as to refine the TIN mesh. The most common method of inferring features from a regular grid DEM is through the use of two-dimensional filters and operators while features are inferred from a TIN by considering the adjacency relationships between triangles. The research in this thesis investigates the utility of a one-dimensional profile-based analysis for the reasons described below.

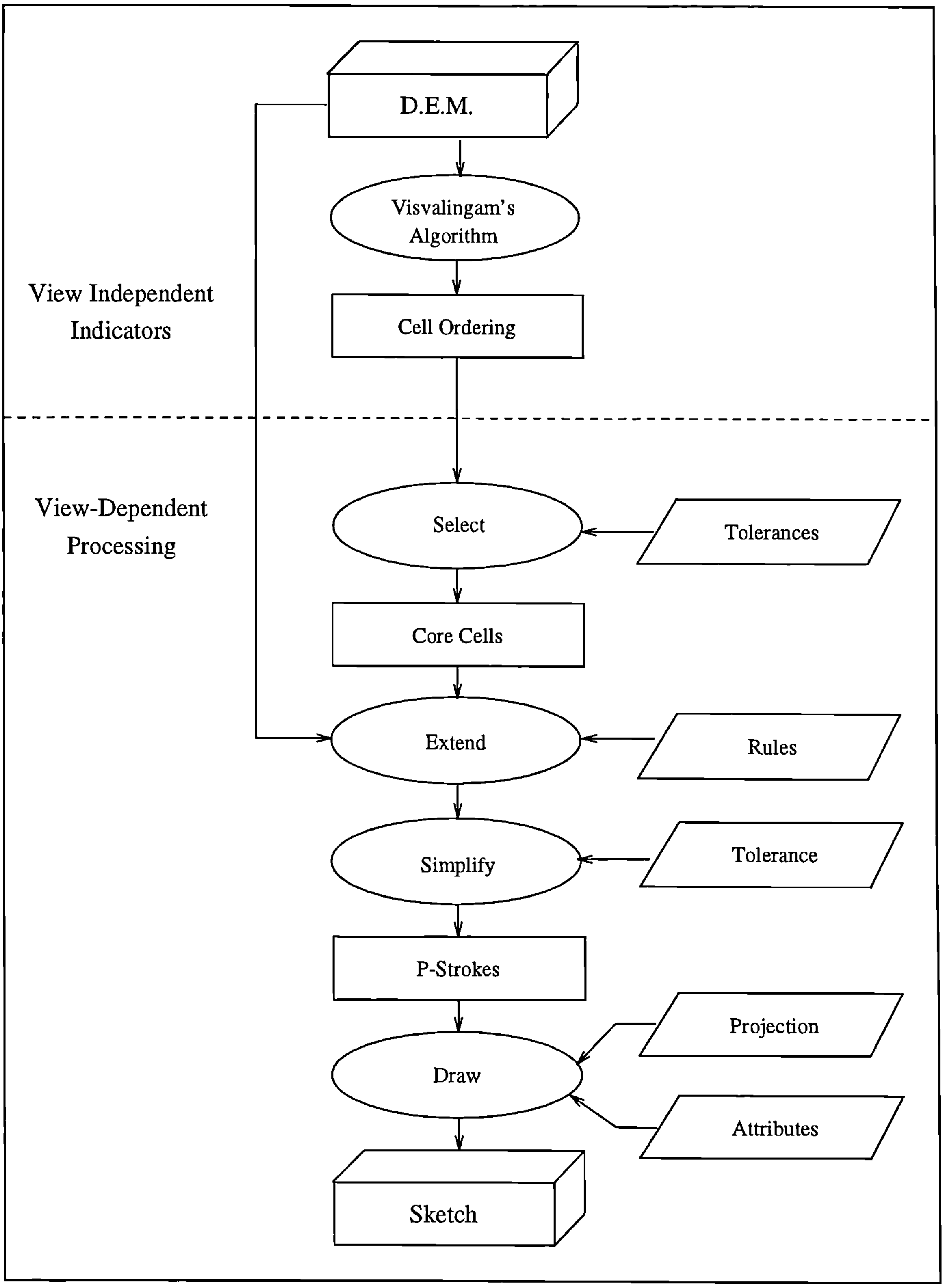


Figure 3.2: The sketching pipeline.

3.3.1 The Sketching Pipeline and Parameters

Figure 3.2 describes the process of sketching which consists of the following stages. The cells of the DEM are ordered using Visvalingam's algorithm, which uses a suitable metric to determine the perceived significance of each cell. Viewing parameters in the form of user supplied tolerances are used to select sets of important cells. These cells are termed core cells. These core cells indicate the positions where marks should appear. A number of rules were devised to determine the length of these marks. In this study, the core cells are extended only along the profiles to form polylines, representing profile strokes. The visual impact of varying the length and direction of strokes were studied. These fragments of the profiles may themselves be simplified to reduce the number of points making up the strokes. The projection system and attributes of the profile strokes (such as colour, width and style) can then be selected and the sketch drawn. An overview of the algorithm is given below:

1. Visvalingam's algorithm is applied to the rows and columns of the DEM to derive two measures of importance for each cell, see figure 3.3(a);
2. For each row of the DEM, starting at the back;
   (a) Identify the core cells (*i.e.* those cells with an importance greater than the user supplied tolerance) based on;
      i. the row-wise importance of each cell in the row Rx. This detects ridges and valleys parallel to the viewer;
      ii. the column-wise importance of each cell in the row Cx. This detects the silhouettes of hills and valleys;
   (b) Extend strings of core cells, see figure 3.3(b). The extended strings of core cells define sections of the original profile line which are termed p-strokes, see figure 3.3(c);
   (c) Simplify the p-strokes using a line-simplification algorithm if necessary.
   (d) Draw the p-strokes.

This approach to sketching DEMs was arrived at through an involved process of exploratory visualisation. It was quite clear from the outset that Visvalingam's algorithm could be used to detect the core information-rich cells. In chapter 4, the utility of other line simplification algorithms is

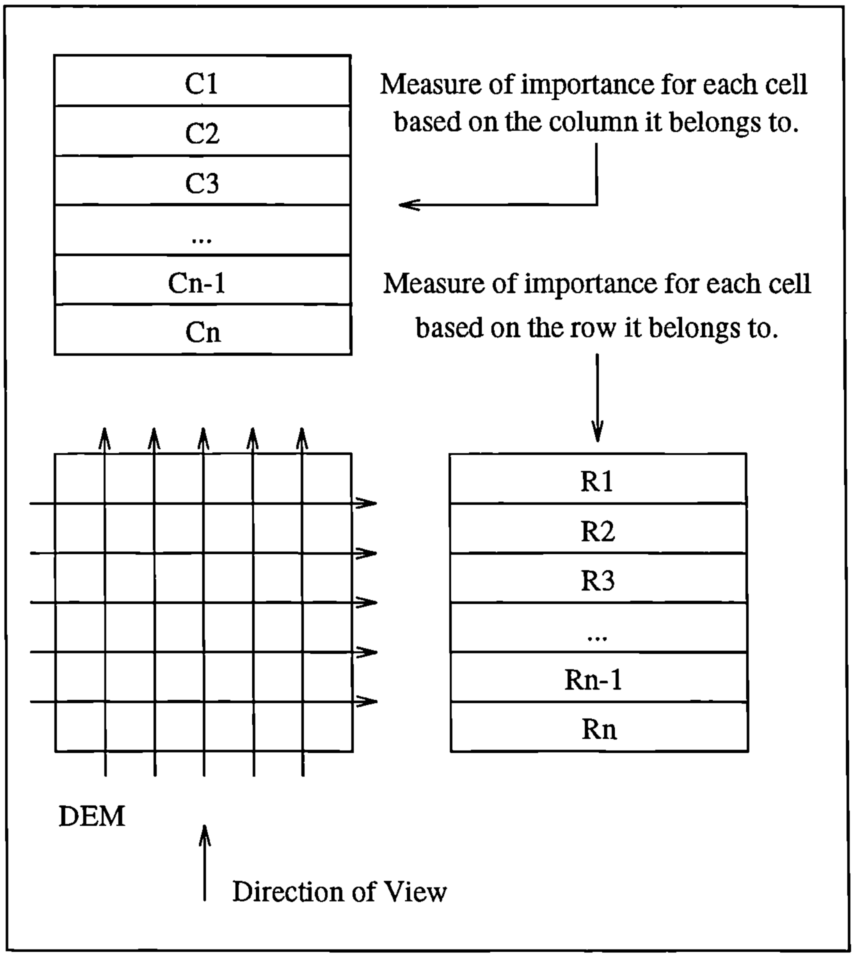


Figure 3.3(a): Cell ordering using Visvalingam's algorithm.

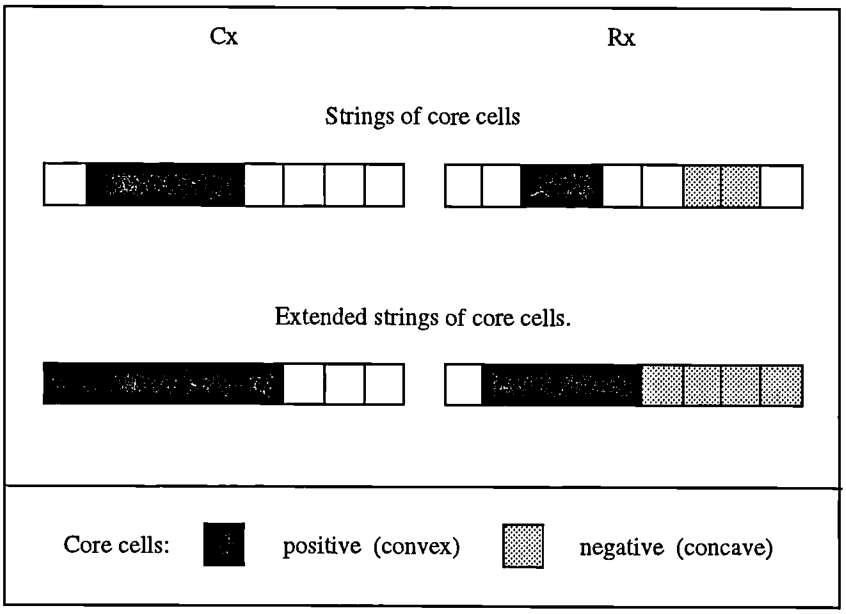


Figure 3.3(b): An example of a simple extension rule. Strings of core cells are extended by one cell to each side.

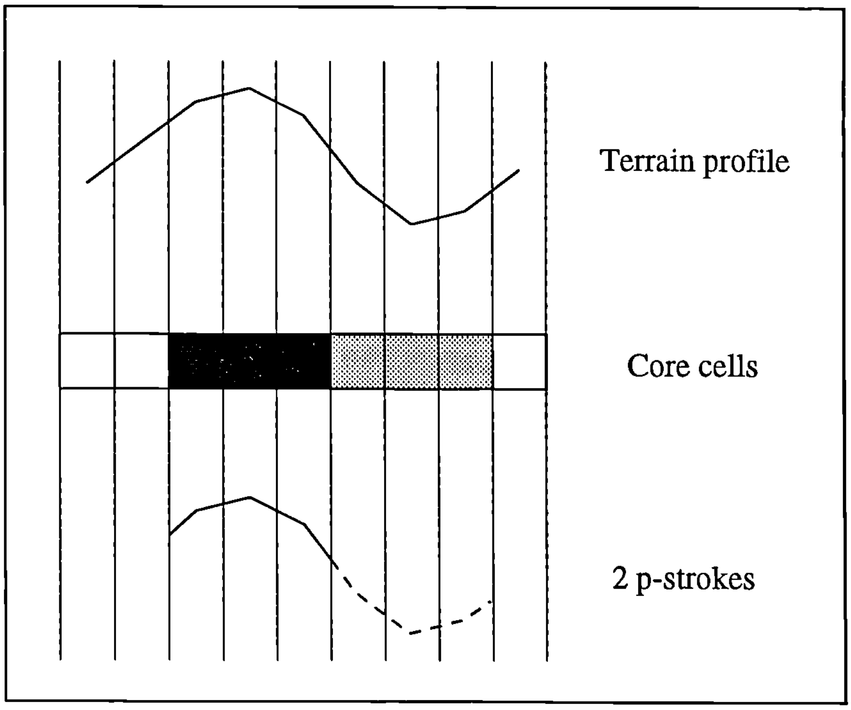


Figure 3.3(c): P-strokes are sections of a terrain profile.

discussed. However, it was not immediately obvious how this information could be visualised. Initial experiments used Visvalingam's algorithm to remove unwanted detail and assumed ambient and later a light source from the south-west which left the foreground light for later inclusion of topographic detail to show form by shading cells. These results were promising and encouraged further research based on Visvalingam's method.

However, since the aim of this programme of research was the artistic depiction of landscapes and not just terrain, it was decided that it could be expedient to show the landforms by polylines so that area fill symbolism, markers and other delineations would be used for showing topographic detail. It was relatively easy to identify and draw in the occluding contours. However, the uplands seemed to float above a plane. This is quite a common phenomena on many landscapes drawn by even skilled artists, including Wainwright (Wainwright, 1973). It took a considerable amount of imagination and effort to find the graphic methods for depicting valleys and other concavities. Too much data was as unhelpful as too little data. This thesis describes the best parameters and we are convinced that it is possible to improve further on this.

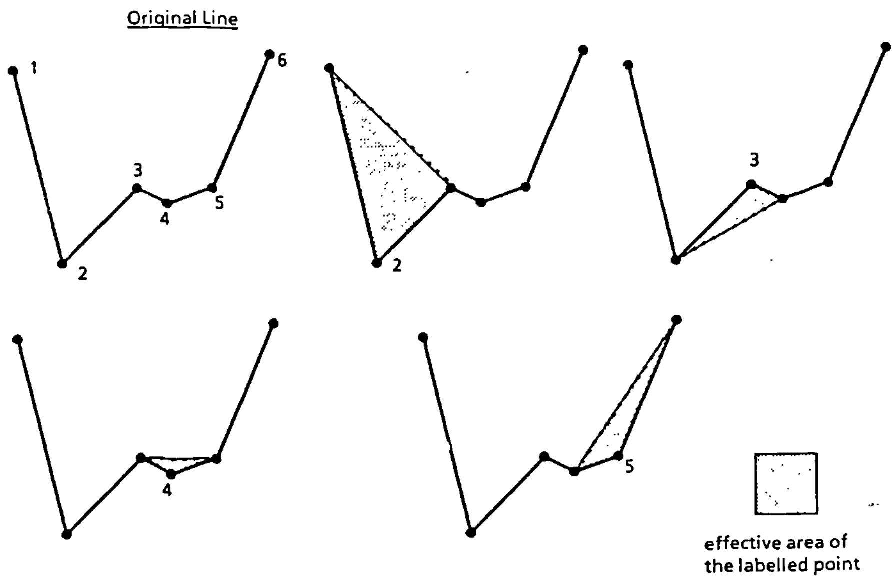
3.3.1.1 Visvalingam's Algorithm for Rating Cells

Visvalingam's algorithm is described by Whyatt (1991) and by Visvalingam and Whyatt (1993). The description of Visvalingam's algorithm given below is reproduced from Visvalingam and Whyatt (1993). It describes the operation of the algorithm with the effective area metric:

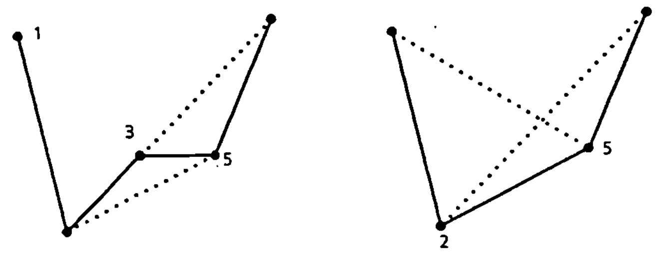
1. Compute the effective area of each point (see figure 3.4(a)).
2. Delete all points with zero area and store them in a separate list;
3. REPEAT
   (a) Find the point with the least effective area and call it the current point. If its calculated area is less than that of the last point to be eliminated, use the latter's area instead. (This ensures that the current point cannot be eliminated without eliminating previously eliminated points.) Delete the current point from the original list and add this to the new list together with its associated area so that the line may be filtered at run time;
   (b) Recompute the effective area of the two adjoining points (see figure 3.4(b));

UNTIL

The original line consists of only 2 points, namely the start and end points.



(a) Effective area of points.



(b) Generalisation by repeated elimination of the smallest area.

Figure 3.4: Visvalingam's algorithm (reproduced from Visvalingam and Whyatt, 1994).

The design of the algorithm was based on the premise that it is difficult to select automatically the shape-preserving points on lines; it is much easier to remove unimportant points. Visvalingam's algorithm makes multiple passes over the line. On each pass it weeds out the point which contributes the least effective area. The effective area of a point is the area of the triangular feature formed by connecting the point with its two neighbours; it represents the area by which the current line would be displaced as a result of removing the point. When a point is removed its effective area is associated with it and the effective areas of adjacent points are recalculated before the next pass. The effective areas are signed to differentiate between convex and concave features. Visvalingam and Whyatt (1993) and Visvalingam and Williamson (1994) used area, which is widely used in traditional cartography, as the measure of significance since the perception of all other characteristics (such as shape) are dependent upon size. Generalisation is often scale-dependent, so the size of features as measured by area was deemed to be most relevant. However, Visvalingam and Whyatt (1993) suggested that Visvalingam's algorithm may be driven using other metrics.

Figure 3.5 illustrates the application of this algorithm to a profile from the Port Talbot DEM shown in figure 3.1. Figure 3.5(a) shows the profile and figures 3.5(b) - 3.5(j) show the effect of filtering the line with different area tolerance values. Initially surface roughness is eliminated, followed by small and then progressively larger features. The algorithm has a tendency to retain the shape of major features while omitting small-scale features in their entirety. Note that a tolerance of about 25 to 50sq metres, provides a minimal simplification and that this sample profile is only grossly generalised with a tolerance of 250sq metres, *i.e.* less than 10% of the points.

Although the two-dimensional algorithm is useful for generalising individual profiles, a DEM cannot be simplified by just plotting the generalised profile lines. In figure 3.6, only the cells which exceed a tolerance of 250sq metres are connected. The resulting image is ugly and not easy to scan. So, the information provided by Visvalingam's algorithm must be used differently. To do so, we attach the following information to each cell of the DEM:

- its height (as usual)
- the effective area which led to its elimination when Visvalingam's algorithm was applied to the row of the DEM that the cell belongs to
- the effective area which led to its elimination when Visvalingam's algorithm was applied to the column of the DEM that the cell belongs to.

Given this information, it is possible to filter the cells based on user-specified tolerances to extract the core cells. These can then be extended to form suggestive strokes.

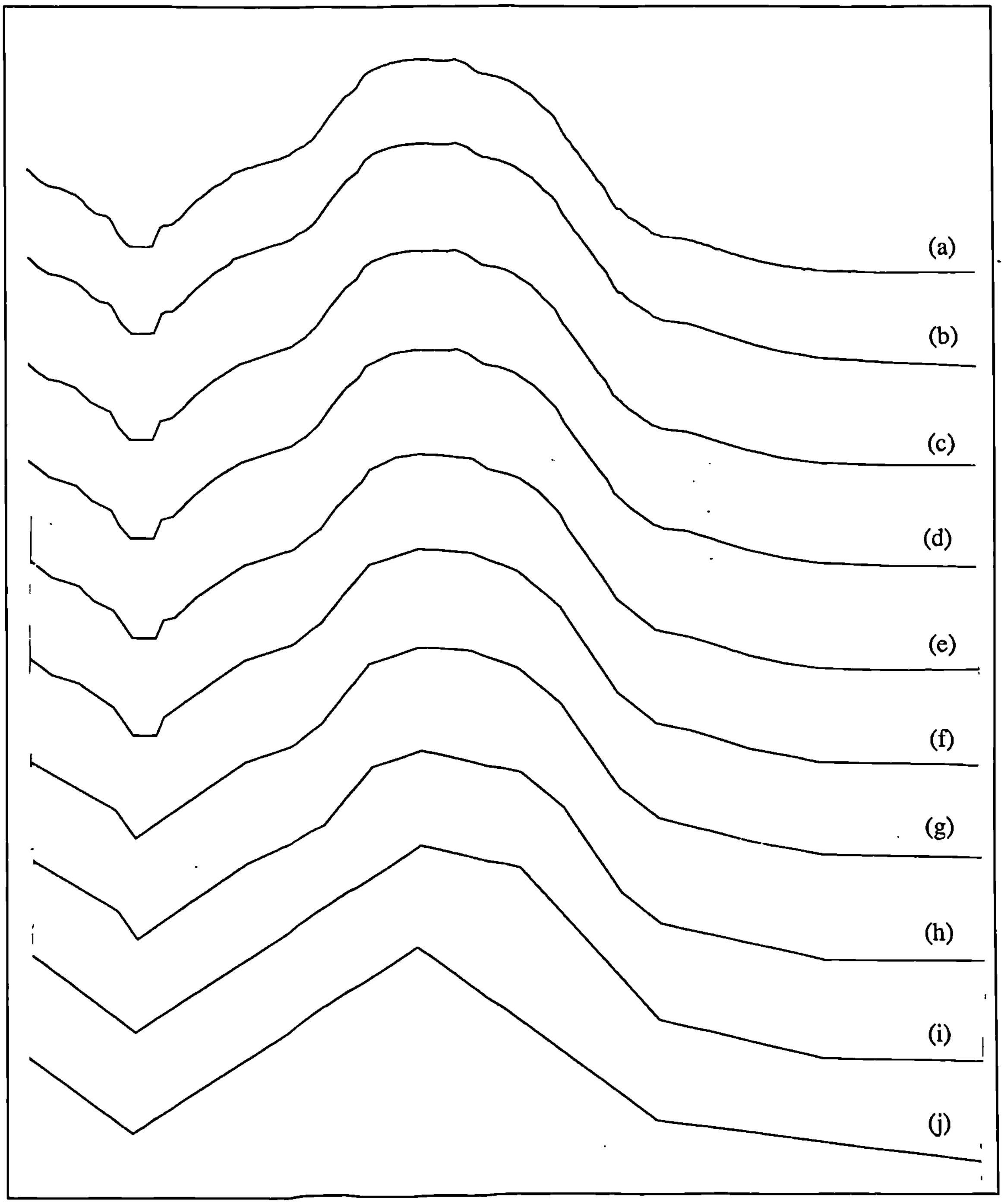


Figure 3.5: Filtering a profile with different area tolerance values: (a) original profile (250 pts.), (b) tolerance = 10 (84 pts.), (c) tolerance = 25 (51 pts.), (d) tolerance = 50 (43 pts.), (e) tolerance = 100 (33 pts.), (f) tolerance = 250 (21 pts.), (g) tolerance = 500 (16 pts.), (h) tolerance = 1000 (13 pts.), (i) tolerance = 4000 (7 pts.) and (j) tolerance = 20000 (5 pts.).

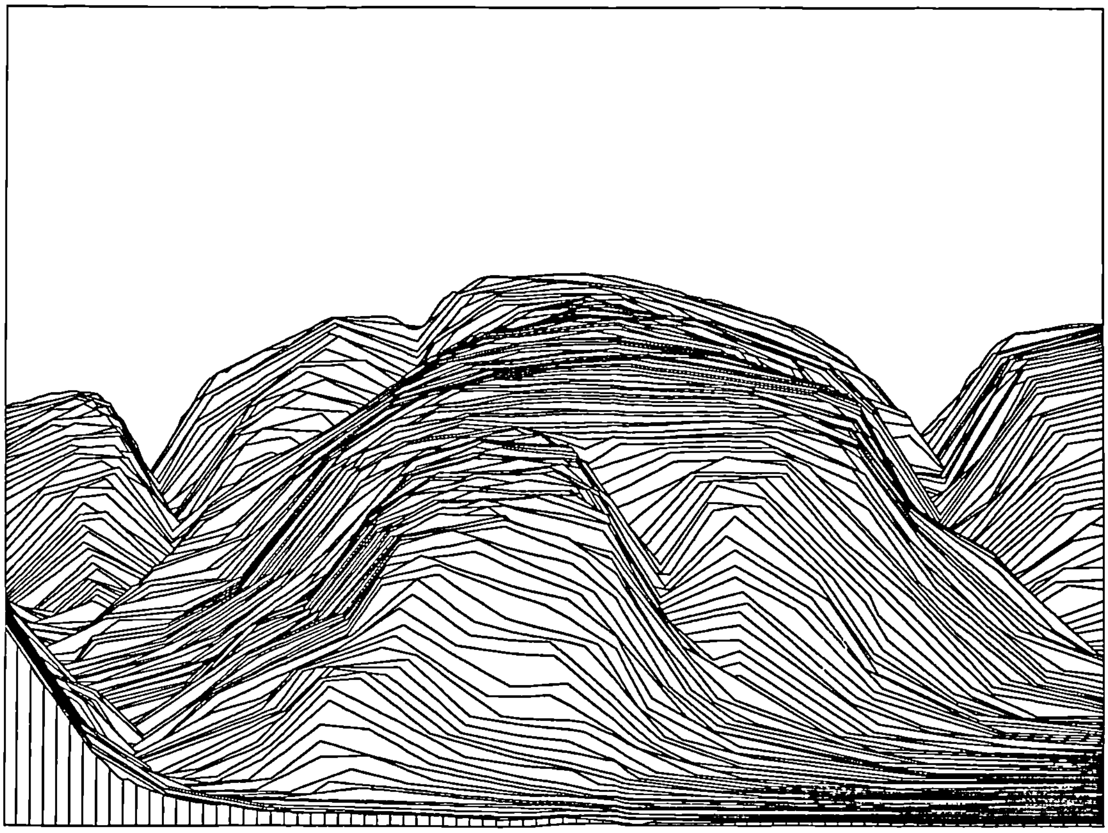


Figure 3.6: DEM simplification by profile line generalisation.

The required information is derived by applying Visvalingam's algorithm to each row and each column of the DEM. The result of applying the algorithm to a row or column is a signed effective area value for each cell. The larger the magnitude of an area value the more important the cell is deemed. Two matrices of area values are built up. One of the matrices contains the area values obtained from applying Visvalingam's algorithm to the rows of the DEM and the other contains the area values obtained when Visvalingam's algorithm is applied to the columns. This is an extension to two-dimensions of the use of tag values which are used with Visvalingam's algorithm (Visvalingam and Whyatt, 1993) and which may be used with the Douglas and Peucker algorithm (Whyatt and Wade, 1988). "These tag values may be used to rank points into a hierarchy of critical points. The concept of a fixed rank order of critical points is convenient since a tolerance parameter may be used to filter out the required points at run time," (Visvalingam and Whyatt, 1993). Visvalingam and Whyatt (1990) were aware how a fixed rank-order limits the scope for producing appropriate scale-related displays.

Visvalingam's algorithm detects features which run perpendicular to the direction of its application. When it is applied to a row of the DEM it detects salient points on features which run in a direction parallel to the DEM's columns. Similarly, applying the algorithm to a column of the DEM detects salient points on features parallel to the rows of the DEM. Both of these directions of application are necessary to adequately detect the form of the terrain, neither is adequate on its own.

The technique of applying a two-dimensional cartographic line simplifiction algorithm to three-dimensional terrain, as described in this thesis for the detection of salient points throughout the DEM, has been used by others in a narrow context. When working with large DEMs it is sometimes convenient to break them into smaller manageable sections which can be processed independently and joined together. Fowler and Little (1979) divided a regular grid into sections and created a TIN for each one. To ensure that TINs generated for adjacent sections fit together adjacent sections share a row and a column of the regular grid. To determine which points along the edge of a section will be included in the hull of the section's triangulation (the hull is the perimeter of the triangulation) a cartographic line simplification algorithm is applied to the profile of the shared row and shared column. Heller (1990) uses the same "profile filtering" technique to determine the points to be included in the hull of his initial triangulation which he progressively refines until statistical fidelity is achieved.

3.3.1.2 From Cells to Profile-Strokes

Sketching may be based on a variety of styles. It was decided to focus on just one style initially. In this study, the utility and limitations of extending the core cells along the profiles to form "profile-strokes" or "p-strokes" was investigated. P-strokes were examined because they:

1. Relate to the DEM - In interactive applications, the user can easily see these p-strokes superimposed on data diagrams to enhance their visual analysis of the data and/or for touching-up of the image. This is similar to the aim of Saito and Takahashi (1990) who tried to make images more comprehensible by the addition of important lines. It is also possible to visually code (via line style, weight or colour) p-strokes on index profiles so that it is easy to deduce the three-dimensional location of features of interest.

2. Relate to how we see - From the time of the ancients, theatre stage props have been slotted into coulisse (grooves in the stage which they fit into) since the visual system is especially sensitive to profiles.

Gombrich (1960, p.130) mentions that in ancient antiquity realism in terms of "illusionist art, perspective and modelling in light and shade" was connected with the design of theatrical scenery. The geographical field sketch uses the coulisse metaphor to emphasise the tendency of ridges and hills to disappear beyond each other.

3. Form a set of neat lines - Many texts in geomorphology and geology show authors' sketches which look untidy, partly because the pencil-strokes are not neatly organised. This is probably due to several factors which include the difficulty of sketching outdoors, an individual's artistic ability and style.

4. Can be computed in parallel - Current photorealistic rendering methods are highly computationally expensive requiring a large amount of CPU time to produce an image. This is especially true when techniques such as ray-tracing and radiosity methods are employed. With real-time displays, for purposes such as flight simulation, the speed of computation is of the utmost importance. Cohen and Gotsman (1994) report that for several years it has been possible to produce a photorealistic image at the cost of minutes of CPU time but today, with technological and algorithmic improvements, you can produce a still image in a few seconds while some high performance parallel systems can produce image sequences at real-time rates. However, there is generally a trade-off between the quality of the images produced and the time taken to produce them. A sketch like approach, like the one advocated here, would be faster and less computationally demanding. The method is conceptually parallel since each row and column of the DEM can be processed individually and does not depend on results from other rows or columns. The speed of the method was not a major concern in this study and is not considered further. Neither is the development of a parallel implementation. The application of parallelism to terrain rendering is discussed by Cohen and Gotsman (1994), Cohen and Shaked (1993) and Miller (1986).

5. Are easy to understand - As previously stated, the emphasis in this study is on assessing the utility of Visvalingam's algorithm for identifying significant information, and less on the conventions for depicting them. P-strokes are sufficient for this initial evaluation.

3.3.1.3 The Extension of P-Strokes and Drawing

This leaves us with a number of further decisions relating to:

a) The definition of the geometry of the p-stroke -

This is the most important of the three decisions as far as this thesis is concerned. At present, the p-strokes may only be varied in two ways, namely by altering:

- the length of extension
- the direction of extension

The core cells, which exceed the tolerance, group into strings of one or more adjacent cells. However, the number of consecutive core cells tends to be short and drawing these alone would not provide a descriptive sketch (see Appendix C). For this reason several rules were devised to extend the strings of core cells. This is done by adding adjoining cells in the profile. The number of adjoining cells added to the string depends on the rule used. The following extension rules were considered:

- no further extension of string giving unextended strokes
- add the adjoining cell on each side to string giving minimally extended strokes
- extend the string to a cell where the effective area is zero or of the opposite sign giving fully-extended strokes. Note that the string includes this cell.

Extending the strings of core cells in this way often causes isolated groups of core cells to become joined together into a single profile stroke. Clearly, the direction of extension only has meaning when strokes are either minimally or fully extended. Strokes may be extended:

- in both directions
- to the right only
- to the left only

In constructing the p-strokes, each point on the profile is regarded as the section of the profile line between the midpoints of it and its two

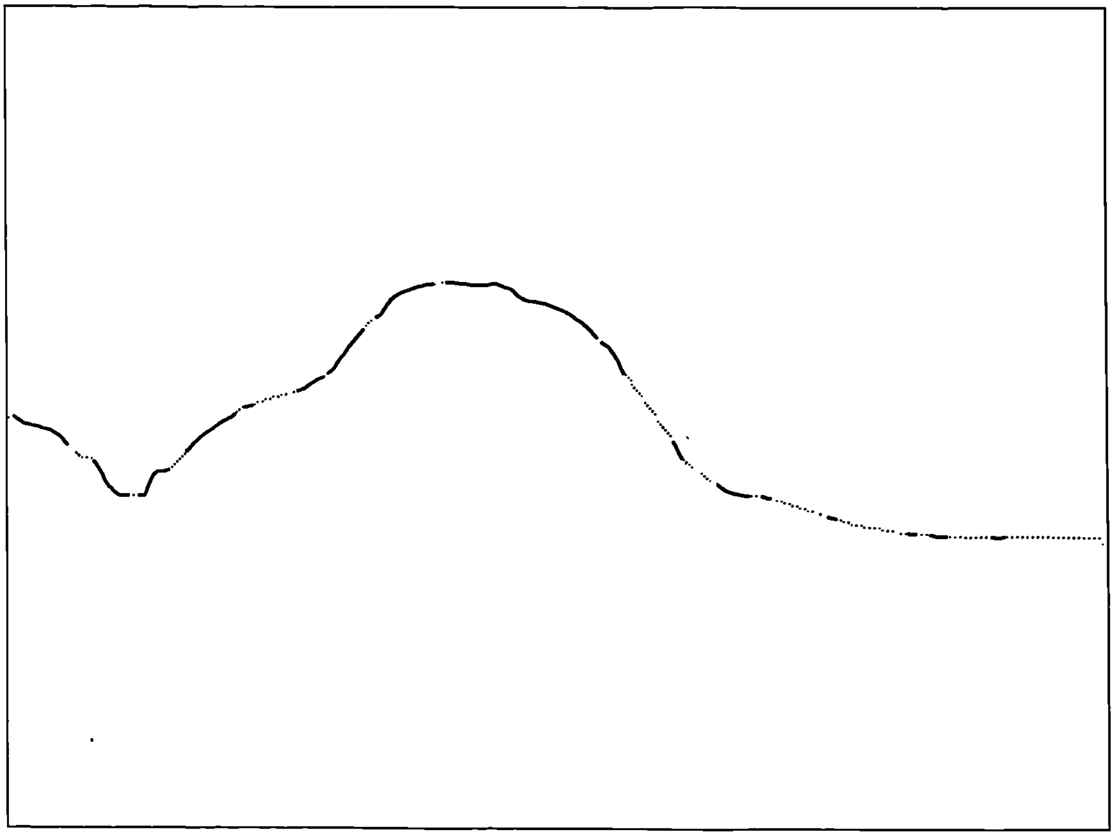


Figure 3.7: Profile strokes for a single profile.

neighbouring points respectively. In practice it is only necessary to extend the p-stroke at its start and end.

Figure 3.7, shows the generation of p-strokes in one profile based on the above ideas. A tolerance of 250 was used to identify the core cells.

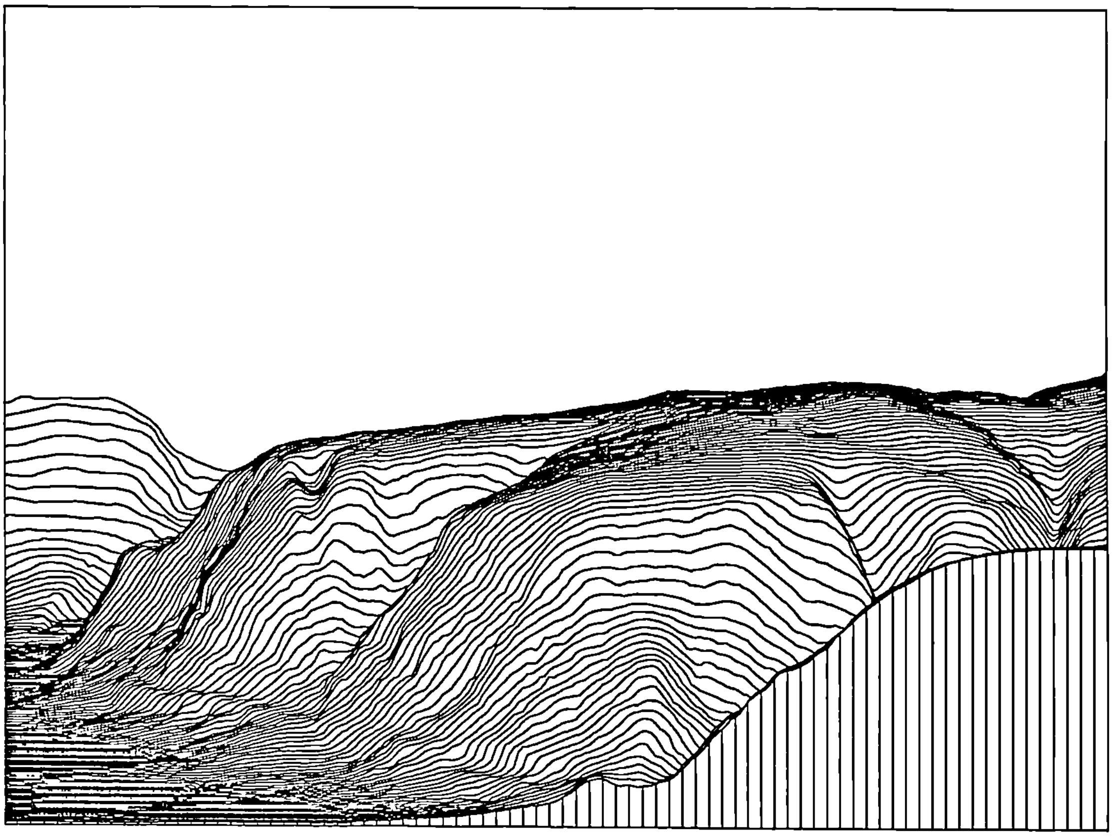
b) The appearance of the P-stroke

Each p-stroke is a polyline and as such its appearance is governed by three attributes which are line style, weight and colour. These are the three standard attributes which determine how lines appear in computer graphics systems. However, the work described in this thesis could benefit from the use of more expressive strokes as described by Hsu and Lee (1994), Dooley and Cohen (1990) and Strassmann (1986) (see section 2.4.3). The use of different line styles, weights and colours can be used to differentiate between the different types of p-strokes to aid in the understanding of the terrain. It was determined through exploratory visualisation that the aesthetically pleasing quality of the sketch could be enhanced by drawing the p-strokes representing concavities in light grey with a dotted line style and the other p-strokes, representing the visually more important convexities, in black with a solid line style to emphasise them. All p-strokes possess the same weight and are a single-pixel wide. Care must be taken when selecting a line style. It was found that dashed line styles do not work well where there are p-strokes on successive profiles whose positions overlap. In such a situation the dashes and the gaps were found to line up creating unintentional patterns and effects. Dashed line styles could be used if it were made so that the alignment effect did not occur on adjacent profiles.

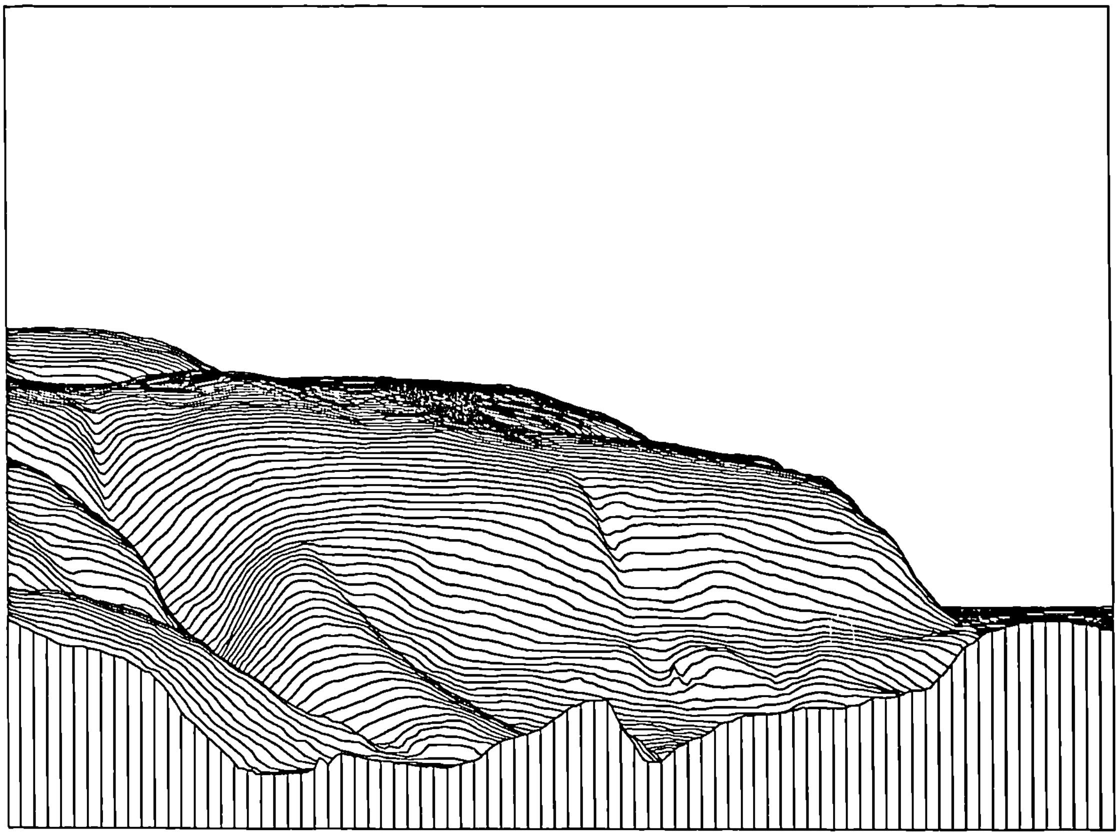
c) The projection of the DEM onto the plane.

It may surprise the reader to learn that the figures presented in this chapter do not make use of perspective. Linear perspective, developed by Brunelleschi and associates, is only one projection or drawing system (Arnheim, 1956). In cartography, the spheroid surface of the earth is projected onto the plane using a variety of mathematical projections (Maling, 1973). Similarly, the three-dimensional model of terrain need not be visualised using linear perspective. Projections used in computer graphics are considered by Foley *et al.* (1990) and Hopgood and Duce (1991). Willats (1990) speaks of a long standing dispute about whether perspective is just one method of projection among many or whether it is unique in giving a true account of the world. While Gombrich (1960, p.243) describes perspective as "the most important trick in the armoury of illusionist art," he later (p.247) states that "perspective is merely one way of describing space and has no absolute validity". The ancient Egyptians knew of perspective yet chose not to use it (Arnheim, 1956, p.74) choosing instead to base their art on "a rigid language of religious and social symbols" (Cole, 1992) while much Oriental art, even today, does not utilise perspective (Segall *et al.*, 1966). Gombrich (1960, p.330) remarks that it is curious that considering the many achievements that have been made by artists it is only the development of linear perspective which has been consistently regarded in the category of true scientific invention (Laurel *et al.*, 1994).

The artist William Hogarth made an amusing engraving in 1754 titled "False Perspective" which is described by Gombrich (1960), McKim (1972) and Cole (1992). In this well known engraving, Hogarth contradicts our expectations of perspective; distant objects are portrayed as larger than similar objects close to us, distant objects overlap closer ones and parallel lines do not converge in the distance. The illusion of depth is reduced as figures far and near make contact. Artists do not always adhere to the rules of perspective if by breaking them they can



(a) View from the south.



(b) View from the north.

Figure 3.8: Port Talbot DEM represented by drawing alternate profile lines. Data supplied by the Ordnance Survey.

produce the desired compositions. Arnheim (1956, p.234) writes "the violations of perspective, which became apparent to the layman only in the work of Cézanne, were committed more subtly by the masters". Falk (1989) describes how the investigation of the use of linear perspective in the work of Piero Della Francesca by means of three-dimensional computer modelling turned up such anomalies while Schaal (1988) discovered perspective anomalies in the work of Albrecht Dürer.

In computer graphics a linear perspective projection is produced by means of a transformation matrix in a similar way to more conventional transforms such as rotations, scales and translations. See Blinn (1993), Foley *et al.* (1990, pp.657-660), Schaal (1988) and Plastock and Kalley (1986, chapter 7).

The figures in this chapter are presented using a vertical oblique projection. This consists of drawing each of the profile lines displaced vertically by a fixed distance from the preceeding ones. When this distance is small the profiles overlap creating a coherent landscape. Drawing begins with the back profile and works forwards using the Painter's algorithm. Each section is filled in solid white to erase p-strokes which should be hidden before the p-strokes are drawn on it. The vertical oblique projection is often employed in Oriental art and some of the images produced using the technique described in this thesis tend to resemble the vertically stacked Chinese landscapes (see figure 3.9). There are other reasons for this similarity. Gombrich (1960, p.208) speaks of "the power of expressing through the absence of brush and ink." In many Chinese paintings the lower parts of mountains are not depicted, as if obscured by mist. If a sketch was made using only convex p-strokes, as in figure 3.11, the same effect results. The similarity does not stop there, Arnheim (1956, p.201) writes "The space-building role of superposition in Chinese landscape painting is well known. The relative location of mountain peaks or clouds is established visually in this way, and the volume of a mountain is often conceived as a skeleton of echelons or slices in staggered formation. The complex curvature of the solid is thus obtained through a kind of 'integral' based on the summation of frontal planes."

An image produced using the vertical oblique projection is closer to a map than the corresponding image shown with a perspective projection since horizontal distance is not distorted with depth.

Figure 3.9: An example of a Chinese landscape painting (reproduced from The Fine Art Society, 1911).

The choice of projection system influences the area visible in an image. If a plan view was drawn of the area shown in any of the figures in this chapter it would be seen to be rectangular. However, if looking at a perspective scene, where the terrain fills the field of view, the plan view would be the shape of a trapezium. A narrow band of terrain is visible in the foreground while a wider area is shown in the distance. This is due to the convergence to a vanishing point in central perspective. An example of this is given in Cohen and Gotsman (1994).

The prevalence of perspective in our culture means that unless strong contradictory visual cues are available to tell us otherwise we assume perspective is present when viewing an image. The figures in this chapter are drawn without perspective. However, when viewing them the assumption of the viewer is that perspective has been used. This leads to the false conclusion that the terrain rises as it becomes more distant. This is true of all three viewpoints (figures 3.8 and 3.1) where the highest point appears at the back or on the most distant profile. The reason for this is the expectation that objects become smaller as they become more distant. In the figures here this is not true therefore distant profiles which are shown at their true size seem larger and gain added importance.

d) Vertical Exaggeration.

In most cases it is necessary to vertically exaggerate profiles to make them look correct, otherwise if they are drawn with no vertical exaggeration they tend to look too flat and the undulations along the profile will not be noticeable. Vertical exaggeration is calculated by dividing the horizontal scale by the vertical.

The amount of vertical exaggeration used is dependent upon several factors. Dickinson (1969, p.152) writes "A vertical exaggeration suited to the purpose of the profile, the terrain and the map scale should be consciously selected." Dickinson goes on to recommend a vertical exaggeration of from two to four for general purpose profiles. However, the scale of the DEM is one of the influencing factors, for smaller scale DEMs and also for gentler terrain a greater degree of vertical exaggeration is recommended. The purpose of a profile also influences the use of vertical exaggeration; for example, it is inappropriate when compiling accurate geological sections (Monkhouse and Wilkinson, 1976, p.120).

Raisz (1938, p.133) reminds us that as the vertical exaggeration changes the character of a profile also changes thereby creating a caricature of the topography. Birch (1964, p.124) writes "over- or under-emphasis of relief alike produce an absurd effect." This is demonstrated in figure 3.10(a) - (c) which shows the effects of changing the vertical exaggeration using the profile shown in figure 3.5. Figure 3.10(a) shows the profile with no vertical exaggeration at all while in figure 3.10(b) the vertical scale has been exaggerated by a factor of three (which is the amount of vertical exaggeration used for figures of the Port Talbot DEM). For figure 3.10(c) the vertical exaggeration has been increased dramatically to ten. In figure 3.10 the profile's character changes from being too flat to being over exaggerated.

Robinson *et al.* (1984, p.374) writes of another reason for introducing vertical exaggeration, "people are tiny in comparison to landforms, which magnifies our perception of the size of mountains and hills, so that in order to match our subjective impressions, almost all pictorial terrain representation must greatly exaggerate the relative heights of terrain features." Lobeck (1924, p.171) advises that it may be desirable to exaggerate the vertical scale of a drawing to get more space and hence produce a clearer sketch. However, the result of doing this is to make it appear as though the observer had made the sketch from a much higher elevation.

3.3.1.4 Viewing

Arnheim (1956, p.70) writes that when dealing with flat objects, the orthogonal projection obtained when the plane of the object is hit by the line of sight at a right angle is the one projection that does complete justice to the visual concept we have of the object. A current limitation of the technique described here is that the DEM can only be viewed from four directions: the front (figure 3.8(a) - looking from the south), the back (figure 3.8(b) - viewing from the north), the left (figure 3.1 - looking from the west) and the right (in the case of the Port Talbot DEM little can be seen when viewing from this side. This is due to the highland nearest to the viewer obscuring almost everything else).

When viewing the DEM from the front or back it is the rows which form the profile lines while when viewed from the sides it is the columns of the DEM instead. The method described here is object centred in terms of cell ordering but the resulting sketch is view centred (see figure 3.2). To produce views from four directions only two sets of profile strokes are needed. The first set is used for both the front and back views while the second set is

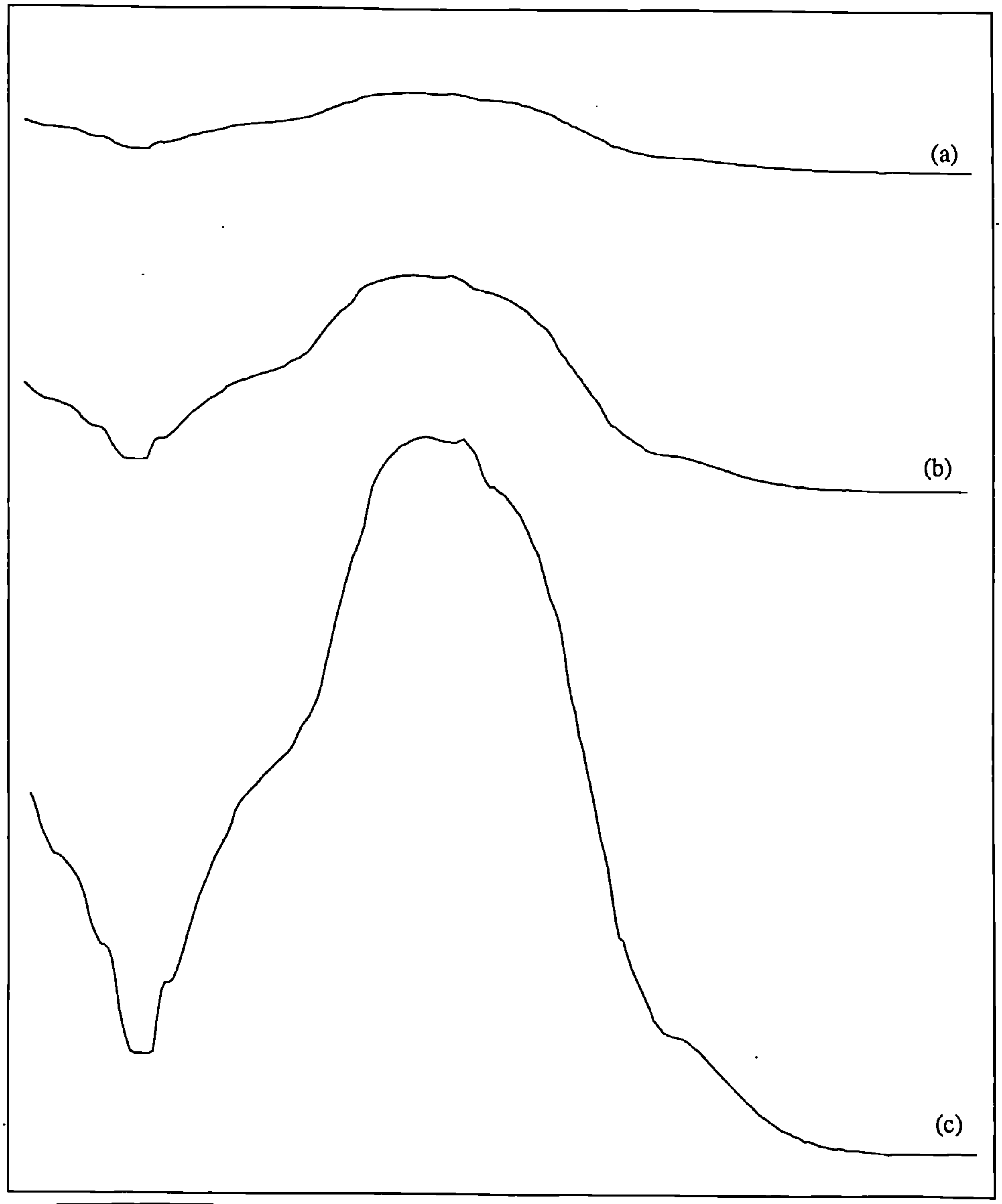


Figure 3.10: The effect of vertical exaggeration: (a) no vertical exaggeration, (b) times three and (c) times ten.

used for the two side views.

Only being able to produce sketches of a DEM from these four viewpoints limits the utility of the method. Experimentation was carried out to produce sketches viewed from an angle. This was achieved by offsetting the horizontal position of each profile. However, it was felt that this technique was unsatisfactory because the p-strokes are no longer orthogonal to the viewer (because the profile lines are not) which results in an incomplete description of the terrain. For the technique described here to work successfully it is necessary that the profile strokes are perpendicular to the line of sight because p-strokes are two-dimensional entities which possess no depth. When they are perpendicular to the line of sight this is not noticeable. However, the closer the p-strokes come to being parallel to the line of sight the less effective is the resulting sketch.

It is easy to see how viewing could be extended to include views from the corners of the DEM. In this case the profile lines would be produced by traversing diagonals. To produce the profile strokes it may be possible to utilise the already calculated effective area values for each cell in a diagonal. However, if this does not provide sufficient information it will be necessary to calculate new effective area values which are orthogonal to and parallel to the line of sight. For some applications these eight viewing positions may be sufficient, selecting the one which is nearest to the actual viewing position. This idea is similar to a short cut method for adding trees to three-dimensional scenes (Sasada, 1987). A two-dimensional image of a tree is produced. This is then always made to face the viewer no matter where he views it from, so he never realises that it is flat. Cartographic delineations are based on a similar idea (Lobeck, 1924, p.172). Extending viewing further so that an appropriate sketch could be produced for any viewing position would involve more complex methods for determining the position of profile lines on the terrain surface.

3.3.1.5 Simplification of the P-Strokes

The profile strokes may be simplified before they are drawn to reduce the level of detail to one appropriate for the size (scale) at which the sketch is to be drawn. This is accomplished using a cartographic line simplification algorithm such as Visvalingam's algorithm. The two end points of each p-stroke are deemed the most important and can not be omitted - at the maximum level of simplification the p-stroke would consist of a line joining these two end points. However, while this gross level of simplification would

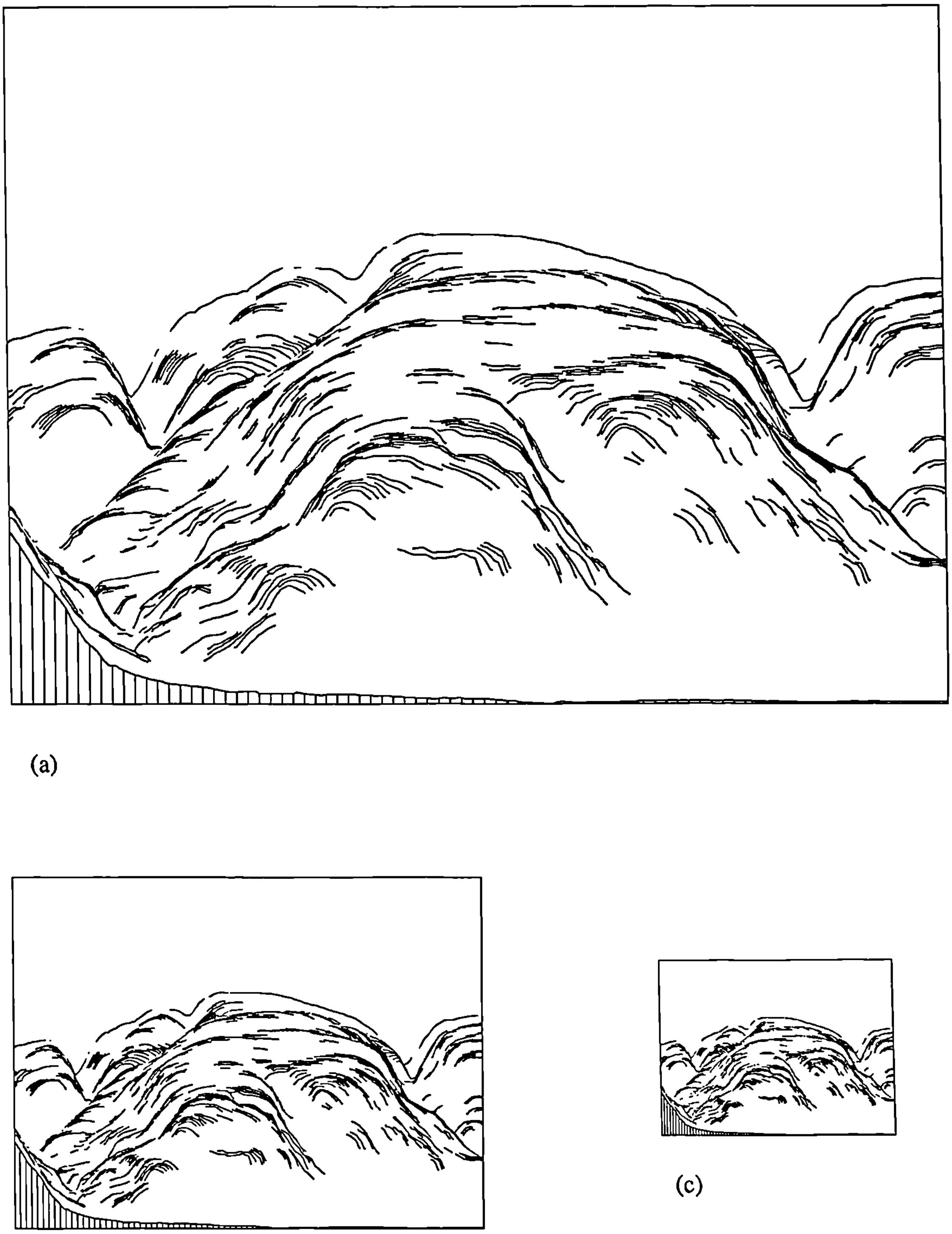
not be appropriate, it is possible to eliminate a large number of points from the p-strokes when drawing small sketches. This serves to enhance the impression and the clarity by removing detail superfluous at the chosen scale. This is the purpose that cartographic line simplification algorithms fulfill in scale-dependent generalisation. A tolerance value is required to determine the level of simplification of the profile strokes. Figure 3.11(a) - (c), shows three versions of the same sketch but at different levels of reduction.
Figure 3.11(b) is half the size of figure 3.11(a) while figure 3.11(c) is half the size of figure 3.11(b). The p-strokes in these figures have not been simplified.

In figure 3.12 the profile strokes have been simplified using Visvalingam's algorithm. Figure 3.12(a) is the same size as the original plot but the p-strokes have been simplified. It contains 36% of the points used in the original. Figure 3.12(b) contains 25% of the points used in figure 3.11(a) while figure 3.12(c) contains 20% of the points used in the original figure. A simplification tolerance of 50 was used for figure 3.12(a), 250 for figure 3.12(b) and 1000 for figure 3.12(c).

Visvalingam and Williamson (1994) found that the Douglas and Peucker algorithm (Douglas and Peucker, 1973) performed better minimal simplification than Visvalingam's algorithm due to the tendency of Visvalingam's algorithm to pull away from curves. Douglas and Peucker's algorithm may therefore produce slightly better results if it was used for p-stroke simplification in place of Visvalingam's algorithm.

To display an appropriate level of detail for small sketches it is not sufficient to merely simplify the profile strokes in this way - though it does help. The level of detail may be decreased to some extent by increasing the tolerance values used to select core cells or by using extension rules which produce shorter p-strokes. There is a need to generalise the sketch by eliminating p-strokes.

Elimination of p-strokes serves as a cue to depth perception and as such could be applied to full sized sketches as well as reduced ones. As objects become further away from us, minor details disappear and eventually we see only the main features. Simplification according to depth would produce this effect by increasing the tolerance values used to select core cells as the distance from the viewer increases. The result would be to select less and less p-strokes as the depth increases until only the main features are picked out in the distance. This concept is the basis of the "mip-mapping" technique devised by Williams (1983). Detailed texture maps are used in the foreground with successively simpler texture maps being used as the distance

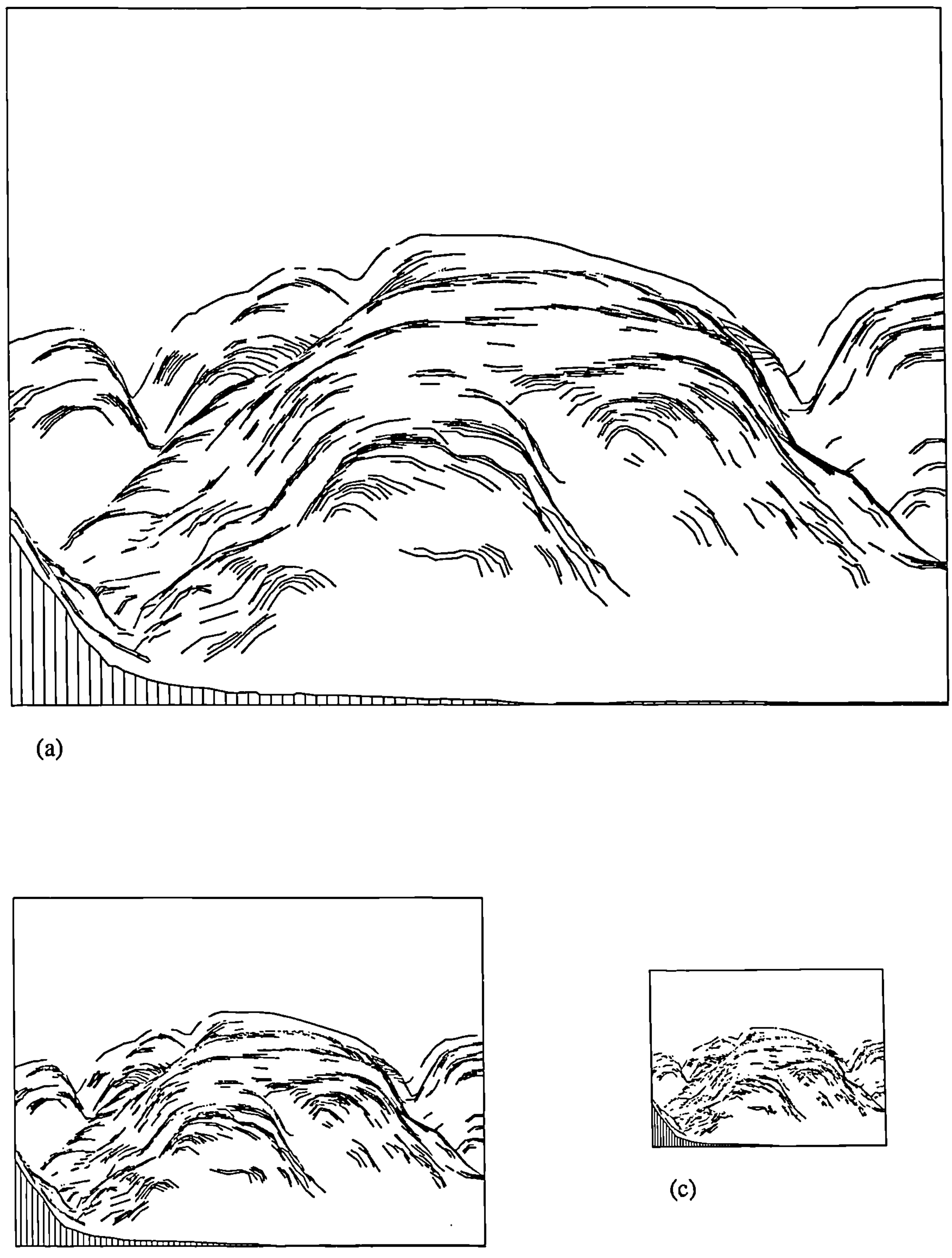


(a)

(b)

(c)

Figure 3.11: Reduction without p-stroke simplification : (a) full size, (b) half size and (c) quarter size.



(a)

(b)

(c)

Figure 3.12: P-stroke simplification : (a) full size, (b) half size and (c) quarter size.

from the viewer increases. Wolff and Yaeger (1994) used the mip-mapping technique in their visualisation of Martian terrain. Kaneda *et al.* (1989) use a similar technique.

3.3.2 Different Types of Pencil Strokes

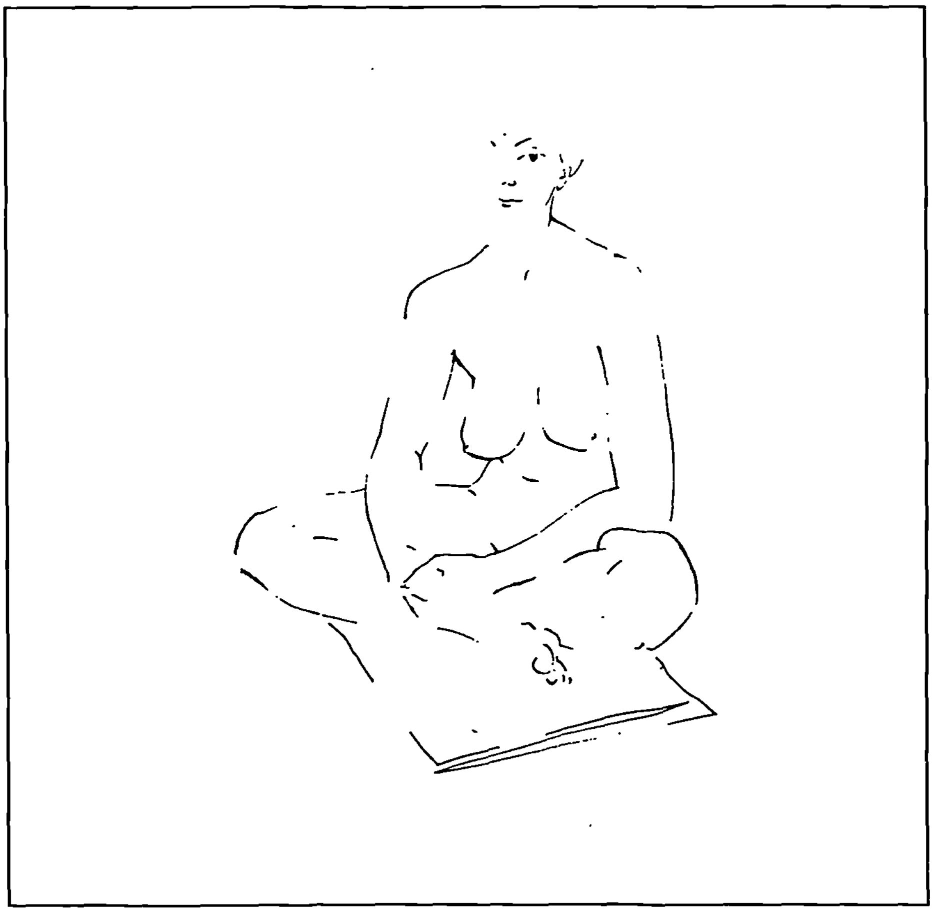


Figure 3.13: Closure is the mind's ability to complete partial images (reproduced from McKim, 1972).

A study of block diagrams makes it apparent that the artist uses different lengths and directions of pencil stroke. The most distinct are the occluding contours (silhouettes) which also form the horizon. The artist does not always draw a continuous line but the strokes are sufficient to enable the visual system to connect the lines. When viewing an image there is such a powerful tendency to perceive meaningful patterns that the mind fills in the missing parts through a process termed "closure" - see figure 3.13 (McKim, 1972, p.57). Indeed, it is the suggestive, rather than explicit, coding which adds to the aesthetic quality of the masters' drawings. Similarly the technique described here does not produce a solid horizon line when viewed from a low angle. The horizon composed of "overlapping" profile strokes is supplemented by drawing the most distant profile as a solid line. This acts as an initial horizon (as well as marking the edge of the DEM). As the other profiles are drawn, using the Painter's algorithm, high parts erase bits of the initial horizon. However, the p-strokes which are drawn do not necessarily fill these gaps, which may in some cases be too large. A similar problem occurs if a perspective projection is used, when drawing the converging tramlines which mark the sides of a DEM. It would be desirable to produce continuous lines in these cases.

The most important occluding contours are indicated by positive effective areas, computed in the direction parallel to the line of sight (+parallel). Since these are the most important lines a minimal tolerance of 1000sq metres is used and the core cells are fully extended. Figure 3.14(a) shows the +parallel profile strokes for the Port Talbot DEM when viewed from the west. In general, the negative effective areas computed parallel to the line of sight tend to locate valleys and would therefore be occluded though it was found that drawing these provides additional information. Because this type of p-stroke is deemed least important of all types of p-stroke, a higher tolerance value of 4000sq metres is used though the core cells are still fully extended. Figure 3.14(d) shows the –parallel profile strokes.

Artists also include other strokes to pick out the form of the land by suggesting the effect of illumination. However, they do not always do this by mechanical adherence to an algorithm based on light source *etc.* Because the sketching technique described here is based on two-dimensional profiles, only the impact of lighting from the right or left was considered. The significant effective areas (outside a tolerance of 4000sq metres) orthogonal to the line of sight are used for this purpose; the positive values (+orthogonal) indicate convex forms (*e.g.* ridges) while the negative values (–orthogonal) indicate concave forms (*e.g.* valleys). Observations suggest that p-strokes which are minimally-extended to the right and not extended to the left best characterise the ridges and spurs. Figure 3.14(b) shows +orthogonal profile strokes of this kind. The valleys are best picked out by p-strokes which are minimally-extended to the left and not extended to the right. Figure 3.14(c) shows –orthogonal profile strokes of this kind. This is consistent with the effects of illumination from the left which is similar to the convention of north-west illumination used in cartography. The resulting sketches are quite pleasing. Figure 3.15 shows the same DEM sketched from three directions.

The four types of profile stroke may be ordered according to importance, as shown in figure 3.14. In general it was discovered that profile strokes describing convexities were most important in describing the terrain with

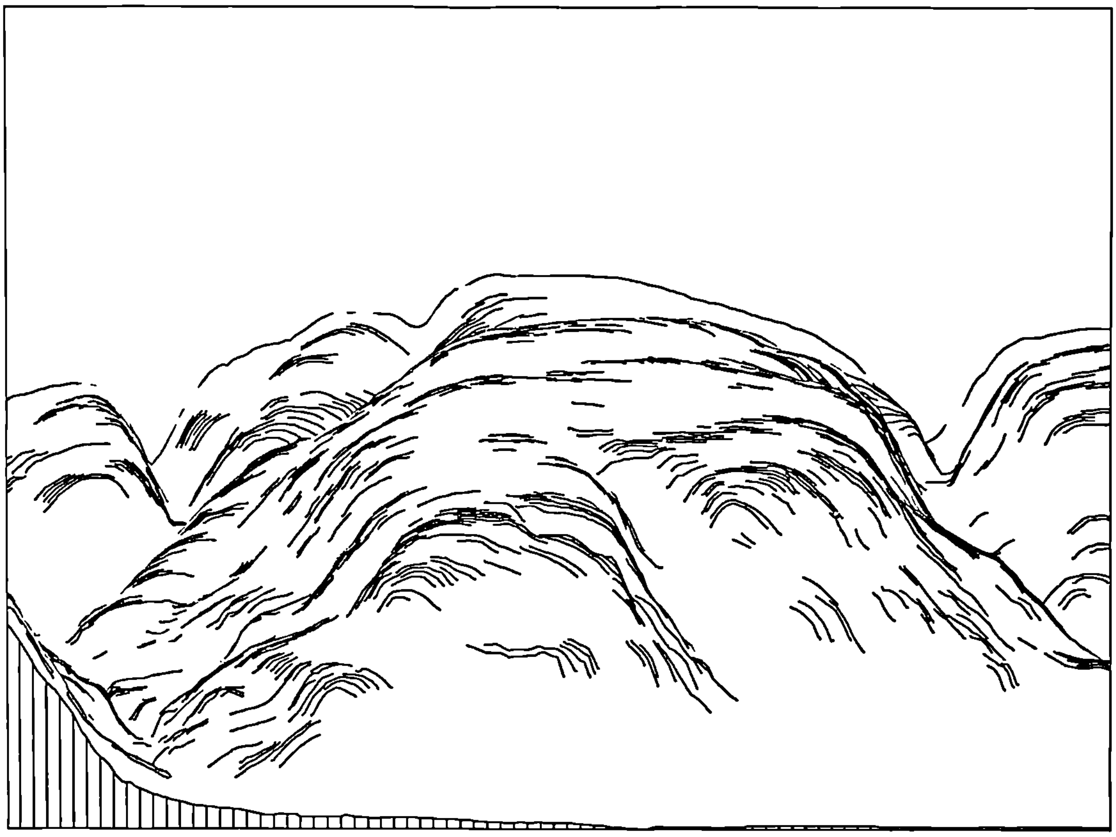


Figure 3.14(a): +parallel p-strokes for Port Talbot DEM, viewed from the west.

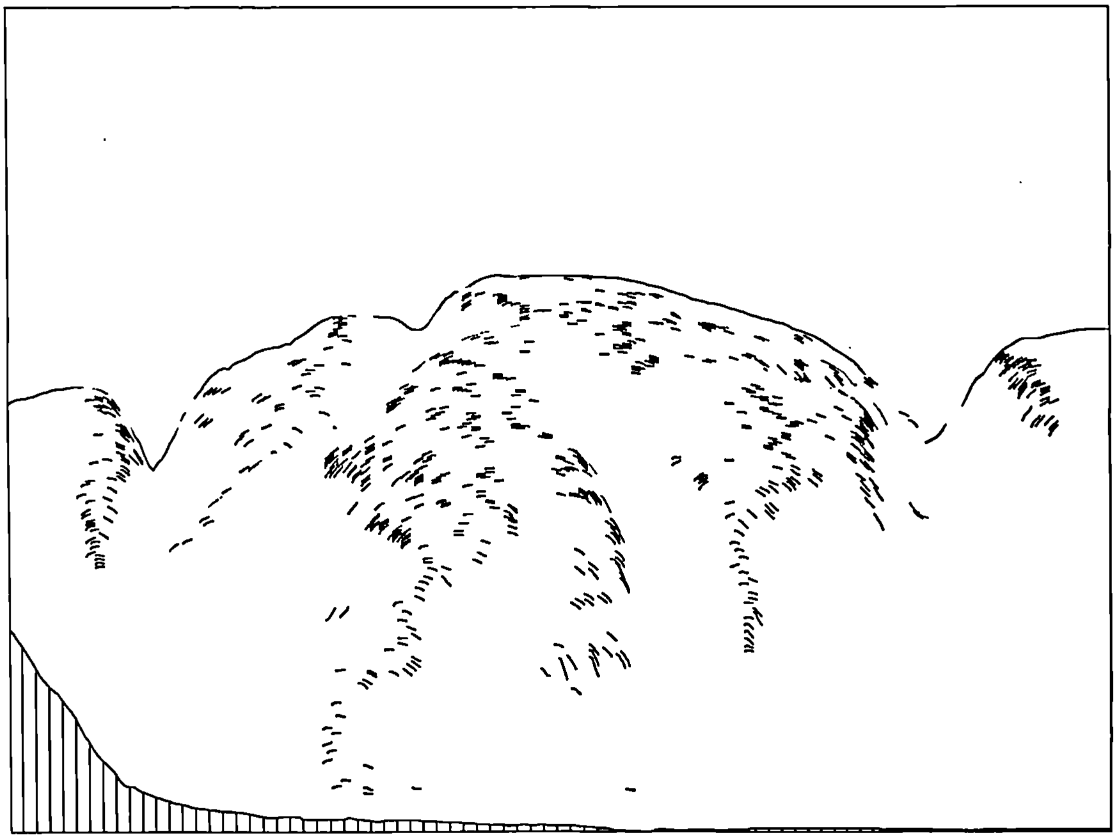


Figure 3.14(b): +orthogonal p-strokes for Port Talbot DEM, viewed from the west.

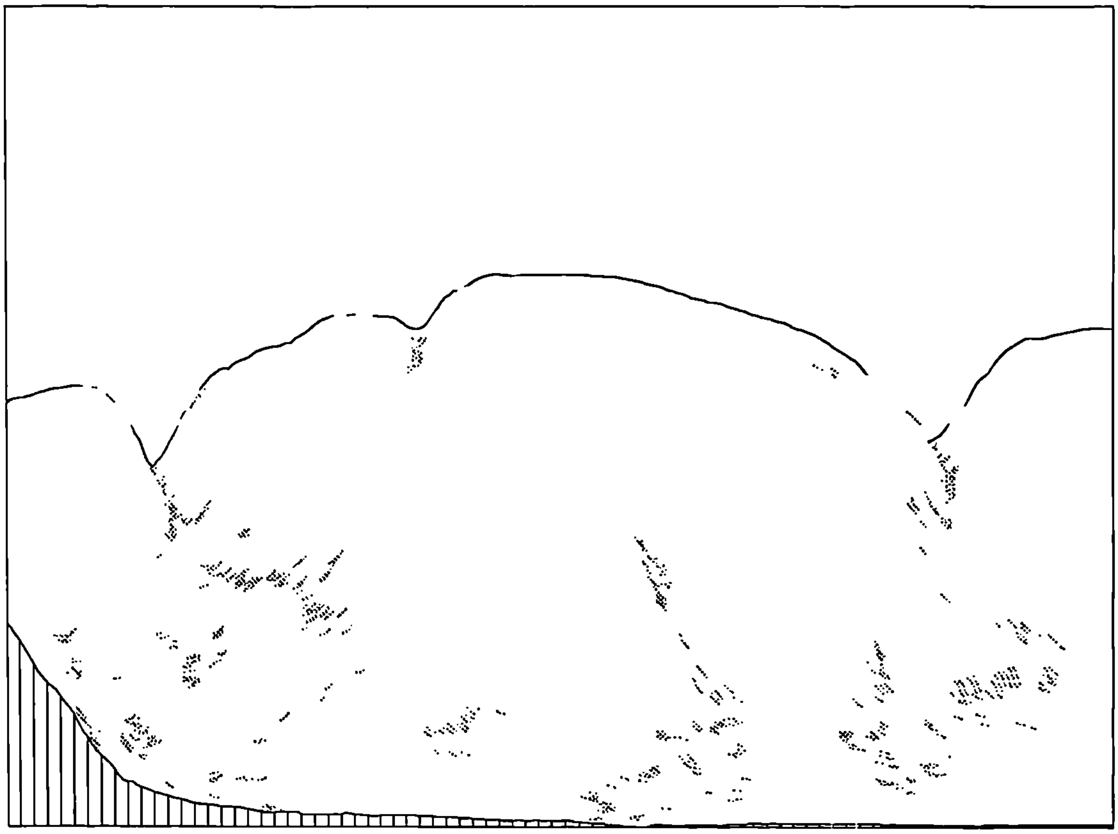


Figure 3.14(c): –orthogonal p-strokes for Port Talbot DEM, viewed from the west.

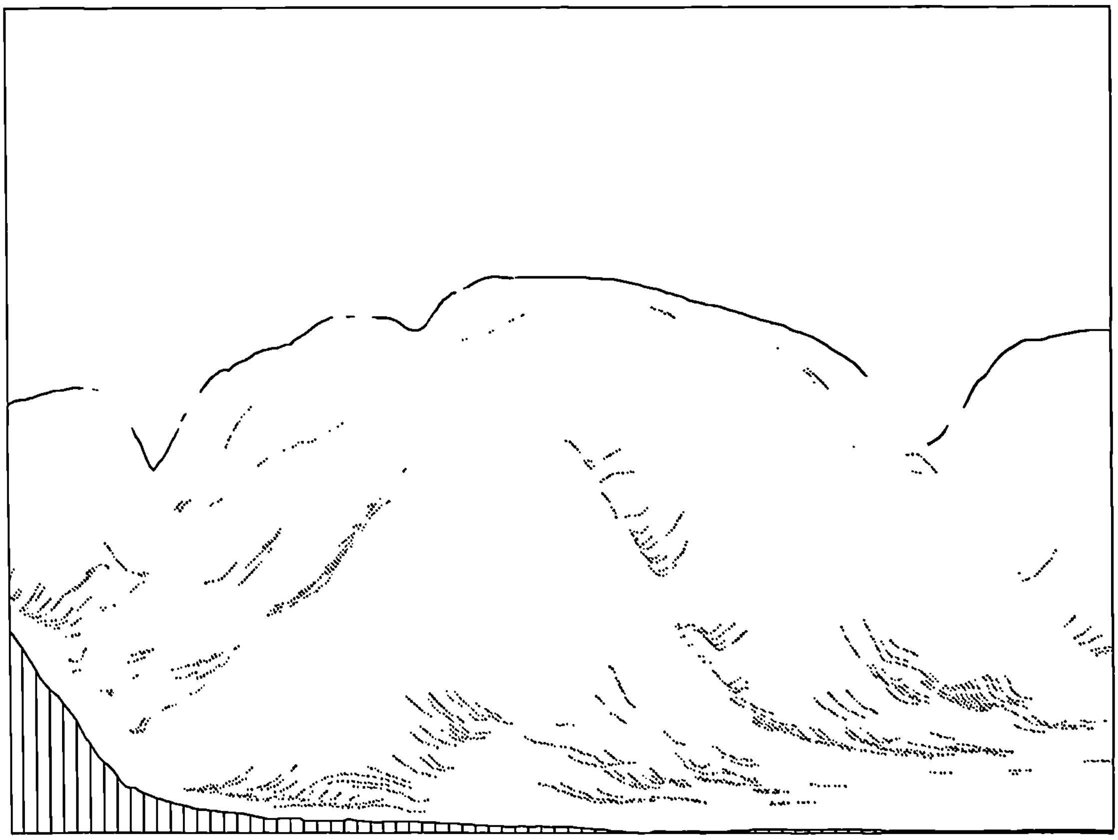


Figure 3.14(d): –parallel p-strokes for Port Talbot DEM, viewed from the west.

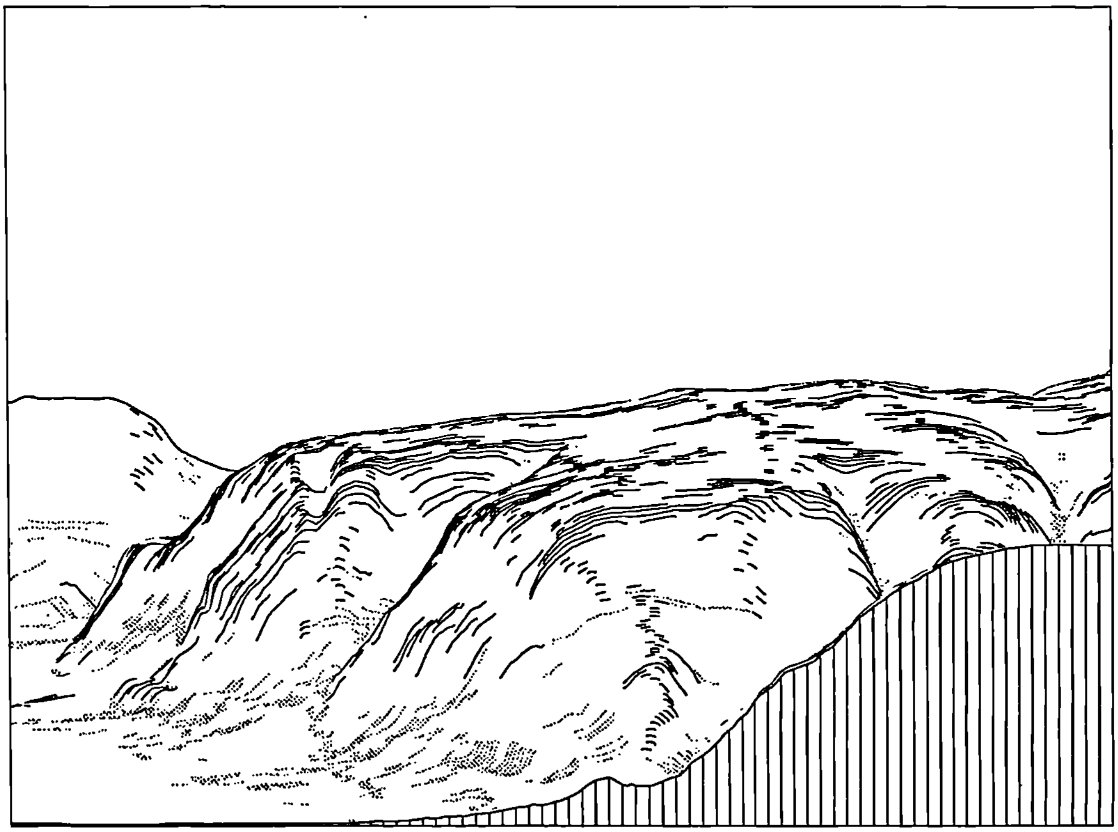


Figure 3.15(a) Sketch of Port Talbot DEM from the south.

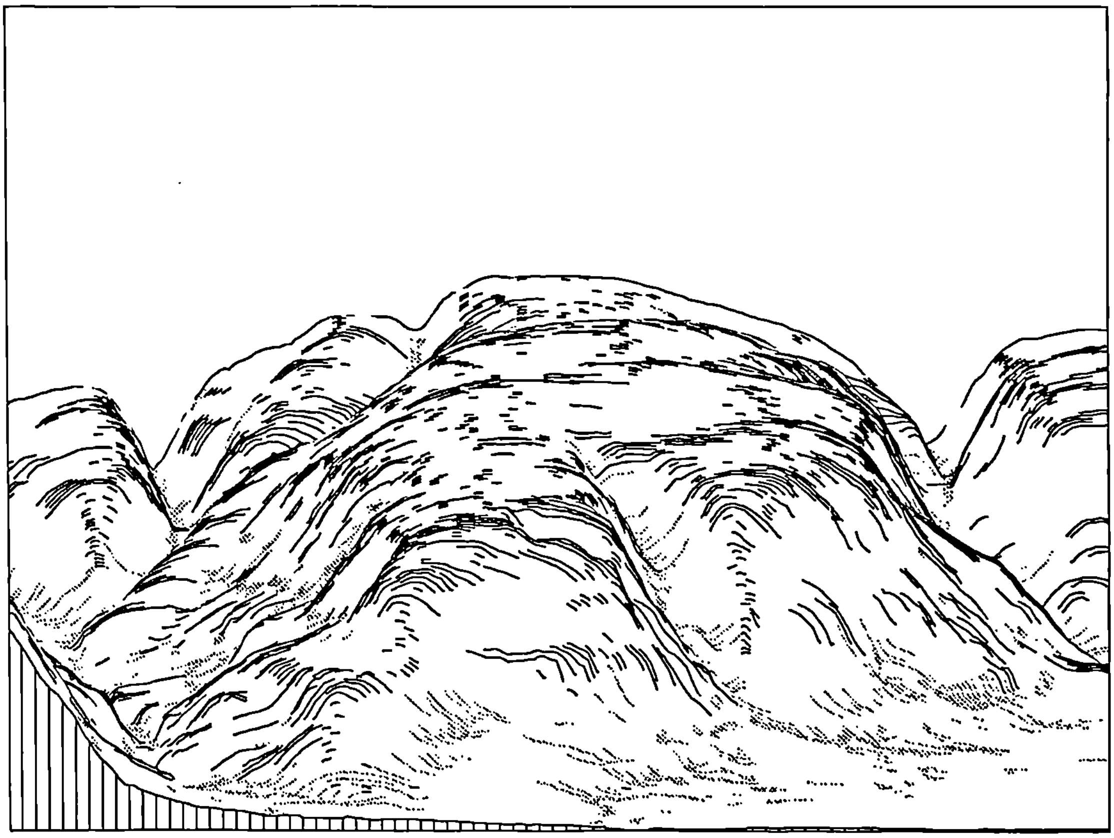


Figure 3.15(b) Sketch of Port Talbot DEM from the west.

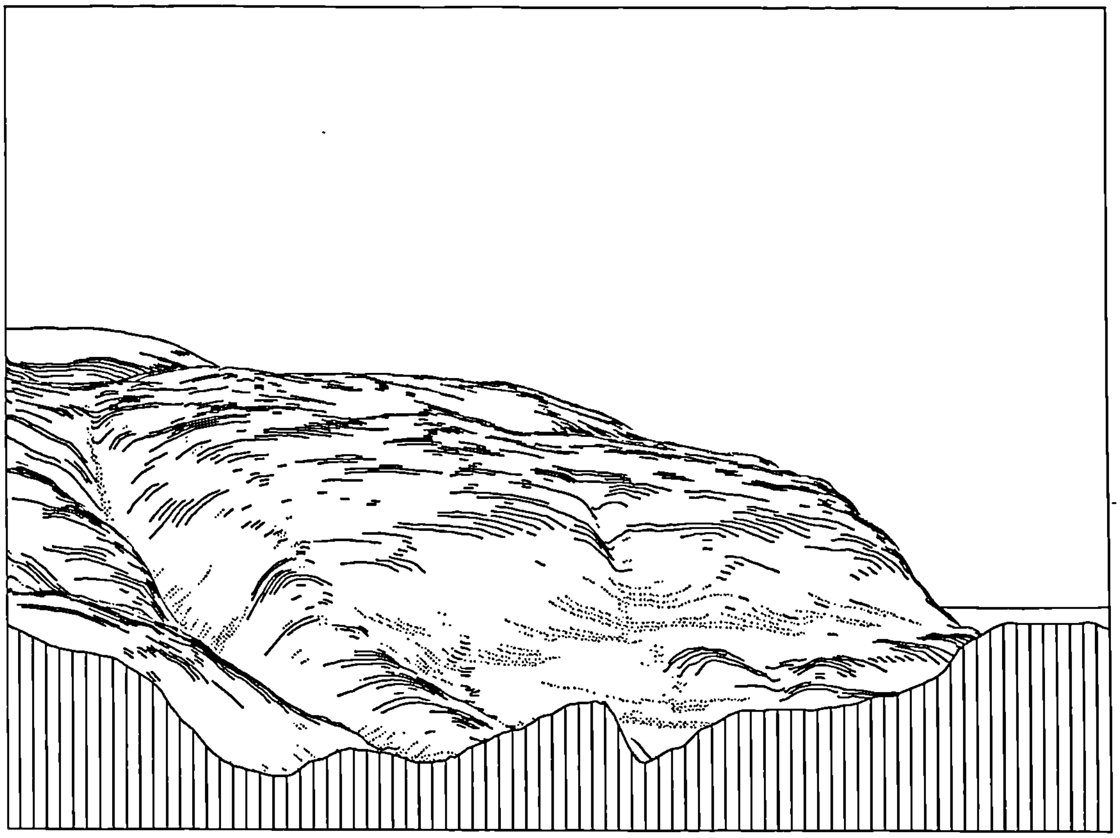


Figure 3.15(c) Sketch of Port Talbot DEM from the north.

+parallel p-strokes, which describe the silhouettes of hills (occluding contours), being most important of all. In terms of concave profile strokes, –parallel p-strokes are deemed least important as these would generally be hidden while –orthogonal p-strokes describe the shape of valleys which we can see. The use of these priorities can be expressed in terms of a visual hierarchy. For example the lower priority of the concave profile strokes can be expressed by varying the attributes of strokes; the use of dotted rather than solid lines or the use of grey instead of black. Both of these attributes have been varied in the sketches shown here. Similarly each type of p-stroke could be differentiated. In this way the meaning of each p-stroke could be derived from its symbolism. For example, instead of showing –parallel profile strokes in the same way as –orthogonal ones, they could be shown by vertical lines to try and give the impression that the concavity being depicted is perpendicular to the viewer. The colour of the p-strokes could also be varied to suggest aerial perspective and/or other effects.

3.3.3 Tolerance Selection

The selection of tolerance values was determined by trial and error. The chosen tolerance values depend on the DEM being sketched, the purpose of the sketch, the size of the sketch and the viewer's preferences. The system developed for experimentation was flexible and interactive in order to allow different values to be quickly tested. Saito and Takahashi (1990) report similar experiences of trial and error testing to achieve the best results with their system for comprehensible rendering.

Figure 3.16 shows a graph, for each type of p-stroke, of the distribution of effective area values. Note that effective area values of zero magnitude are included in both positive and negative graphs. It is clear from these graphs that the vast majority of points in the DEM are tagged with an effective area value of small magnitude. The corresponding graphs for other DEMs differ slightly but still retain the same characteristic shape. Graphs such as these can be used as an aid to selecting tolerance values.

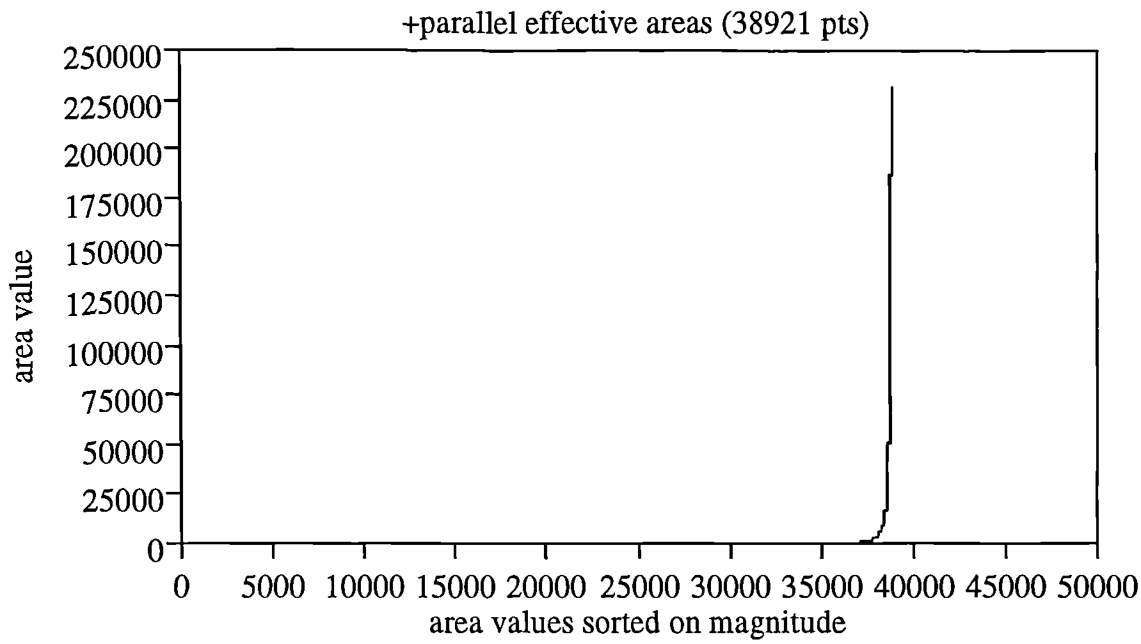


Figure 3.16(a) Graph of +parallel effective areas for Port Talbot DEM.

3.3.4 Timings

The timings presented here provide only a general idea of the speed of this technique. The ideas presented in this thesis were implemented in a prototype system without any regard for speed and it was from this prototype that the timings were taken. However, a more efficient implementation could greatly improve these times, especially if the inherent parallelism in the view independent stage of the technique was utilised.

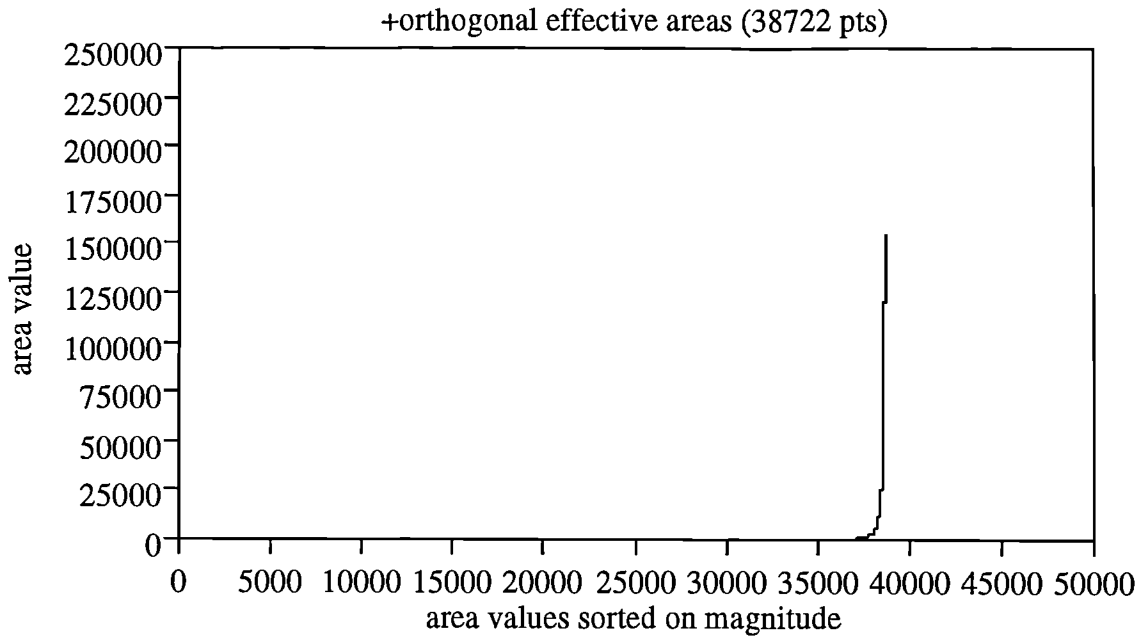


Figure 3.16(b) Graph of +orthogonal effective areas for Port Talbot DEM.

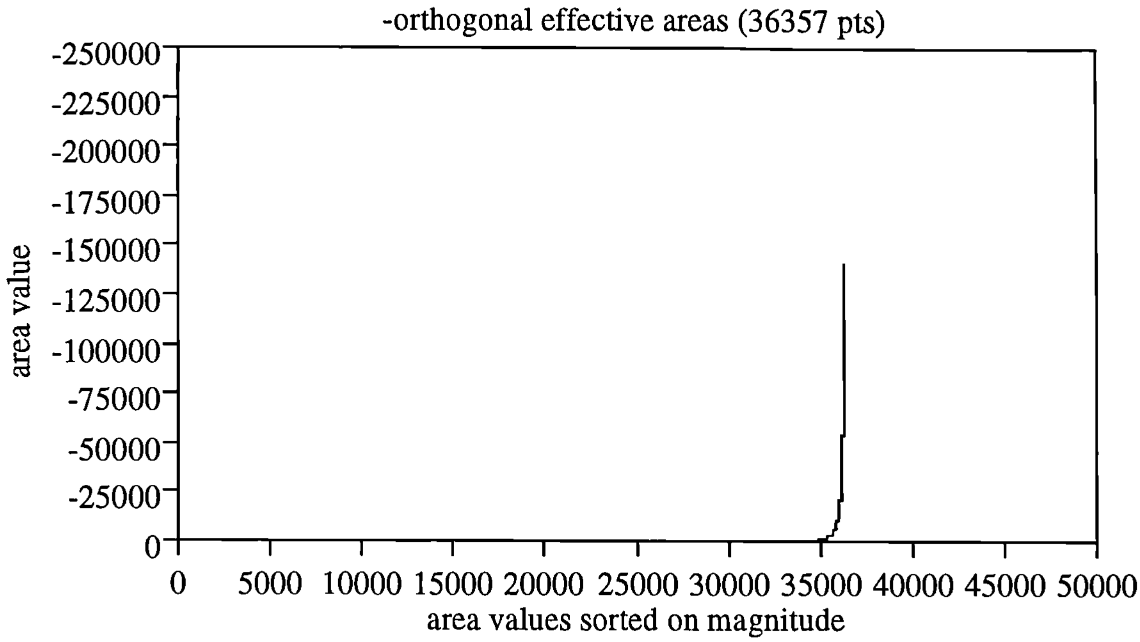


Figure 3.16(c) Graph of –orthogonal effective areas for Port Talbot DEM.

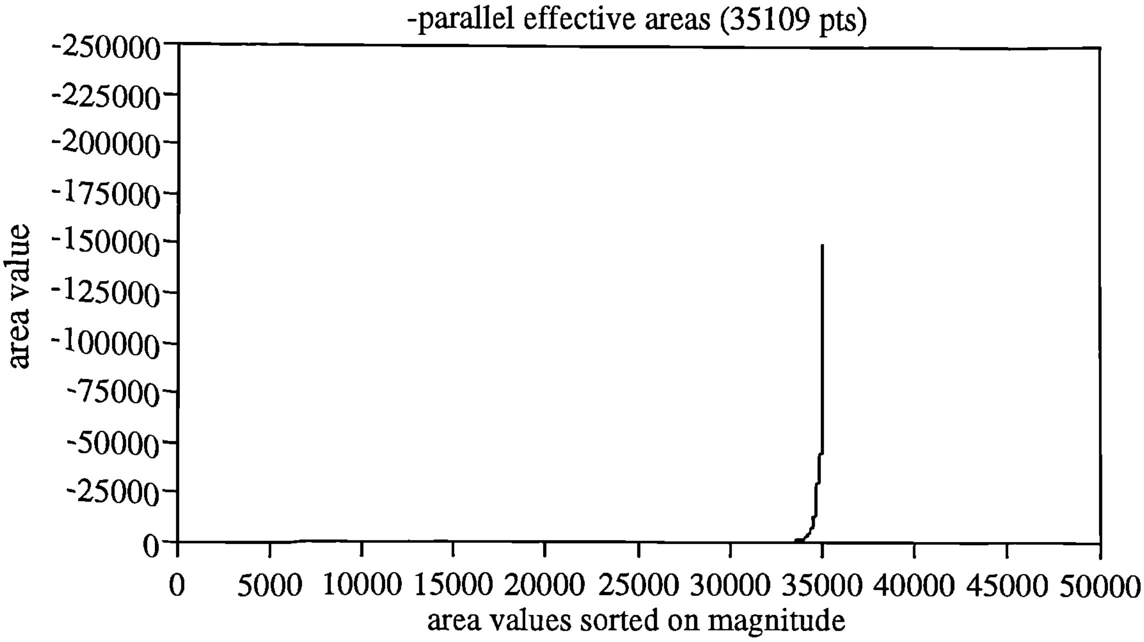


Figure 3.16(d) Graph of –parallel effective areas for Port Talbot DEM.

The view independent part of this technique, which uses Visvalingam's algorithm to order the cells of a DEM, is the most time consuming of the two stages. The prototype system, written in C and running on a Sun IPX workstation under the Unix operating system, took 2 minutes and 7 seconds to order the 62,500 cells in the 250 x 250 OS DEM. However, once the cells have been ordered, many sketches can quickly be created from different directions and with different sketching parameters. The amount of time taken to render a sketch depends to some extent on the amount of detail but a typical sketch, such as those shown in figure 3.15, takes approximately 5 seconds to render. Rendering time could also be improved by a more efficient implementation.

To achieve aesthetically pleasing results it is necessary to manipulate the sketching parameters using trial and error, as was the case with tolerance selection (see section 3.3.3). This is facilitated by the speed at which sketches can be drawn. The amount of time taken to experiment with different sets of parameters depends on the experience of the user. An experienced user might be able to select suitable parameters in several minutes while a novice could take an hour of experimentation to achieve the same results.

3.4 SUMMARY

This chapter described a technique for extracting artistic sketches from regular grid DEMs which does not rely on high level semantic knowledge. The technique, which is profile based, uses Visvalingam's two-dimensional cartographic line simplification algorithm to detect perceptually important points. Groups of salient points, termed core cells, are extended along profile lines to form "profile strokes" or "p-strokes" which simulate the multi-directional pencil strokes of an artist. In addition this chapter has pointed to the challenge of mapping physiographic regions and described a number of other aspects of landscape mapping which merit investigation, such as projections and delineations. It has also identified several aspects of DEM sketching which need attention. These include:

1. how is information of interest located?
2. how should these be connected into automatic and meaningful descriptions of surfaces for analytical purposes (the problem of terrain modelling is still not satisfactorily resolved for analytical purposes)?
3. what styles of depiction are there and how can the marks be generated?

The resulting parsimonious sketches can be aesthetically pleasing and resemble those produced by artists, geographers and cartographers. This research is of interest to a variety of disciplines including cartography, geography, geology, scientific visualisation and psychology, and several applications, such as the military, civil engineering, architecture, land use planning, tourism and orienteering.

Chapter 4

Comparison of Core Cell Selection Techniques

4.1 INTRODUCTION

The previous chapter described an original technique for producing artistic sketches from regular grid DEMs. The sketching technique is based on the identification of a set of important DEM cells which are termed "core cells". So far, Visvalingam's algorithm, driven by effective area, has been used for this purpose. However, Visvalingam's algorithm can also be driven by other metrics. This chapter compares the core cells selected by Visvalingam's algorithm when driven by effective area and perpendicular distance. These results are also compared with those produced by another cartographic line simplification algorithm, the Douglas-Peucker algorithm, which is the most widely used algorithm of its kind. The aim of this chapter is to determine which line simplification method selects the best set of core cells for sketching. Each method is evaluated in terms of one-dimensional terrain profile simplification, the two-dimensional distribution of core cells across the DEM and the resulting sketches.

4.2 ALGORITHMS FOR LINE GENERALISATION

The cartographer's art is more concerned with facilitating visual information processing than with depicting the world as it is. Cartographic visualisation involves the generalisation of information and its depiction in symbolic form according to a set of conventions. Thus the aims of cartography are counter to those of photorealism (Visvalingam, 1991).

There is growing interest in formalising our knowledge on computer generalisation of computer maps (Buttenfield and McMaster, 1991). However, the science and the art of generalisation remains one of the most challenging intellectual and practical problems in digital cartography. One of the most widely studied topics is that of line generalisation. Many line generalisation algorithms have been proposed (for example Opheim, 1981; Dettori and Falcidieno, 1982; Deveau, 1985; Roberge, 1985). Two line generalisation algorithms are used in this thesis, Visvalingam's algorithm (Visvalingam and Whyatt, 1993) and the Douglas-Peucker algorithm (Douglas and Peucker, 1973).

The Douglas-Peucker algorithm is the most widely used line-simplification algorithm. It is the only line-simplification algorithm supported by a number of mapping packages and is often the only line simplification algorithm to be described in textbooks on cartography (Visvalingam and Whyatt, 1990). The algorithm relies on selection, selecting a hierarchy of most important points (*i.e.* top down), based on perpendicular distance. Several studies have determined it to be mathematically (McMaster, 1986) and perceptually (Marino, 1979; White, 1983) superior. However, other workers have expressed dissatisfaction (Morrison, 1975; Dettori and Falcidieno, 1982; Van Horn, 1985; Monmonier, 1986; Muller, 1987; Thapa, 1988). This prompted Visvalingam and Whyatt (1990) and Whyatt (1991) to carry out a systematic and detailed analysis of the algorithm. Visvalingam and Whyatt (1990) stated that the Douglas-Peucker algorithm is only suitable for eliminating redundant points (weeding) and for minimal simplification of lines.

Visvalingam's algorithm works by repeated elimination, eliminating the least important point at each stage (*i.e.* bottom up). It appears to be capable of abstracting from coordinate data, captured from 1:50,000 maps, appropriate generalised representations for a range of smaller scales including 1:10,000,000 (Visvalingam and Whyatt, 1993). Visvalingam and Williamson (1994) demonstrated that the algorithm was also suitable for generalising roads, digitised at 1:1,250 scale, for depiction at much smaller scales. The most distinctive property of Visvalingam's technique is that it can be used to filter out scale-related features. Small-scale features are eliminated in their entirety before large-scale features become caricatured and eliminated in their turn. The algorithm also tends to segment smoothly varying sections of lines, for example the corners of roads at junctions and turning curves/circles on roads. As pointed out by Visvalingam and Williamson (1994) this makes these in-line features identifiable within intelligent knowledge-based generalisation systems.

A digital elevation model encodes one dimensional variations in height over a two-dimensional matrix. One of the reasons why the Douglas-Peucker algorithm is unable to generalise map data is because it cannot cope with complex incurved and branched lines on a plane. Such problems can occur in natural terrain with under-cut cliffs. However, by definition, these special cases cannot be represented in DEMs. The aims of the experiments described in this chapter were thus to establish whether the limitations of the Douglas-Peucker method, as observed with map data, were also present in height data and to study the utility of Visvalingam's algorithm in the one-dimensional case. Also, both Visvalingam and Whyatt (1993) and Visvalingam and Williamson (1994) had used the concept of effective area to articulate Visvalingam's algorithm in the two-dimensional case. Visvalingam and Whyatt (1993) pointed out that effective area was just one of many alternative metrics but chose to investigate its utility since other properties, such as shape, are only discriminable when the size of features exceeds a perceptual threshold. Although area is widely used in manual generalisation, it was quite possible that another metric may be more appropriate for terrain.

4.3 COMPARISON OF PROFILE SIMPLIFICATION

The aims of this section are:

1. Observe the impact of alternative metrics on the behaviour of Visvalingam's algorithm when applied to sections across terrain.

2. Compare the relative merits and limitations of the Douglas-Peucker algorithm and Visvalingam's algorithm for generalising one-dimensional data.

4.3.1 Measurement of the Impact of a Point

Visvalingam's algorithm generalises a line by eliminating the point whose removal has the least impact on the current line. The perceptual impact of a point may be measured in several ways. The effective area measures the areal displacement of the resulting line from the current line while the perpendicular distance, which is also the metric used by the Douglas-Peucker algorithm, produces results similar to a vertical displacement metric. People are more susceptive to vertical displacement than area.

Although the Douglas-Peucker algorithm also uses the metric of perpendicular distance, at each cycle it measures the distance of intervening points from a line joining two end points in all cases. In Visvalingam's algorithm the offset of each point is calculated relative to its two neighbours, the effect is bound to be different. A number of terrain profiles taken from two DEMs were simplified using Visvalingam's algorithm, driven by each of these metrics. The results were then compared at several levels of generalisation. Figure 4.1 shows the results of applying Visvalingam's algorithm, using effective area and perpendicular distance, to one of these profiles.

Both effective area and perpendicular distance perform well. After removing 66% of the points it is difficult to perceive a difference between the generalisation, produced by either metric, and the original. With 16% of points remaining the generalised profile is noticeably smoother while with 8% of the points the generalisation has become angular but is a good caricature. Slight differences can be observed between effective area and perpendicular distance at 16% of the points. However, the differences only become pronounced below 8%, where the inclusion or omission of a single point makes an easily perceivable difference to the generalised profile.

4.3.2 Simplifying Profiles with the Douglas-Peucker Algorithm

The two previous comparisons of the Douglas-Peucker algorithm and Visvalingam's algorithm (Visvalingam and Whyatt, 1993; Visvalingam and Williamson, 1994) indicated that the former was more suitable for weeding and minimal simplification, while the latter was capable of caricatural generalisation. These case studies were based on two-dimensional map data. Coastlines, for example, are very complex in shape. In this section we examine whether these previous conclusions are also applicable to one-dimensional data, such as profiles across terrain.

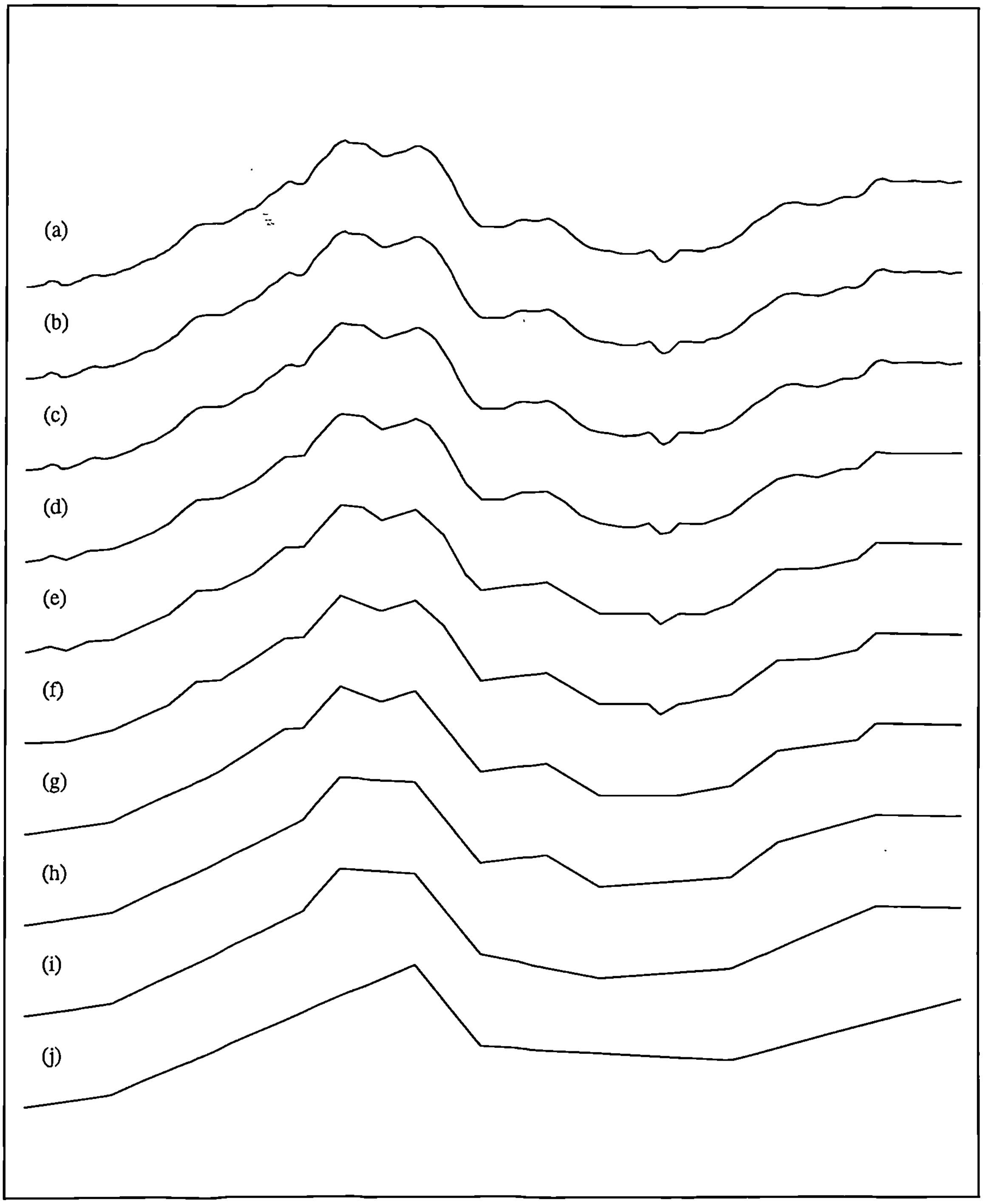


Figure 4.1(a): Filtering a profile using effective area : (a) original profile (302pts.), (b) tolerance = 0 (225pts.), (c) tolerance = 120 (99pts.), (d) tolerance = 555 (49pts.), (e) tolerance = 2,805 (30pts.), (f) tolerance = 4,200 (24pts.), (g) tolerance = 10,035 (17pts.), (h) tolerance = 18,000 (12pts.), (i) tolerance = 39,525 (10pts.) and (j) tolerance = 84,120 (6pts.).

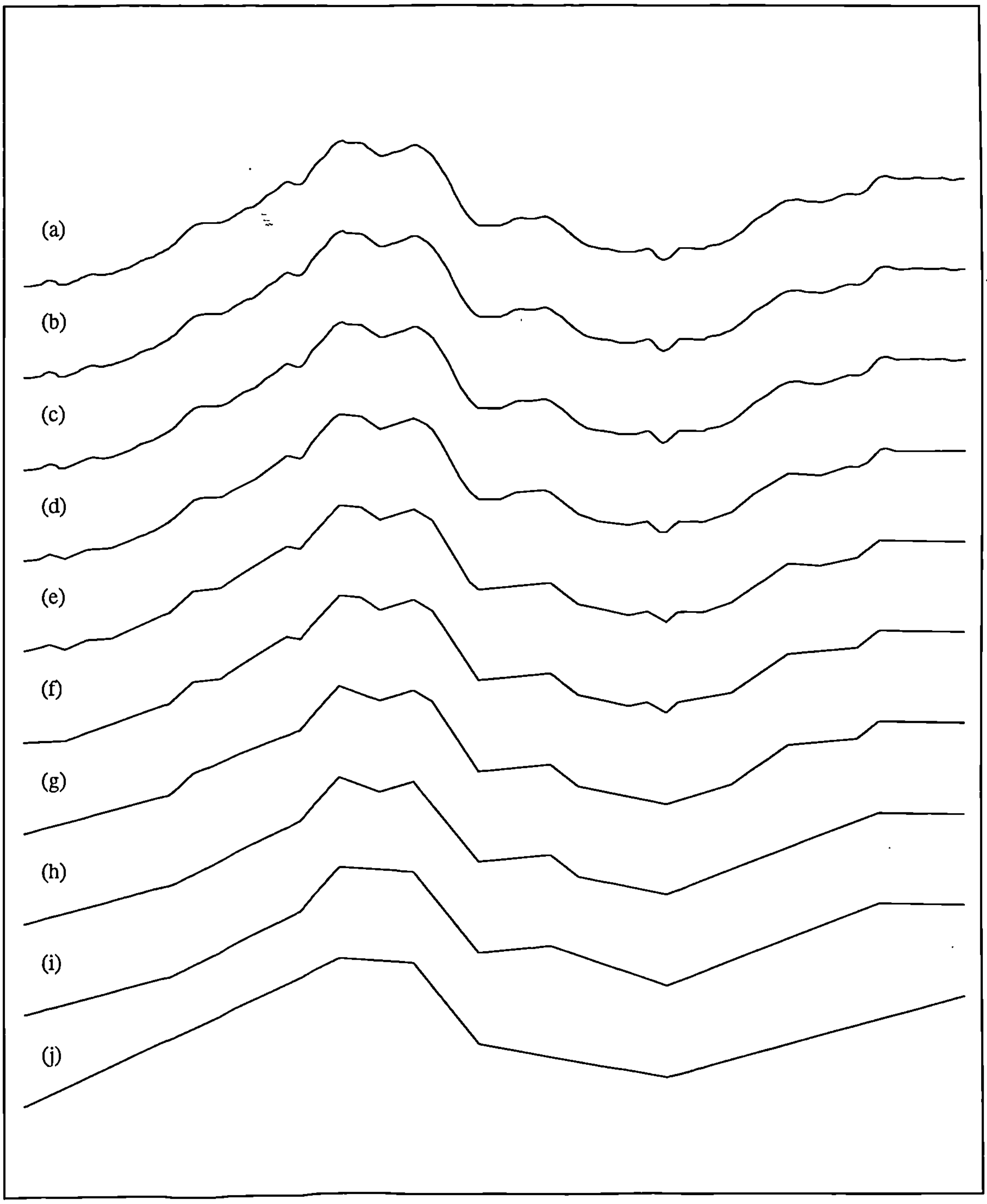


Figure 4.1(b): Filtering a profile using perpendicular distance : (a) original profile (302pts.), (b) tolerance = 0 (225pts.), (c) tolerance = 1.8 (101pts.), (d) tolerance = 5.1 (50pts.), (e) tolerance = 13.8 (30pts.), (f) tolerance = 16.9 (24pts.), (g) tolerance = 29.1 (17pts.), (h) tolerance = 38.8 (12pts.), (i) tolerance = 41.4 (10pts.) and (j) tolerance = 78.6 (6pts.).

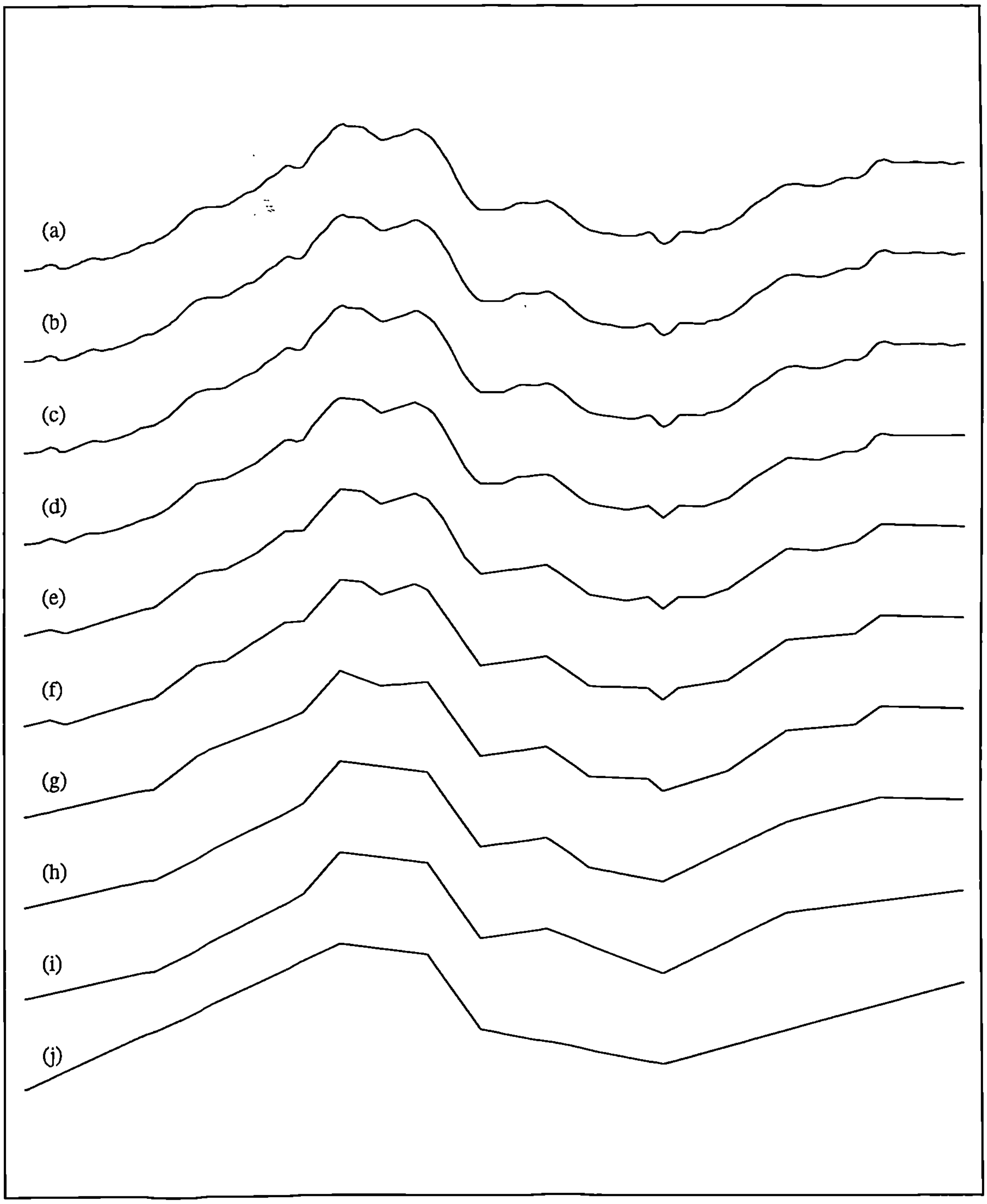


Figure 4.2: Filtering a profile using the Douglas-Peucker algorithm : (a) original profile (302pts.), (b) tolerance = 0 (225pts.), (c) tolerance = 1.9 (100pts.), (d) tolerance = 5.4 (50pts.), (e) tolerance = 10.8 (30pts.), (f) tolerance = 16.2 (24pts.), (g) tolerance = 26.5 (17pts.), (h) tolerance = 39.1 (12pts.), (i) tolerance = 41.5 (10pts.) and (j) tolerance = 94.5 (6pts.).

The previous section discussed the results of using Visvalingam's algorithm, driven by a number of different metrics, to simplify several terrain profiles taken from across two DEMs. The Douglas-Peucker algorithm was applied to the same set of terrain profiles and the results were compared with those of Visvalingam's algorithm. Figure 4.2 shows one such profile at several levels of simplification. The results are similar to those produced by Visvalingam's algorithm. When 33% of the points are retained it is difficult to perceive a difference between the generalised profile and the original. 16% of the points produce a noticeably smoother profile while 8% of the points is still sufficient to provide a good caricature.

Neither algorithm is ideal. Both were found to cause distortion and combination of features at highly caricatural levels of generalisation (below 8% of points). The former problem can be observed in figure 4.2(g), where half of the "V" at the bottom of the valley has been removed leaving a lopsided generalisation. Feature distortion also occurred with Visvalingam's algorithm when applied to other test profiles, using the effective area and perpendicular distance metrics. The latter problem can be observed with generalised profile (h) in figure 4.2 and figure 4.1(c), where the valley has become combined with highland to the right. Combination of features also occurred with effective area on different test profiles. These deficiencies prevent either algorithm from correctly segmenting a terrain profile into its constituent features.

The Douglas-Peucker algorithm has a tendency to preserve spikes, selecting points on or very close to local maxima and minima. It was such points of maximum curvature that Attneave (1954) labelled "critical points". In contrast Visvalingam's algorithm, using effective area, selects such points less frequently, tending to cut through and average. Visvalingam's algorithm, with the perpendicular distance metric selects more of these critical points. This is evident in figures 4.1(c) and 4.2 where the bottom of the valley is preserved. However, the algorithm which selects the highest number of critical points does not necessarily produce the best simplification.

It was observed that the Douglas-Peucker algorithm more consistently picked the same points on adjacent profiles which, due to their proximity, varied only slightly. This minor variation caused Visvalingam's algorithm, especially with the effective area metric, to select a more varied set of points for very similar profiles. However, the Douglas-Peucker algorithm is more sensitive to direction of application. If it is applied to a terrain profile and the profile's mirror image there is a discrepancy between the sets of points selected. The metric used by Visvalingam's algorithm influences sensitivity to direction of application though all of the metrics tried proved less sensitive than the Douglas-Peucker algorithm. These effects are caused by the concepts that underlie each algorithm. The Douglas-Peucker algorithm is based on point selection while Visvalingam's algorithm is based on point elimination.

It was also observed that the Douglas-Peucker algorithm suffers from edge effects. Features which occur near the ends of profiles are not detected. Visvalingam's algorithm does not suffer from this problem. A characteristic of Visvalingam's algorithm is that it pulls away from curves.

For one-dimensional terrain profiles Visvalingam's algorithm, using both effective area and perpendicular distance, was found to perform as well as the Douglas-Peucker algorithm for weeding and minimal simplification. Compare simplified profile (c) in figures 4.1(a), 4.1(b) and 4.2.

Previous studies which determined the Douglas-Peucker algorithm to be a superior line simplification algorithm used simple two-dimensional test data, hence the algorithm's deficiencies remained hidden. Similarly, the Douglas-Peucker algorithm performed well in this study because of the simpler one-dimensional terrain profiles used.

While Visvalingam's algorithm and the Douglas-Peucker algorithm each have their own characteristics, it was found that the results produced by each were comparable not just for weeding and minimal simplification but also at caricatural levels since the virtues and vices of each tend to even out. In general, while one algorithm might out perform the other and caricature part of a profile particularly well this would be at the expense of another part where the other algorithm had the advantage. On occasion, one or the other produces superior results. However, this variation was found not just across different profiles but with the same profile at different levels of generalisation.

4.3.3 Types of Detail within Lines

The points in a terrain profile may be thought of as describing five types of line detail. These five types of detail are described below in relation to the example profile used previously:

1. Some points fall within the range of measurement error or are completely redundant since they lie on a straight line. These points can be removed without any visible change to the profile.
2. The removal of points with a small effective area value omits some degree of roughness from the profile.

3. As the tolerance value is raised, smaller scale features are excluded.

4. Most of the remaining points describe the general shape of the main features.

5. Finally, a few points segment the profile into a number of large scale features. These points define the position of important features, *e.g.* two points define the main mass of highland, marking its start and end.

As the tolerance increases, the ideal line simplification algorithm would eliminate all of the points in each of the classes. It is clear from figures 4.1 and 4.2 that both Visvalingam's algorithm and the Douglas-Peucker algorithm can adequately remove first the redundant points (weeding) (see generalised profile (b)) and secondly minor roughness (see generalised profile (c)). Most small scale features have been removed at the stage of generalisation reached in profiles (g) and (h). The points retained in profile (i) describe the general shape of the large scale features. However, both algorithms fail to select the correct set of points to segment the profile into its constituent parts.

4.4 CORE CELL DISTRIBUTION

This section compares sets of core cells selected by Visvalingam's algorithm, using effective area and perpendicular height as metrics, and the Douglas-Peucker algorithm. The purpose of this comparison is to determine which set of core cells most accurately describes the form of the DEM. Section 4.5 investigates which set of core cells is most appropriate for the production of artistic sketches.

4.4.1 Comparison with Contours

Each set of core cells is evaluated in two-dimensions by comparison with contour lines, covering the same area as the regular grid DEM used in the previous chapter. The DEM and contour lines cover one quarter of the 1:10,000 sample datasets released by the Ordnance Survey of Great Britain and model the hilly area behind Port Talbot (see Appendix B). A grid has been superimposed over the contour lines to aid comparison by providing a system of reference. Figure 4.3(a) - (c) shows the core cells selected by each method. Core cells shaded black identify convexities while those represented by hollow outlines identify concavities. To make the results comparable, tolerances were chosen so that each method selected approximately the same number of core cells. The tolerances used are shown in table 4.1 while the total number of core cells selected by each method and the number used for each type of profile stroke are presented in table 4.2.

Tolerances for Core Cell Selection			
	Visvalingam's Algorithm		Douglas-Peucker Algorithm
	Area Metric	Height Metric	
+parallel	1000	8	8
+orthogonal	4000	16	17
-orthogonal	4000	17	17
-parallel	4000	17	17

Table 4.1: Tolerances used by each method for core cell selection.

Core Cell Selection Statistics			
	Visvalingam's Algorithm		Douglas-Peucker Algorithm
	Area Metric	Height Metric	
+parallel	1555 (2.5%)	1541 (2.5%)	1572 (2.5%)
+orthogonal	573 (0.9%)	623 (1.0%)	651 (1.0%)
-orthogonal	595 (1.0%)	553 (0.9%)	543 (0.9%)
-parallel	813 (1.3%)	825 (1.3%)	807 (1.3%)
Total	3536 (5.7%)	3542 (5.7%)	3573 (5.7%)

Table 4.2: Number of cells selected as core cells by each method. Figures in brackets show percentages of cells selected from total (62,500).

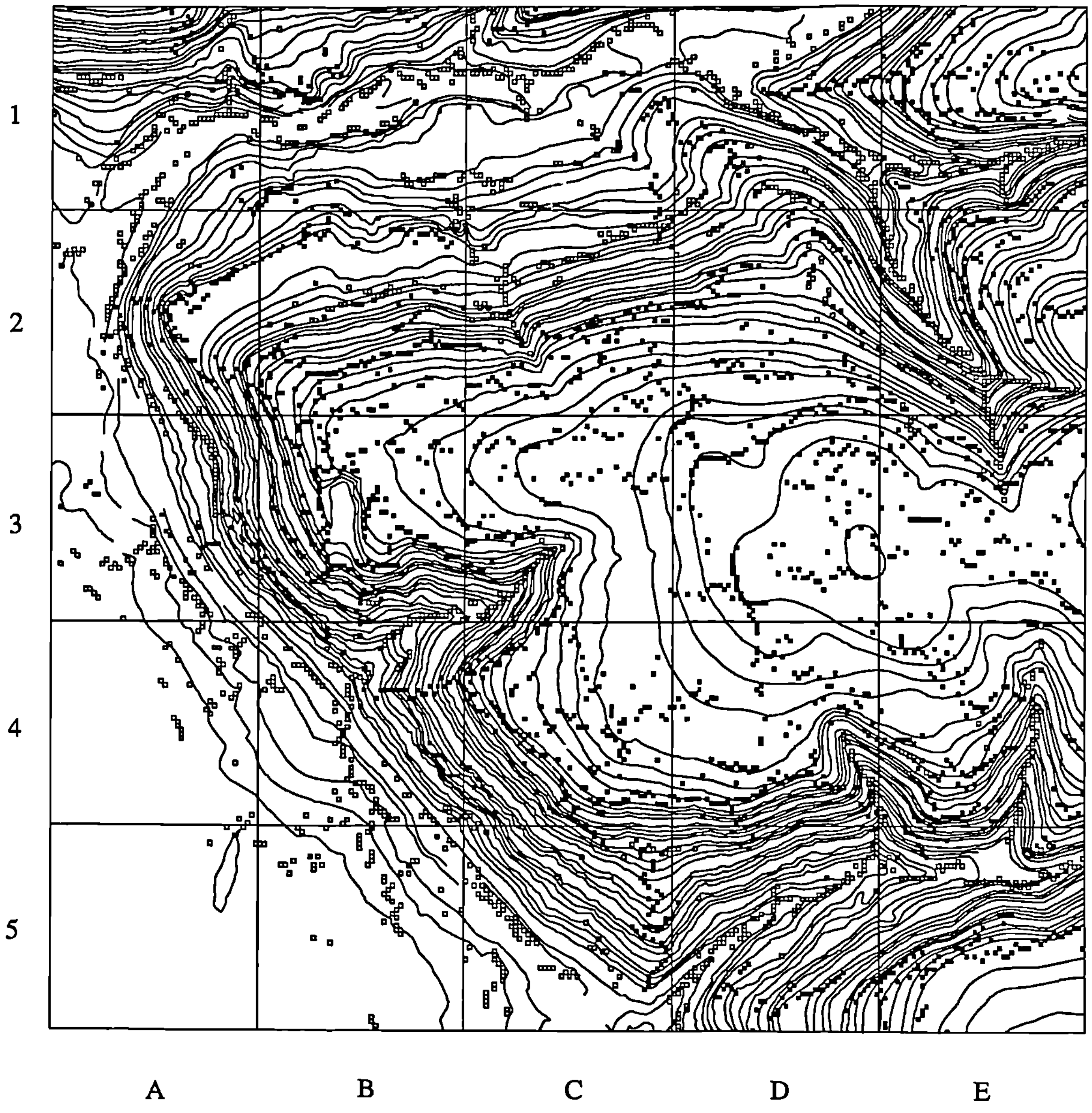


Figure 4.3(a): Core cells selected using Visvalingam's algorithm with effective area as the metric. 3,536 cells selected from 62,500 (5.7%).

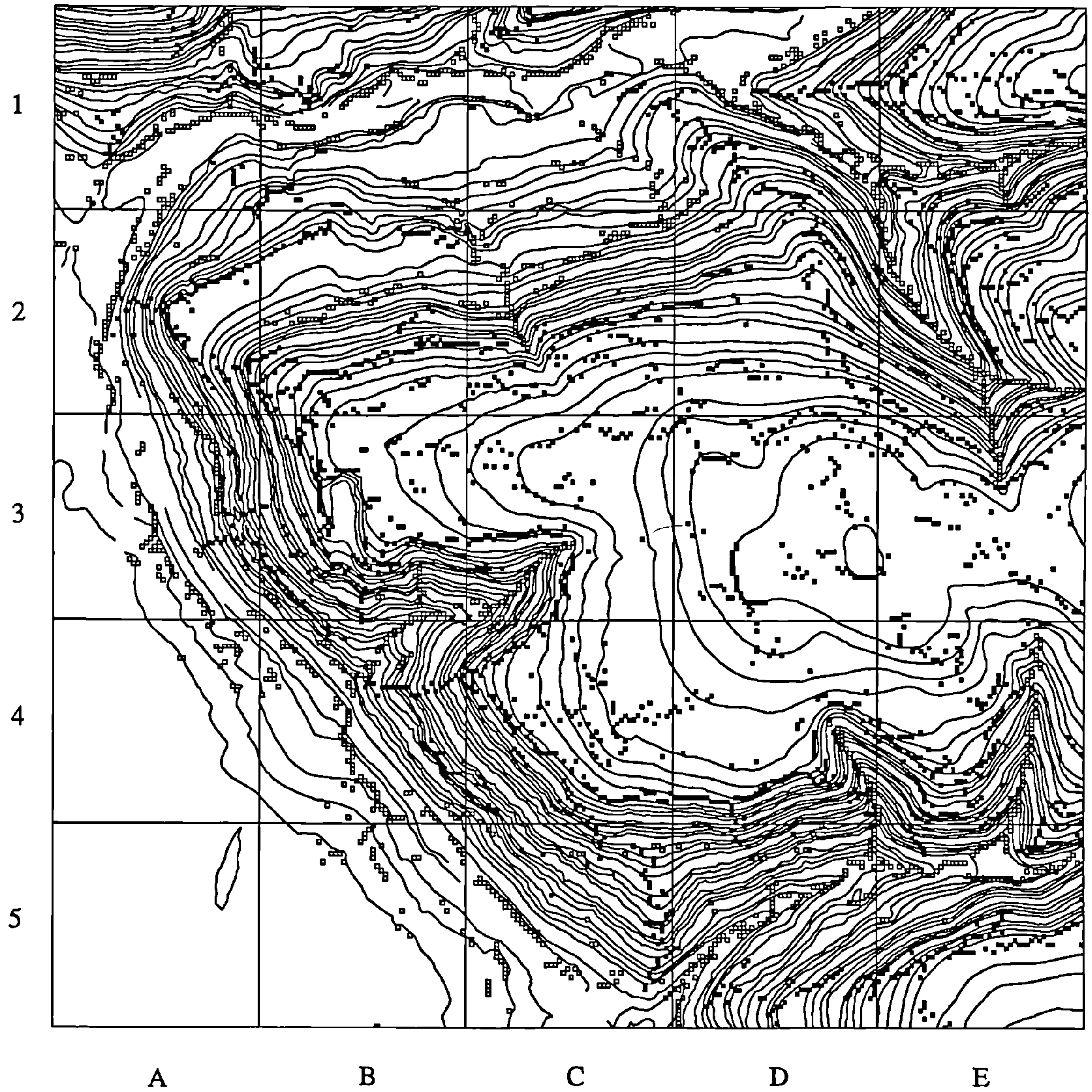


Figure 4.3(b): Core cells selected using Visvalingam's algorithm with perpendicular height as the metric. 3,542 cells selected from 62,500 (5.7%).

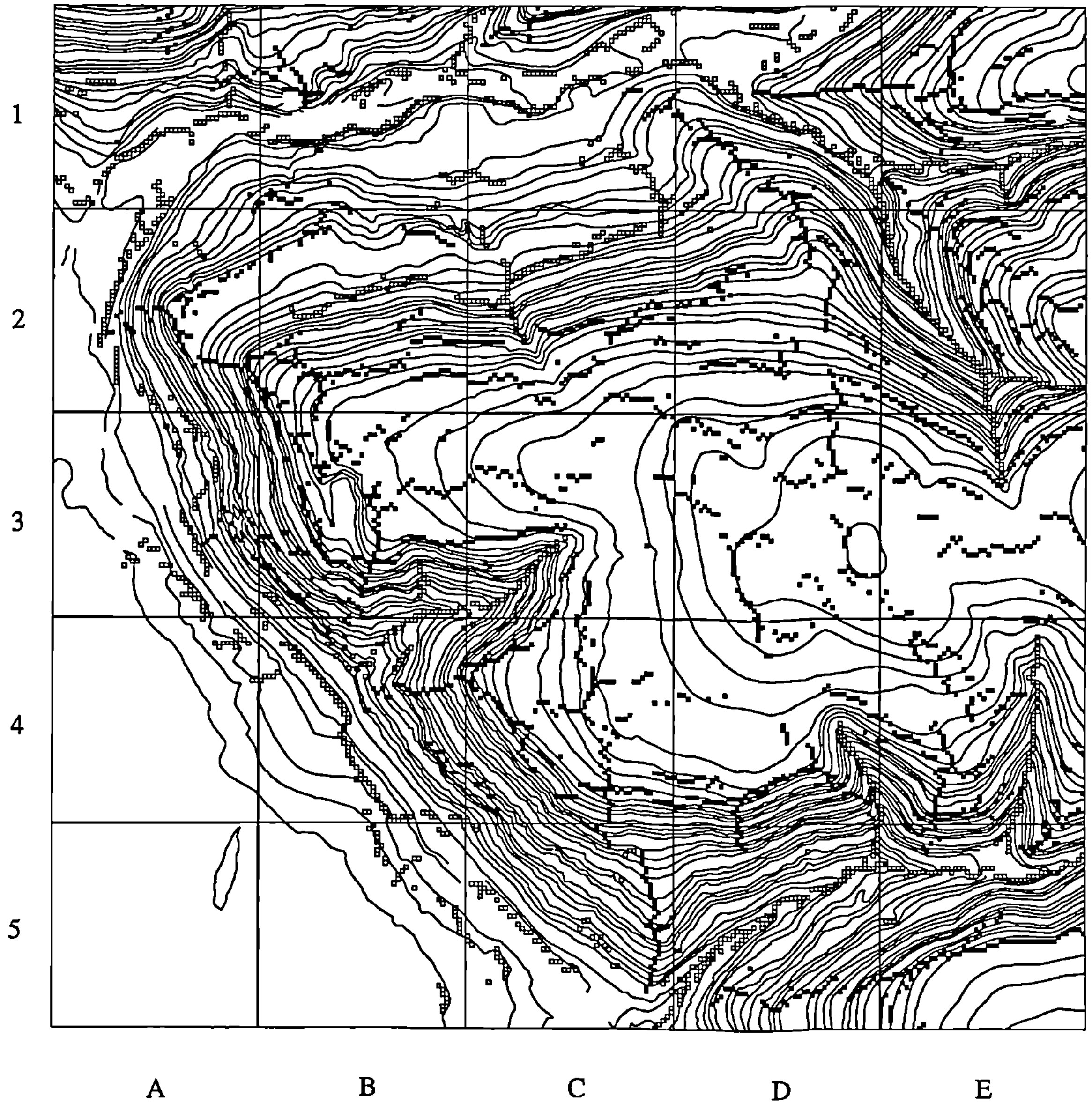


Figure 4.3(c): Core cells selected using the Douglas-Peucker algorithm. 3,573 cells selected from 62,500 (5.7%).

The differences between the methods is more pronounced at higher tolerances, where generalisation is caricatural. When 5.7% of DEM cells are selected as core cells, the results of Visvalingam's algorithm and the Douglas-Peucker algorithm become similar. The most noticeable difference, at this level of generalisation, is the distinct lines of core cells detected by the Douglas-Peucker algorithm when compared to the distributed cells selected by Visvalingam's algorithm. The perpendicular distance metric selects less distributed core cells than the effective area metric but the alignment is still far less distinct than produced by the Douglas-Peucker algorithm. Despite the fact that core cells are detected on individual profiles, the necessary similarity of adjacent profiles accounts for the alignment of core cells across the DEM. The greater degree of alignment present in the set of core cells selected by the Douglas-Peucker algorithm suggests that it is less sensitive to the minor variations which occur from profile to profile. This is because the top down approach of the Douglas-Peucker algorithm is more consistent than the bottom up approach used by Visvalingam's algorithm.

The major valleys in the top and bottom right corners are picked out clearly by all three methods and so are the smaller valleys in squares B2 and C4. The top of the upland area has its shape more accurately picked out by Visvalingam's algorithm, especially at higher levels of generalisation, though it is harder to connect up. The ridges detected by the Douglas-Peucker algorithm are the most distinct (*e.g.* the ridge in squares D4 and D5 and the ridge in square C3) while those detected by the effective area metric are least distinct. The most distinct line describing the base of the upland is chosen by the Douglas-Peucker algorithm.

The surface specific features (see section 2.4.1.2) detected by the Douglas-Peucker algorithm include ridges (see squares C1 and D5) and valleys (see squares E2 and E4) as well as breaks of slope (see squares D2 and A4). However, these lines are not necessarily the "correct" lines and some provide a false impression. For example, the line detected in square E3 implies there is a ridge at the top of the saddle when in reality it is fairly flat. In such a case, the cells selected by Visvalingam's algorithm convey the form of the terrain in a more appropriate way.

4.4.2 Conclusions

The Douglas-Peucker algorithm detects distinct lines of core cells which are easier to connect for the partitioning of the landscape into its constituent features however, there is evidence to suggest that the lines detected may give a false impression of the landscape. Visvalingam's algorithm, using the effective area metric, provides more information but it is harder to use because it is more distributed. Visvalingam's algorithm, using the perpendicular height metric, is a compromise. The set of core cells it selects is less scattered than those produced with the effective area metric but less aligned than those produced by the Douglas-Peucker algorithm, despite using the same metric.

4.5 COMPARISON OF SKETCHES

The aim of this section is to determine which method detects the best core cells for creating artistic sketches, using the procedure described in the previous chapter (see figure 3.2). Figures 4.4 – 4.6 show sketches from different viewpoints, using core cells detected by Visvalingam's algorithm, with effective area and with perpendicular height as the metric, and the Douglas-Peucker algorithm. The tolerances used for core cell selection are shown in table 4.1 while sketching parameters are shown in table 4.3 (the choice of parameters was described in section 3.3.2).

4.5.1 Sketch Statistics

Table 4.4 provides sketch statistics.

Sketches from opposite sides of a DEM will have identical statistics if all types of profile stroke are extended symmetrically. This is independent of core cell selection (see figure 3.2). However, as can be seen from the sketching parameters (table 4.3), orthogonal p-strokes are extended asymmetrically. This creates small differences because determination of p-strokes for a terrain profile's mirror image cause different p-strokes to overlap.

The sketches for each method are produced from approximately the same number of core cells (see table 4.2) using the same sketching procedure to make them comparable. However, the Douglas-Peucker sketches consist of fewer, shorter p-strokes because the core cells are more aligned, as previously observed. The core cells selected by Visvalingam's algorithm, using the effective area metric, produce more p-strokes because the core cells are more scattered while the overall number of cells is greater because small, separate groups of core cells are extended and join with others. Visvalingam's algorithm with the perpendicular height metric is, as expected, between the two extremes.

Parameters for Sketching				
	Extension Rule		Colour	Style
	Left	Right		
+parallel	full	full	black	Solid
+orthogonal	none	minimal	grey	Dotted
-orthogonal	minimal	none	grey	Dotted
-parallel	full	full	black	Solid

Table 4.3: Parameters used for sketching by all three methods.

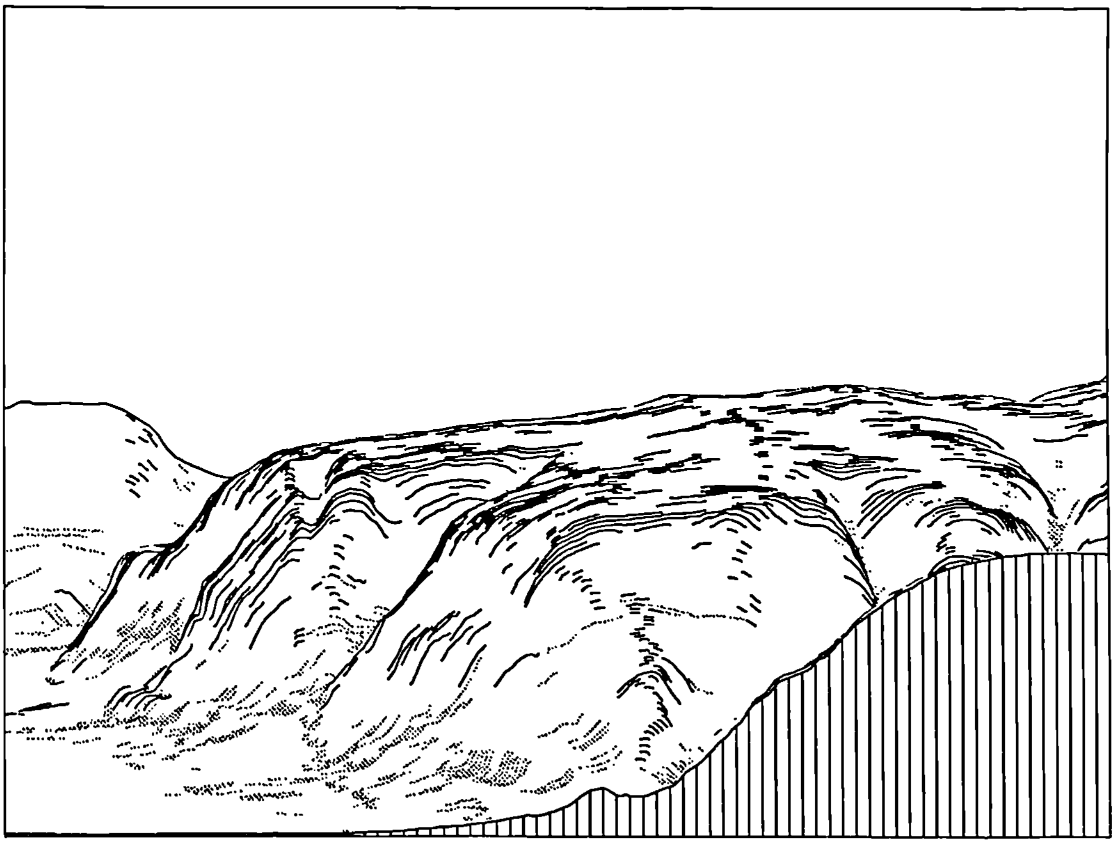


Figure 4.4(a): Sketch of Port Talbot DEM from the south, based on core cells selected by Visvalingam's algorithm using effective area metric.

Sketch Statistics			
	Visvalingam's Algorithm		Douglas-Peucker Algorithm
	Area Metric	Height Metric	
Sketch from South			
+parallel	765 (9347)	713 (8097)	647 (7237)
+orthogonal	465 (1852)	516 (2051)	534 (2121)
-orthogonal	652 (2599)	650 (2590)	603 (2401)
-parallel	554 (4823)	523 (4465)	595 (4085)
Total	18621 (29.8%)	17203 (27.5%)	15844 (25.4%)
Sketch from North			
+parallel	765 (9347)	713 (8097)	647 (7237)
+orthogonal	464 (1842)	515 (2046)	532 (2118)
-orthogonal	649 (2586)	650 (2584)	602 (2398)
-parallel	553 (4817)	513 (4451)	489 (4071)
Total	18592 (29.7%)	17178 (27.5%)	15824 (25.3%)
Sketch from West			
+parallel	774 (8435)	699 (7305)	620 (6454)
+orthogonal	652 (2593)	750 (2989)	755 (2994)
-orthogonal	780 (3100)	796 (3170)	787 (3127)
-parallel	493 (3857)	474 (3495)	433 (3158)
Total	17985 (28.8%)	16959 (27.1%)	15733 (25.2%)

Table 4.4: Number of profile strokes drawn for sketches using core cells determined by different methods. Figures in brackets show total number of cells included in each type of p-stroke.

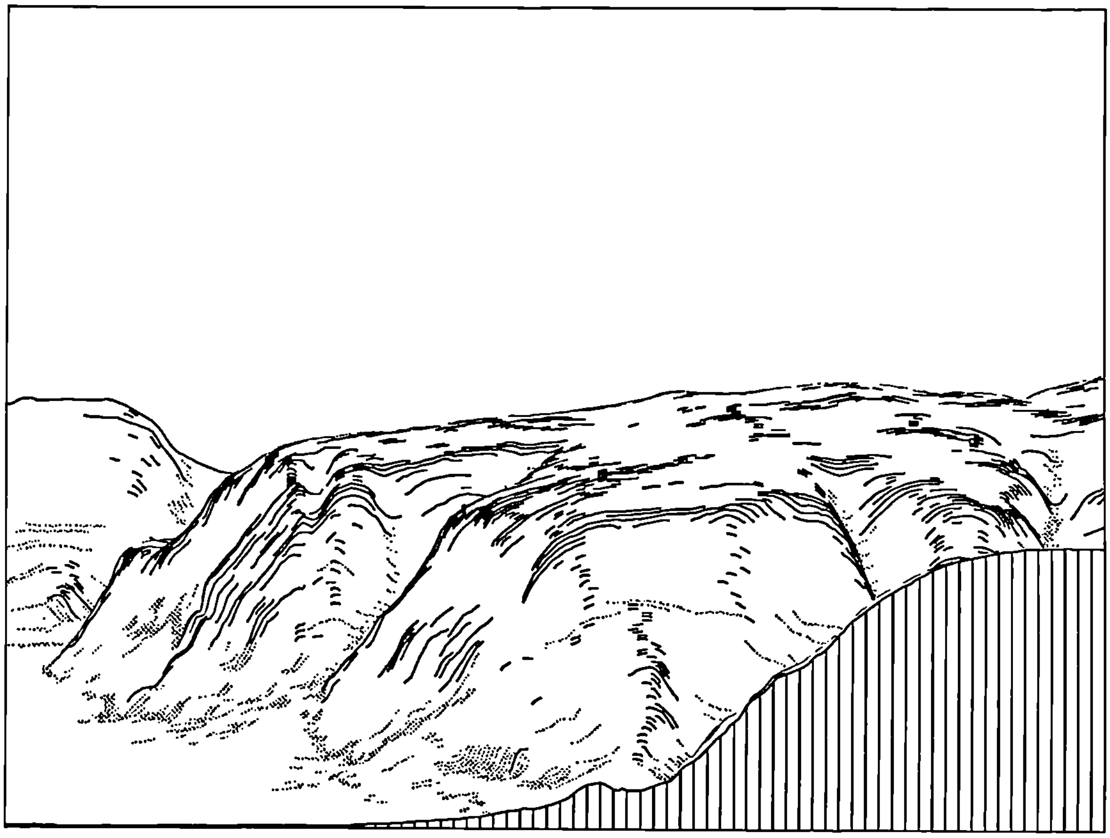


Figure 4.4(b): Sketch of Port Talbot DEM from the south, based on core cells selected by Visvalingam's algorithm using perpendicular distance metric.

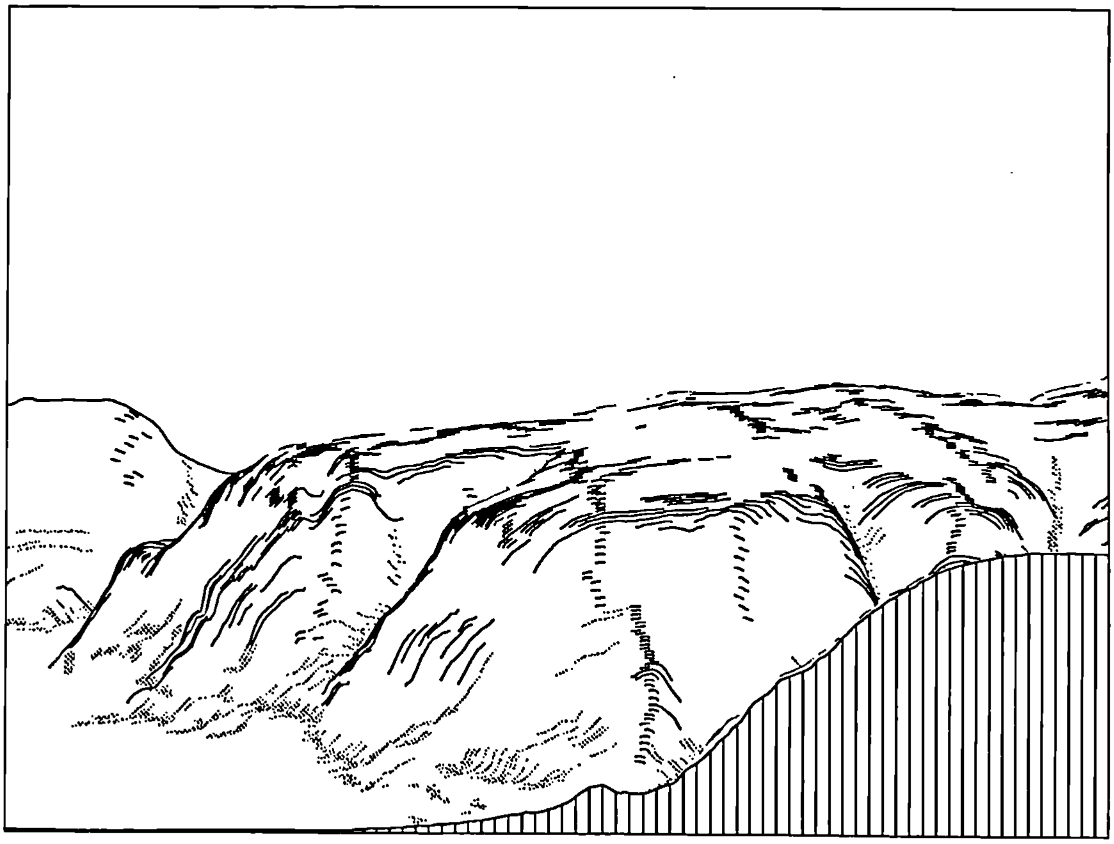


Figure 4.4(c): Sketch of Port Talbot DEM from the south, based on core cells selected by the Douglas-Peucker algorithm.

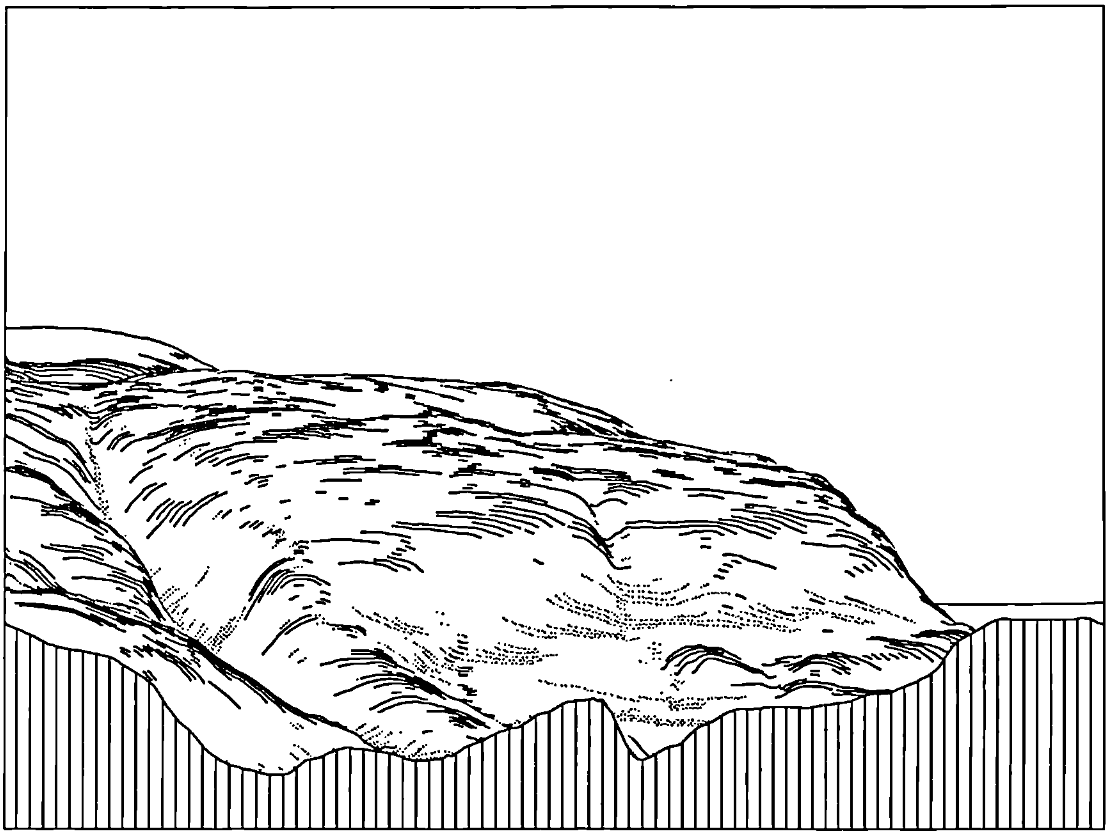


Figure 4.5(a): Sketch of Port Talbot DEM from the north, based on core cells selected by Visvalingam's algorithm using effective area metric.

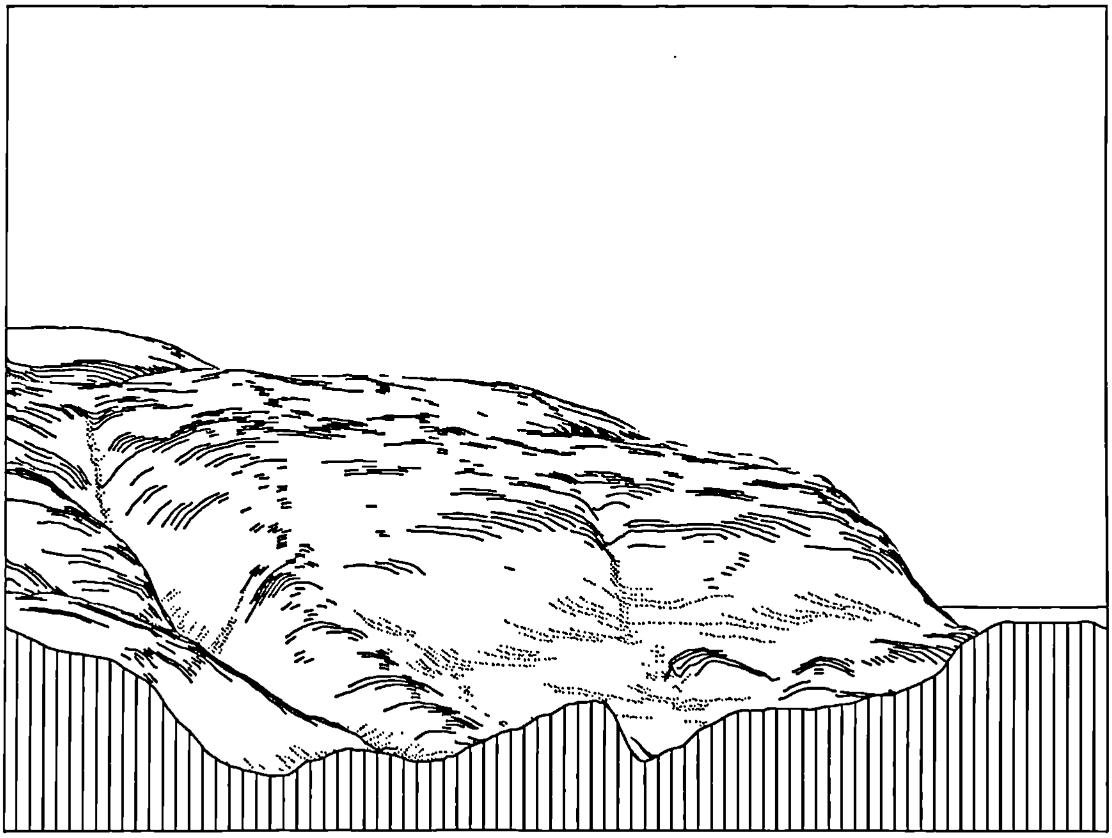


Figure 4.5(b): Sketch of Port Talbot DEM from the north, based on core cells selected by Visvalingam's algorithm using perpendicular distance metric.

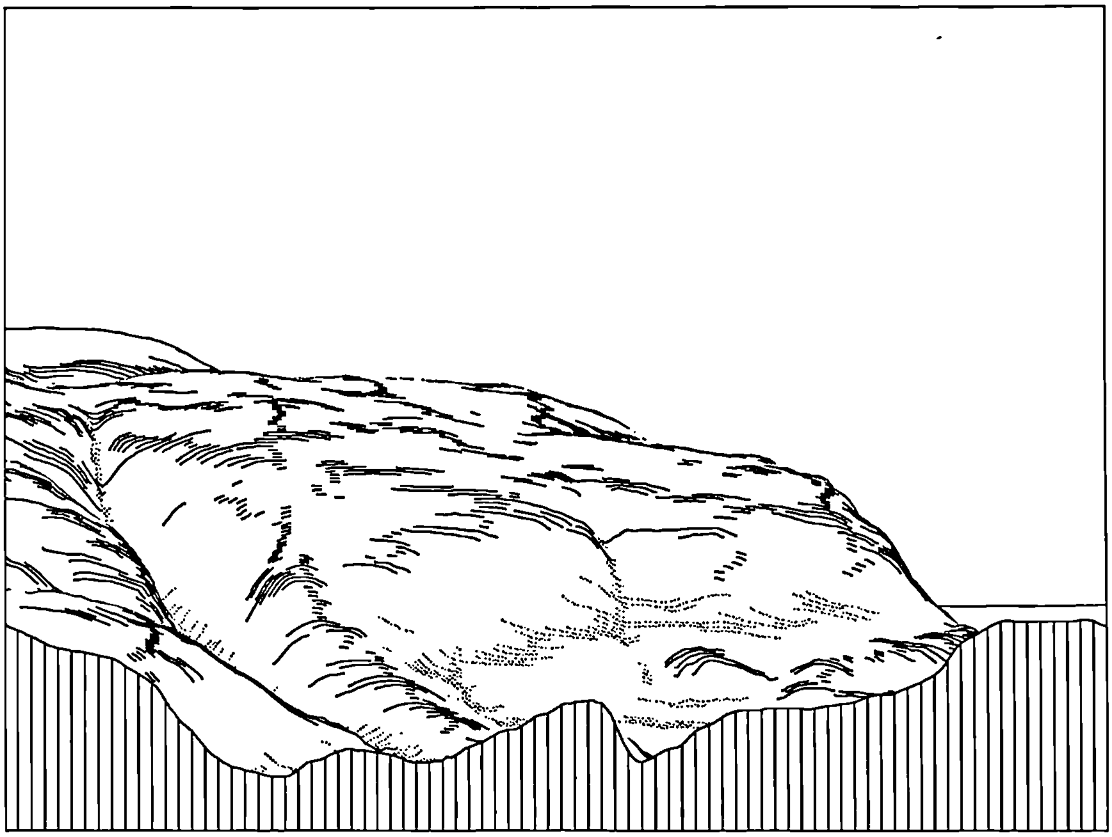


Figure 4.5(c): Sketch of Port Talbot DEM from the north, based on core cells selected by the Douglas-Peucker algorithm.

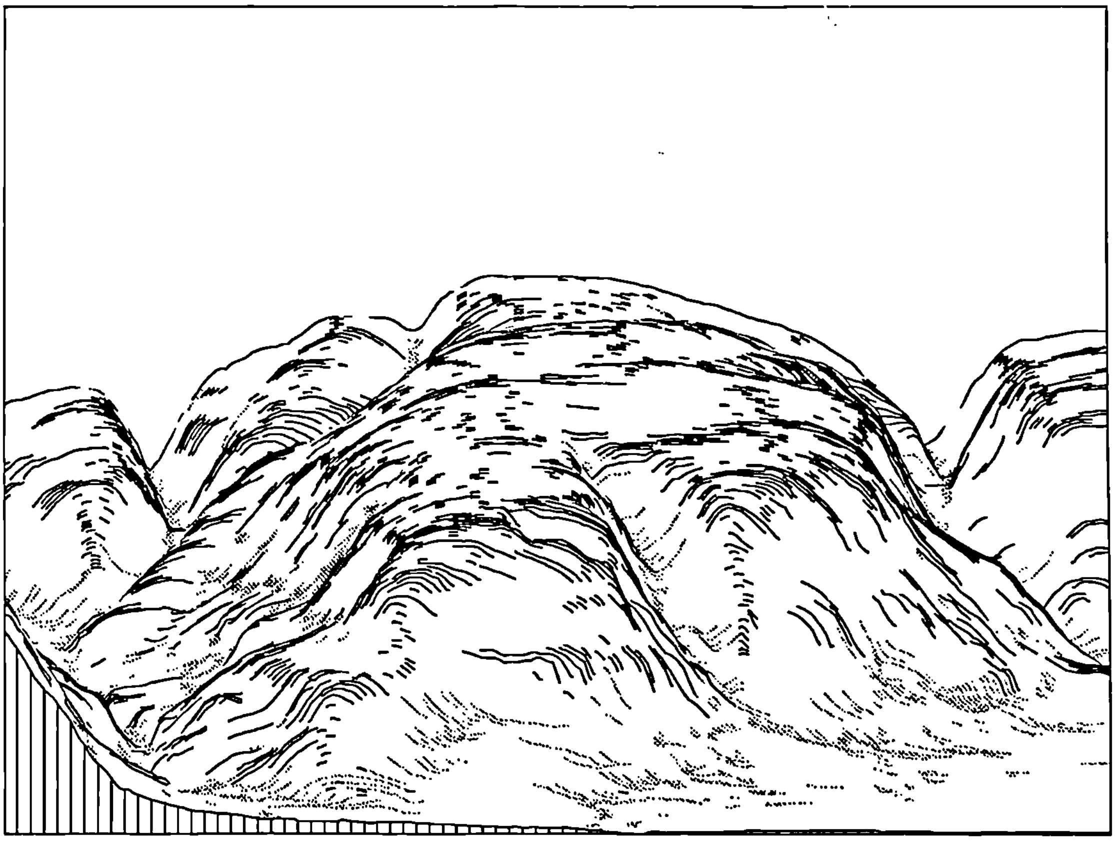


Figure 4.6(a): Sketch of Port Talbot DEM from the west, based on core cells selected by Visvalingam's algorithm using effective area metric.

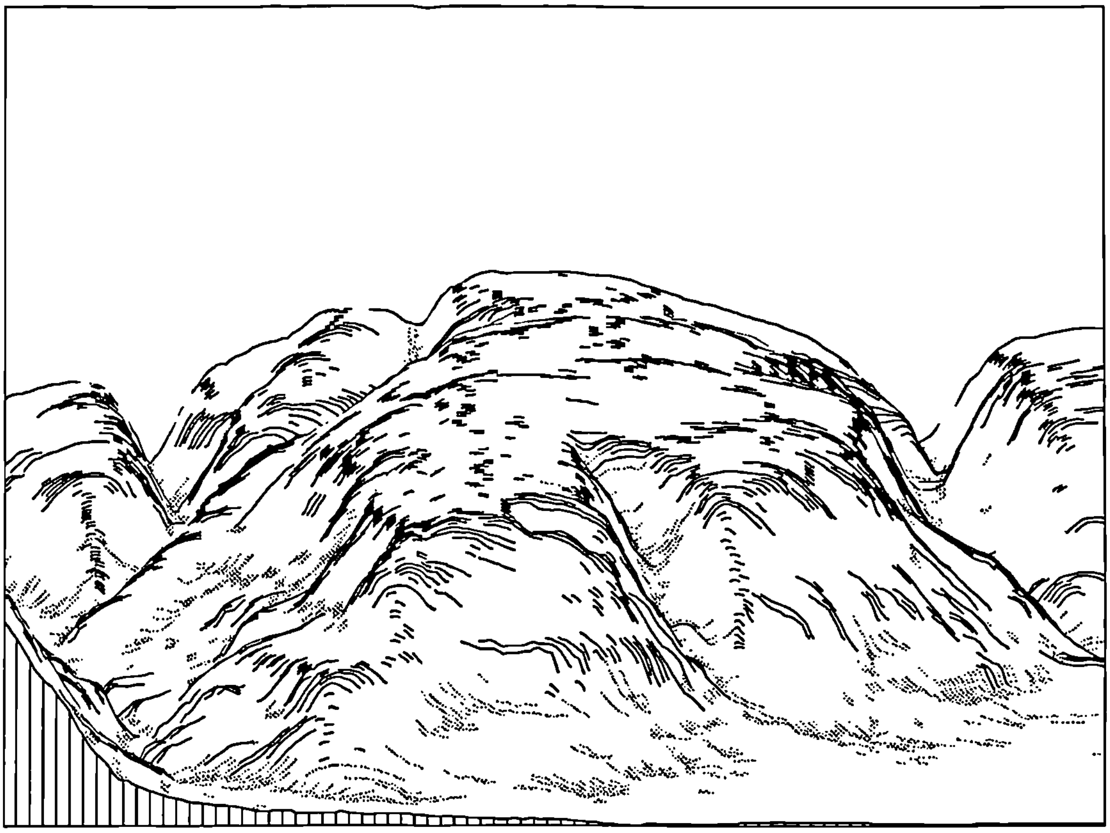


Figure 4.6(b): Sketch of Port Talbot DEM from the west, based on core cells selected by Visvalingam's algorithm using perpendicular distance metric.

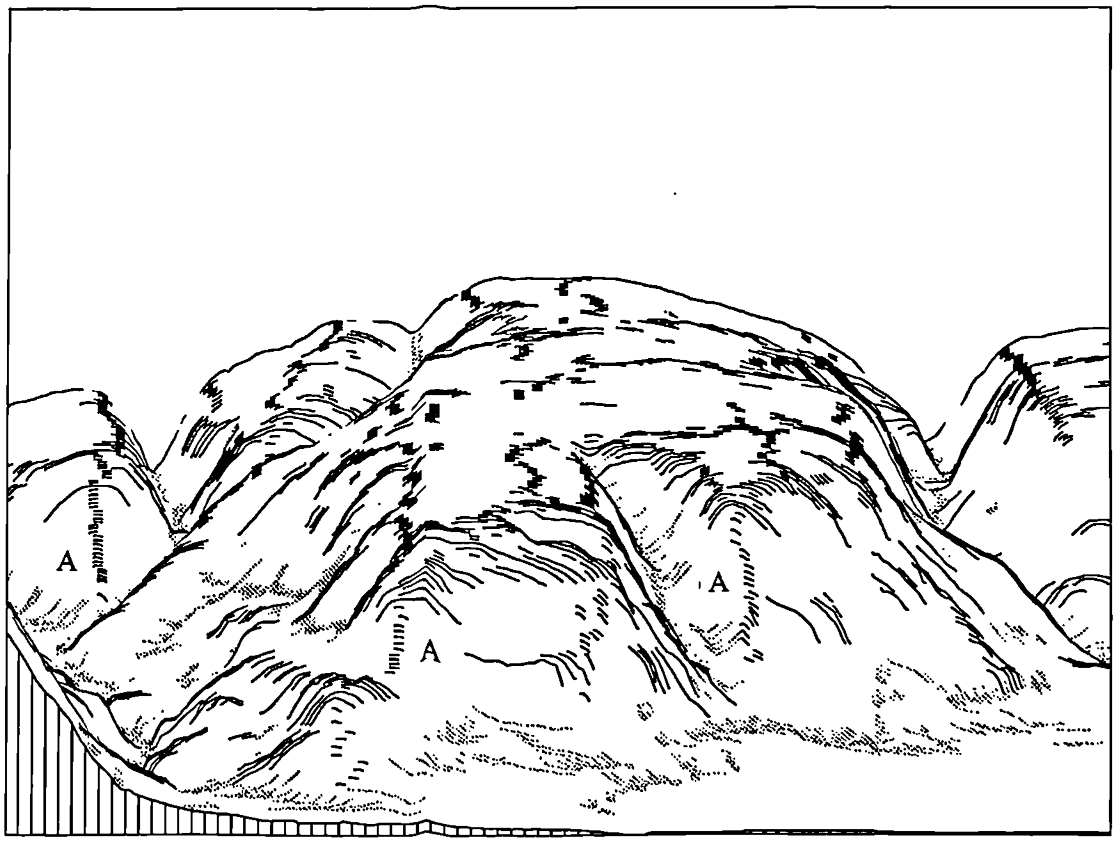


Figure 4.6(c): Sketch of Port Talbot DEM from the west, based on core cells selected by the Douglas-Peucker algorithm.

4.5.2 Visual Comparison

The highly visual nature of this project makes a visual comparison the only one which is meaningful. In the previous section it was determined that core cells detected by the Douglas-Peucker algorithm form more distinct lines than those detected using Visvalingam's algorithm. However, for the production of artistic sketches, the alignment of core cells detracts in several ways:

- The alignment of the core cells produces aligned profile strokes. The distinct lines detected by the Douglas-Peucker algorithm are made visible through the alignment of the orthogonal p-strokes. This effect is particularly noticeable where the bottom of a valley or the crest of a ridge appears vertical in a sketch. This creates a column-like effect which can be observed at the positions marked "A" in the sketch of the Port Talbot DEM from the west (figure 4.6(c)). The other Douglas-Peucker based sketches suffer from this problem to a lesser extent. The greater dispersion of core cells selected by Visvalingam's algorithm, using either metric, result in some p-strokes being drawn on the ridge crest/valley bottom while others are drawn to either side of it. This creates a more pleasing effect which better conveys the form of the terrain and which is closer to how an artist would draw.
- When profile strokes come very close together, due to the proximity of adjacent profiles, a black smudging effect is created by the increased area of black ink. This effect can be seen in sketches from all three directions but is most obvious in views from the west. Sketches produced using core cells selected by Visvalingam's algorithm exhibit this effect but it is much more pronounced in those based on core cells selected by the Douglas-Peucker algorithm. This is due to the alignment of orthogonal p-strokes.
- The undesirable alignment of orthogonal p-strokes produced by the Douglas-Peucker algorithm results in bare, white spaces devoid of description. Sketches produced with Visvalingam's algorithm, provide a scattering of p-strokes to describe such places in a similar fashion to that used by an artist.

4.5.3 Conclusions

Sketches produced using core cells selected by the Douglas-Peucker algorithm are inferior because they lack connectivity. The method of elimination was found to be superior to selection. However, it is difficult to choose between sketches produced using effective area and perpendicular distance. There is clearly a need for further work to determine which of these is superior.

The core cells detected by the Douglas-Peucker algorithm may prove more useful with other sketching procedures. The distinct lines detected indicate that this would be the case for sketching procedures in which the strokes of the sketch no longer follow the profile lines but join core cells on different profiles. It may be possible to combine the strengths of both in a single sketching procedure.

4.6 SUMMARY

The previous chapter introduced a novel method of producing artistic sketches of regular grid DEMs. The sketching procedure was based on the detection of salient points on the surface of the DEM. These points were termed "core cells". Visvalingam's algorithm, using effective area as the metric, was used for the purpose of detecting these cells. This chapter observed the impact of alternative metrics on the behaviour of Visvalingam's algorithm. The Douglas-Peucker algorithm, which is the most widely used line simplification algorithm, was also evaluated as an alternative to Visvalingam's algorithm for core cell selection.

One-dimensional terrain profiles generalised using Visvalingam's algorithm, with effective area and perpendicular distance, and the Douglas-Peucker algorithm were compared. The types of detail found in terrain profiles was also classified. It was found that comparable results were produced by Visvalingam's algorithm, with effective area and perpendicular distance, and the Douglas-Peucker algorithm. These were deemed worthy of further investigation.

The distribution of core cells across a DEM, produced by simplifying the terrain profile for each row and column, was compared. It was found that the core cells selected by the Douglas-Peucker algorithm formed distinct lines while those selected using Visvalingam's algorithm were more scattered.

However, since the purpose for selecting core cells is to provide a basis for the sketching procedure described in the previous chapter, sketches produced from each set of core cells were compared. Those produced from the more scattered core cells of Visvalingam's algorithm were deemed most aesthetically pleasing and most resembled those that an artist might produce. Because more work is necessary to determine the superiority of either effective area or perpendicular distance, effective area will continue to be used in future chapters.

Chapter 5

Sketching A Smaller Scale DEM

5.1 INTRODUCTION

This is a short chapter which presents the results obtained when the novel sketching procedure proposed in Chapter 3 was applied to a smaller scale DEM.

5.2 DIFFERENT TEST DATA

Chapter 3 described an original technique for extracting artistic sketches from regular grid DEMs. In Chapter 3 the technique was illustrated using a large scale (1:10,000) DEM which covered a quarter of the small sample dataset released by the Ordnance Survey (OS) of Great Britain. This DEM modelled the hilly area behind Port Talbot, in Wales, and the resulting sketches of it proved to be very promising. In this chapter the same sketching technique is applied to another, smaller scale DEM (1:24,000). This DEM is part of a larger United States Geological Survey (USGS) DEM for the terrain around West Point in New York.

The new DEM consists of 201 x 201 heights with a 30m grid spacing. Figure 5.1(a) - (d) shows this DEM, represented by profile lines, from four directions. The terms front, back, left and right are used instead of north, south, east and west because the correct orientation of the DEM is unknown. The same degree of vertical exaggeration used in the previous chapters for the OS DEM (*i.e.* x3) is used for the new DEM though a higher viewpoint is shown, in order to reveal more of the terrain. If figures showing these two DEMs were compared, it would appear that the OS DEM describes higher terrain however, this is an effect of scale and the new USGS DEM has a maximum elevation twice as high as that of the OS DEM (the maximum elevations being 500m and 250m respectively).

Both the previously used OS DEM and the new USGS DEM are described in detail in Appendix B.

5.3 RESULTS OF SKETCHING

When the sketching parameters previously used were applied to the new DEM the resulting sketches looked cluttered and were difficult to comprehend (see figure 5.2(a) - (d)). This led to the determination of a new set of parameters. Figure 5.3(a) - (d) shows sketches of the DEM from four directions using the new sketching parameters which are presented in table 5.1. As can be seen, from both the table and the sketches, +orthogonal profile strokes are not shown at all. While they made an important contribution to the sketches of the OS DEM, they were largely responsible for the cluttered appearance of the new sketches. Their removal leaves more to the imagination but greatly improves the sketches, making the convexities defined by the +parallels stand out clearly. The tolerances for the remaining types of p-stroke and their colour and style are the same as those used for the OS DEM however, the extension rules have changed. The length of parallel p-strokes have been minimised to provide a more economical sketch. The ridges recorded in the DEM, which are described by +parallel p-strokes are unlikely to be perfectly perpendicular to us therefore the core cells which identify them span several profiles. Fully extending these strings of core cells results in overlapping lines. It was found that for this DEM the use of shorter +parallel profile strokes produced a crisper sketch. This does of course mean that the form of some convexities are described less fully but overall this results in more aesthetically pleasing sketches. Conversely the –orthogonals were extended to produce a shading effect in the valleys. The –parallels were shortened so that this shading effect would not extend too far.

5.4 OBSERVATIONS

The sketches of the DEM from the front and back are superior to those from the sides because of artifacts. Artifacts can be seen in figure 5.1, where the DEM is represented by profile lines but show up more clearly in the resulting

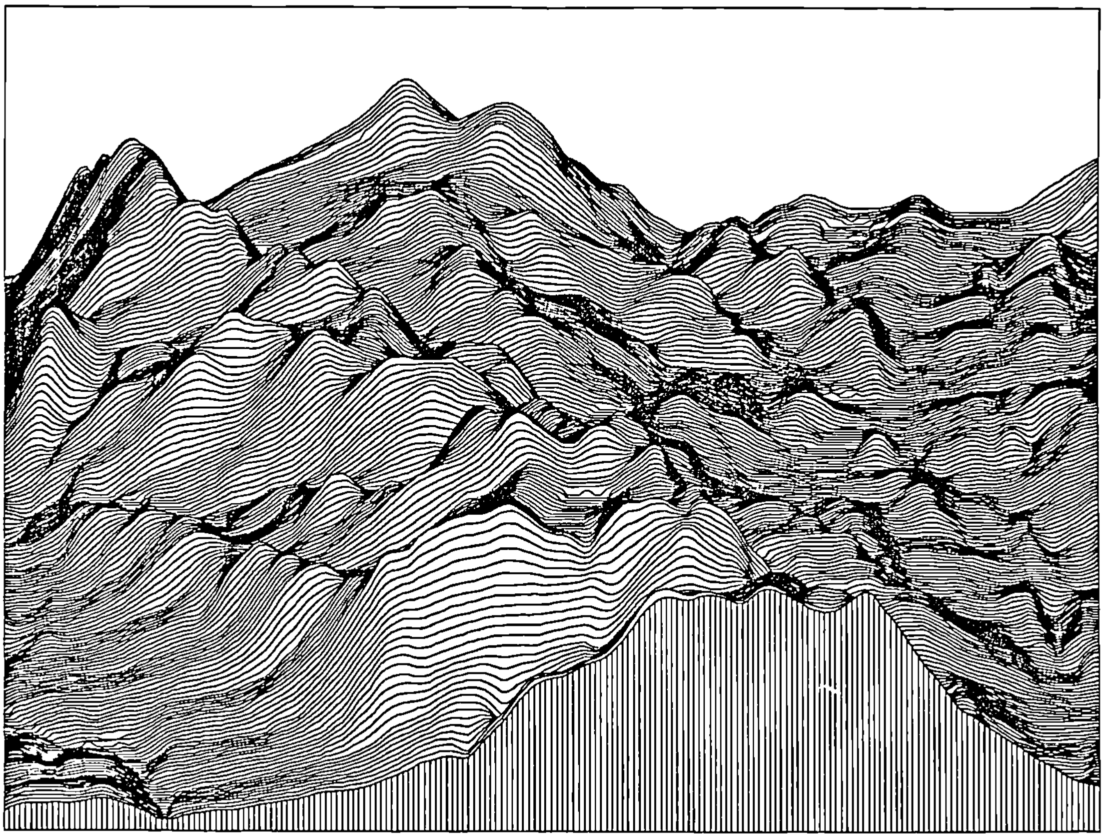


Figure 5.1(a): 1:24,000 USGS DEM represented by profile lines. Viewed from front.

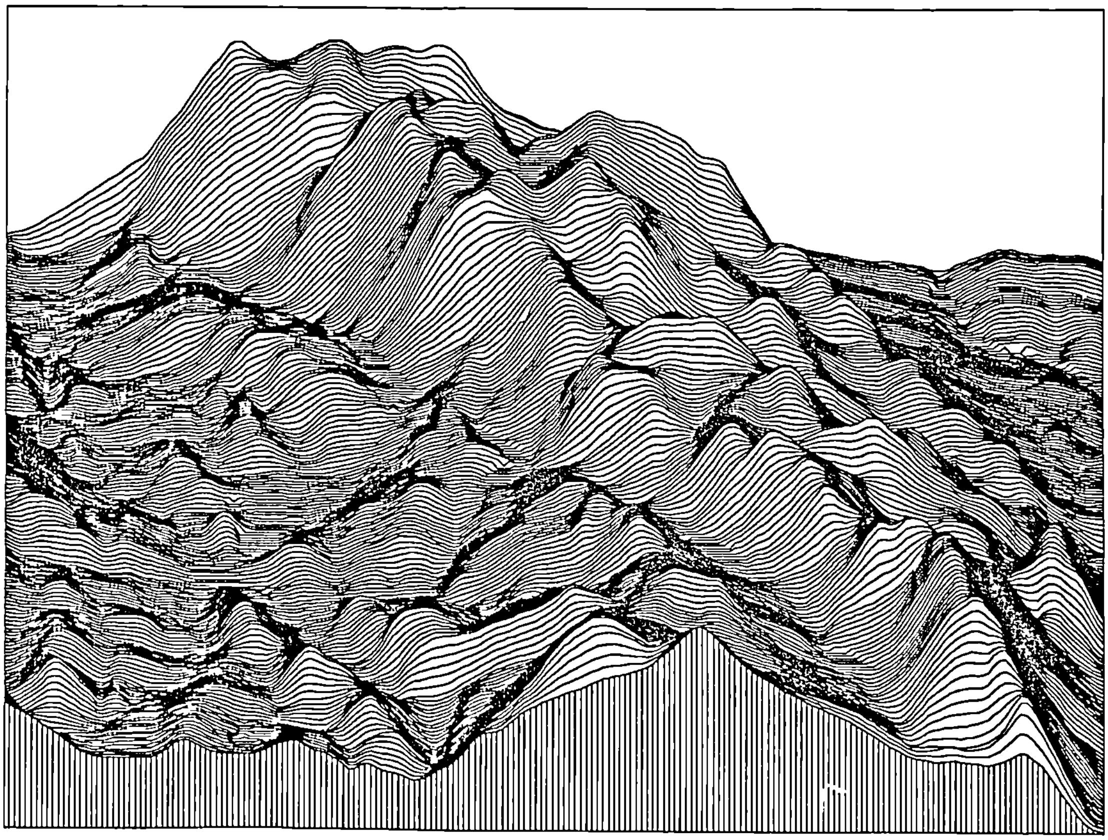


Figure 5.1(b): 1:24,000 USGS DEM represented by profile lines. Viewed from back.

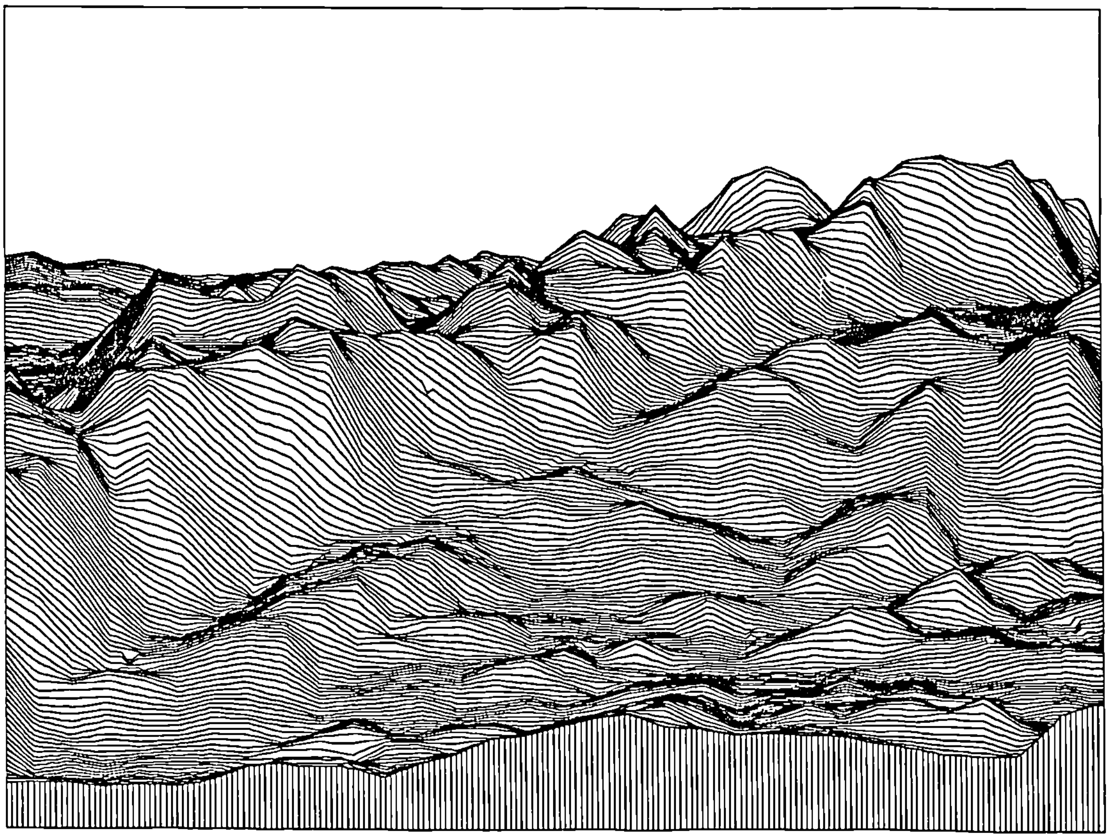


Figure 5.1(c): 1:24,000 USGS DEM represented by profile lines. Viewed from left.

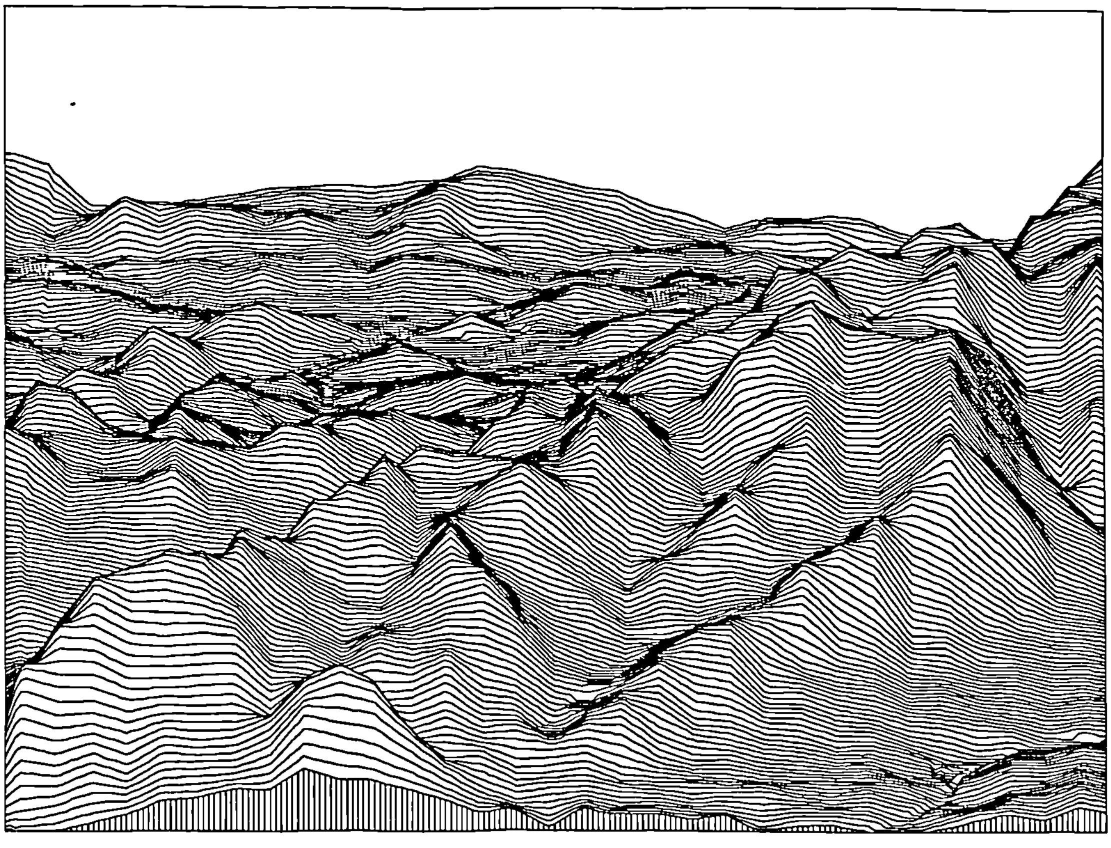


Figure 5.1(d): 1:24,000 USGS DEM represented by profile lines. Viewed from right.

Parameters for Sketching					
	Extension Rule		Colour	Style	Tolerances
	Left	Right			
+parallel	minimal	minimal	black	Solid	1000
+orthogonal	-	-	-	-	-
-orthogonal	full	full	grey	Dotted	4000
-parallel	minimal	minimal	black	Solid	4000

Table 5.1: Sketching Parameters and Tolerances.

sketches. They are especially noticeable in the side views, where a vertical striping effect can be observed. These artifacts are produced during the DEM creation process as explained by Mark (1984, p.170) who goes on to state that "Many images produced from these models have clearly visible 'stripes' ". The selection of core cells along these prominent artifacts detracts from the resulting sketches. This is apparent in figures 5.2 and 5.3, (c) and (d), where the vertical striping effect is reproduced by the –orthogonals.

Sketching a DEM makes artifacts which may be difficult to see in other forms of terrain representation explicit. This technique may also be applicable to the detection of artifacts in artificial terrain. Artifacts occur in artificial terrain where initial edges are retained throughout the subdivision process. Dixon (1994a) used numerical methods to detect artifacts in terrain which he generated. An avenue for further investigation would be to sketch artificial terrain in the hope of detecting these artifacts. This would allow the comparison of various artificial terrain generation techniques to determine which produced the least artifacts.

Sketches of smaller scale DEMs, such as those in figures 5.2 and 5.3, could benefit from the application of depth cueing (see section 2.4.2.8) to help distinguish features in the foreground and in the distance. This technique is commonly applied in the sketches of artists.

5.5 CONCLUSION

In general it was found that a reduction of detail was needed to compensate for the reduction in DEM scale, to produce aesthetically pleasing sketches. This is the underlying concept of scale dependent cartographic generalisation. If this is not done, sketches which are cluttered and hard to comprehend are the result. The application of the sketching procedure to DEMs at a variety of scales would help to further determine the scale-related nature of sketching which must also consider the size at which the sketch is to be drawn. Since the p-strokes are drawn with a constant thickness regardless of sketch size, a large sketch can include more detail without becoming cluttered.

5.6 SUMMARY

This chapter described the application of the novel sketching technique proposed in this thesis to a 1:24,000 DEM. The sketching parameters were varied to produce aesthetically pleasing results. However, core cell selection is sensitive to the artifacts present in the DEM and this detracts from the quality of the sketches.

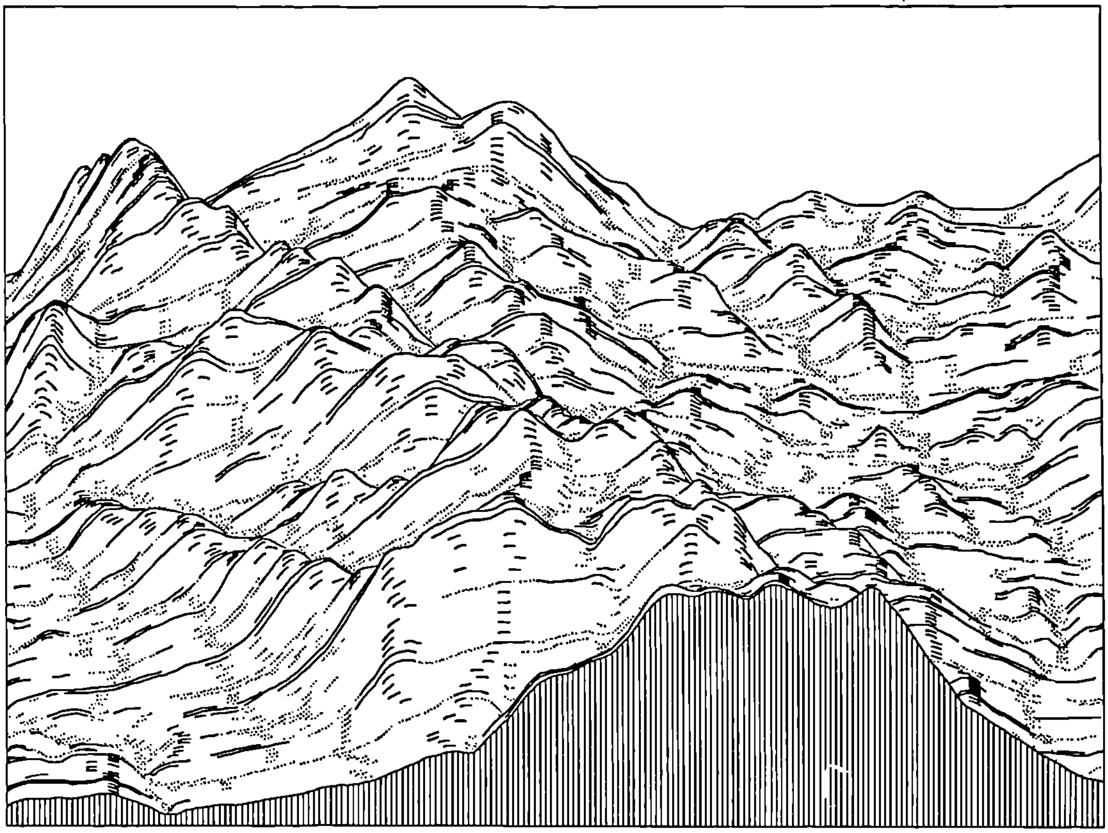


Figure 5.2(a): Sketch of 1:24,000 DEM from the front, using previous sketching parameters.

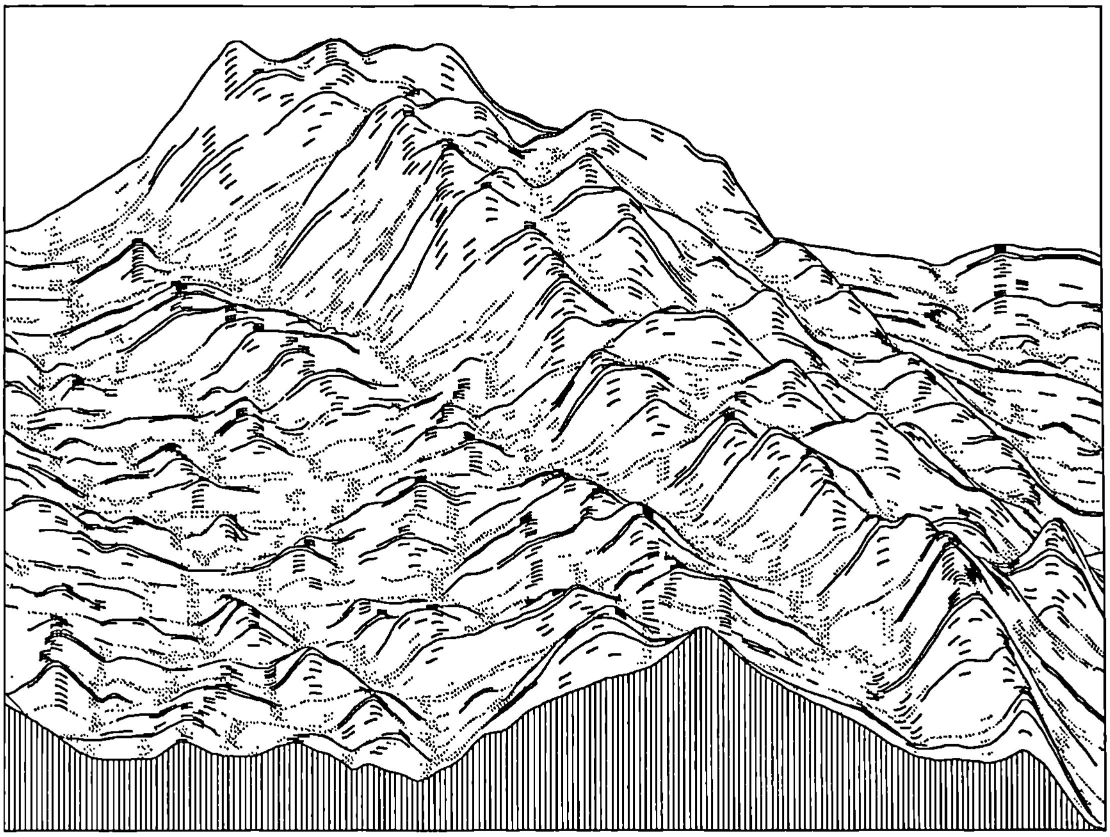


Figure 5.2(b): Sketch of 1:24,000 DEM from the back, using previous sketching parameters.

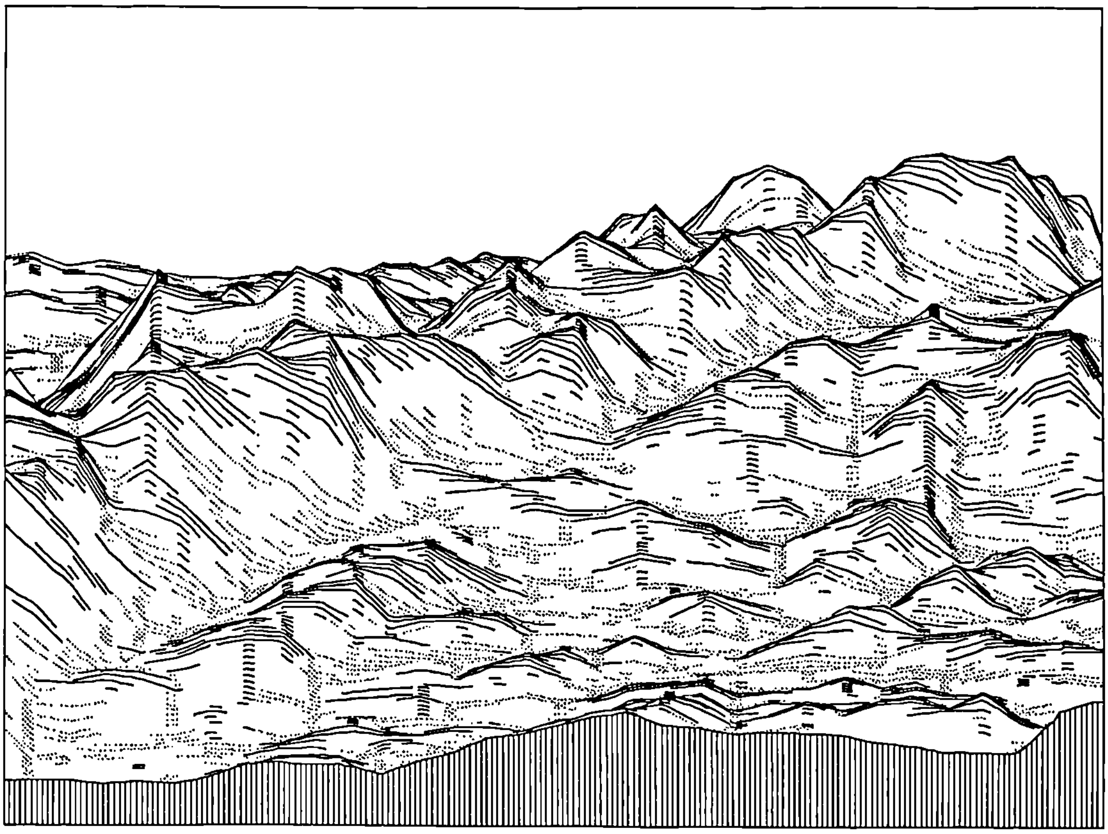


Figure 5.2(c): Sketch of 1:24,000 DEM from the left, using previous sketching parameters.

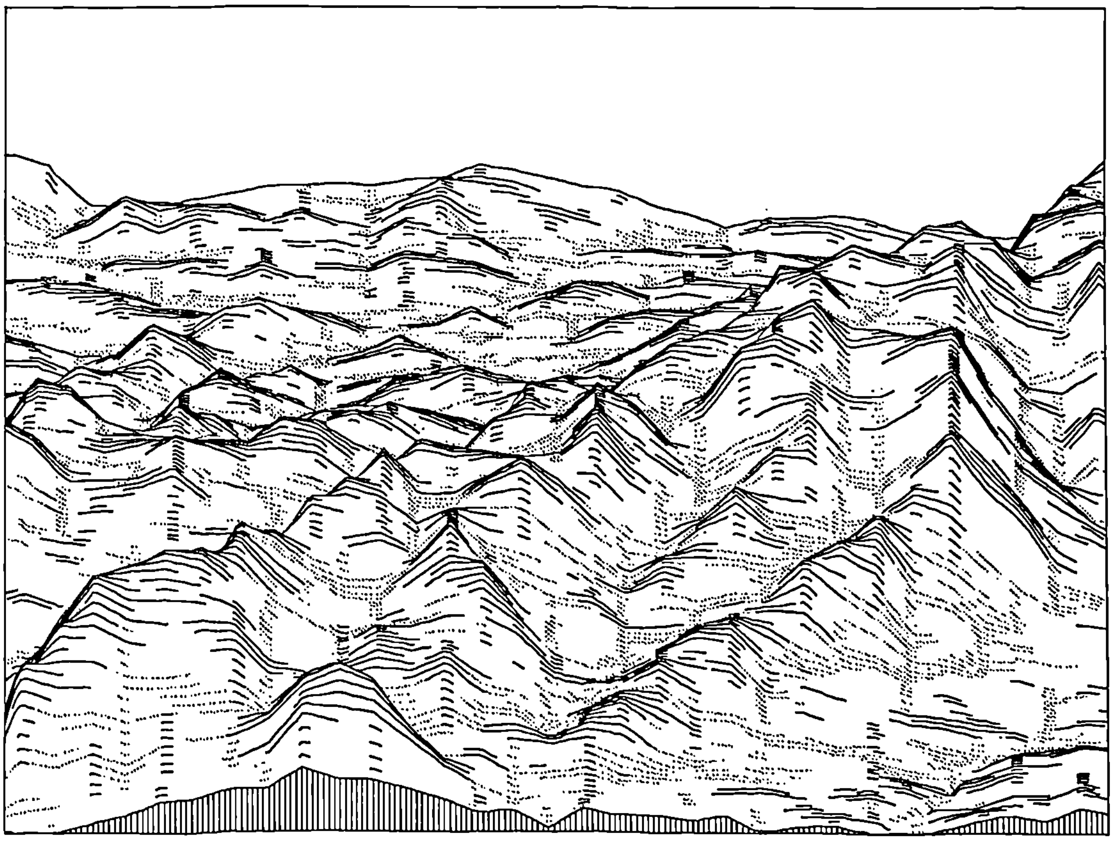


Figure 5.2(d): Sketch of 1:24,000 DEM from the right, using previous sketching parameters.

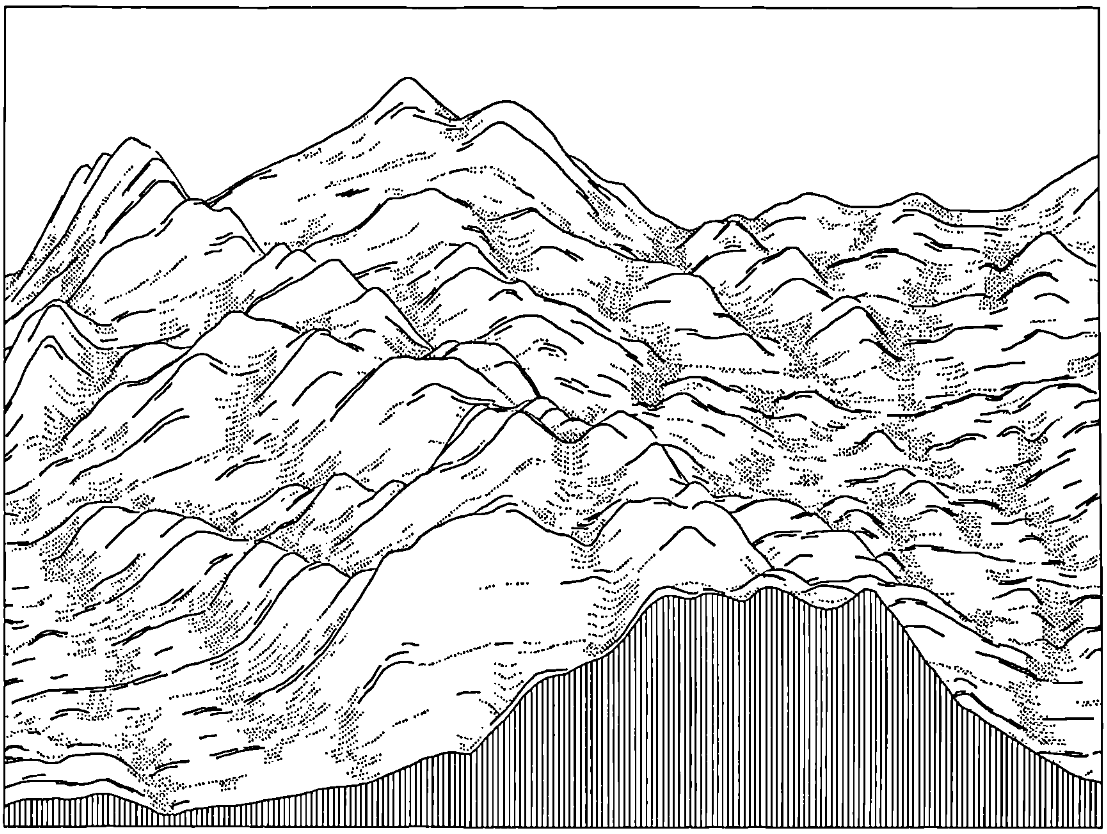


Figure 5.3(a): Sketch of 1:24,000 DEM from the front, using new sketching parameters.

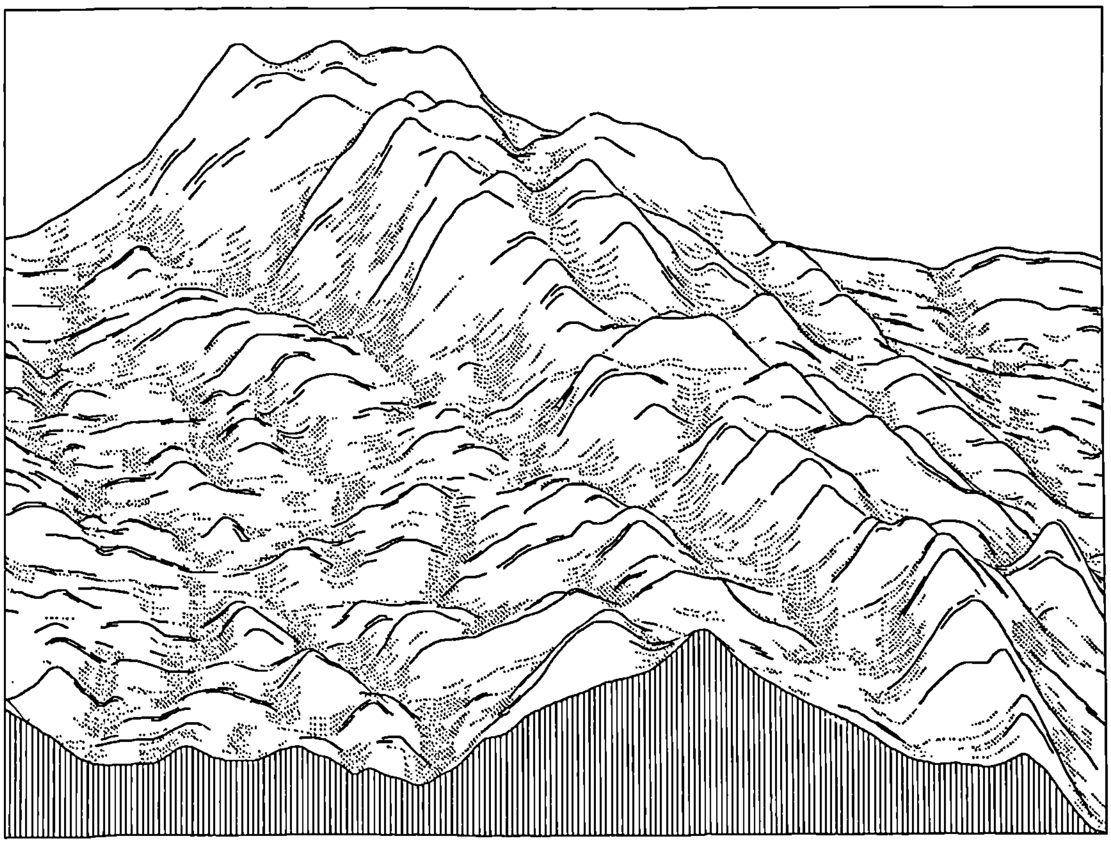


Figure 5.3(b): Sketch of 1:24,000 DEM from the back, using new sketching parameters.

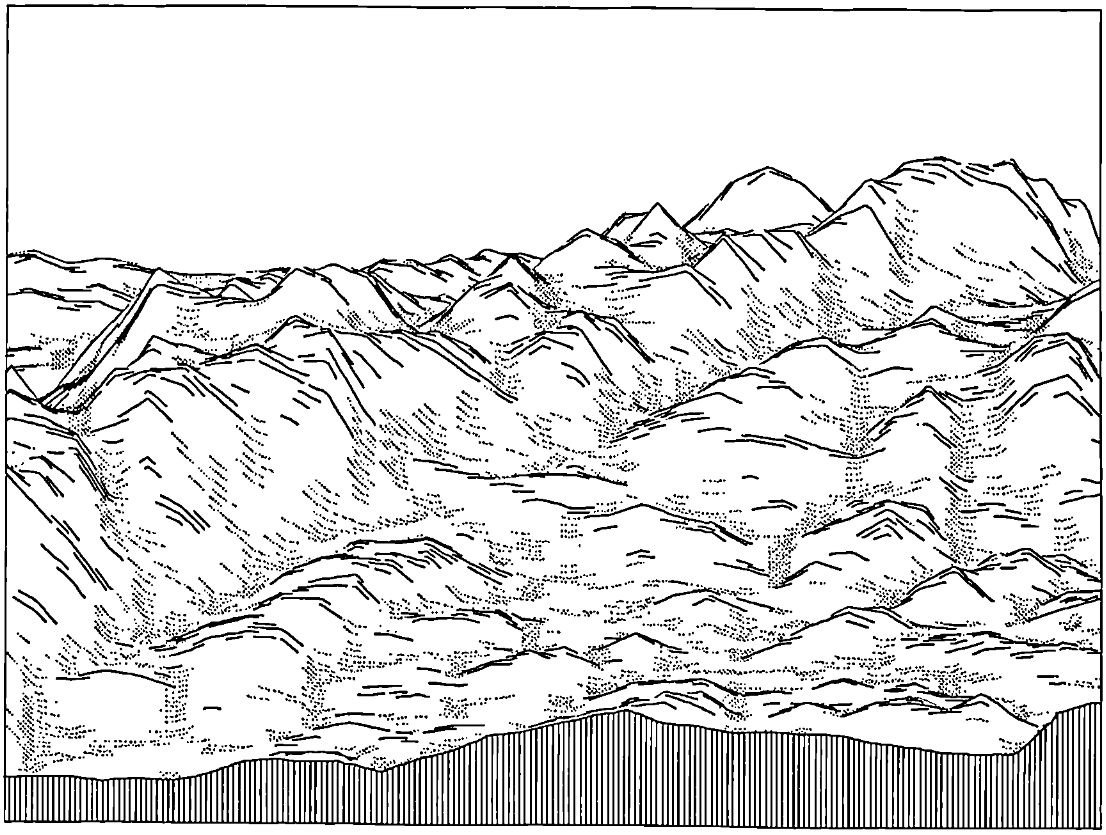


Figure 5.3(c): Sketch of 1:24,000 DEM from the left, using new sketching parameters.

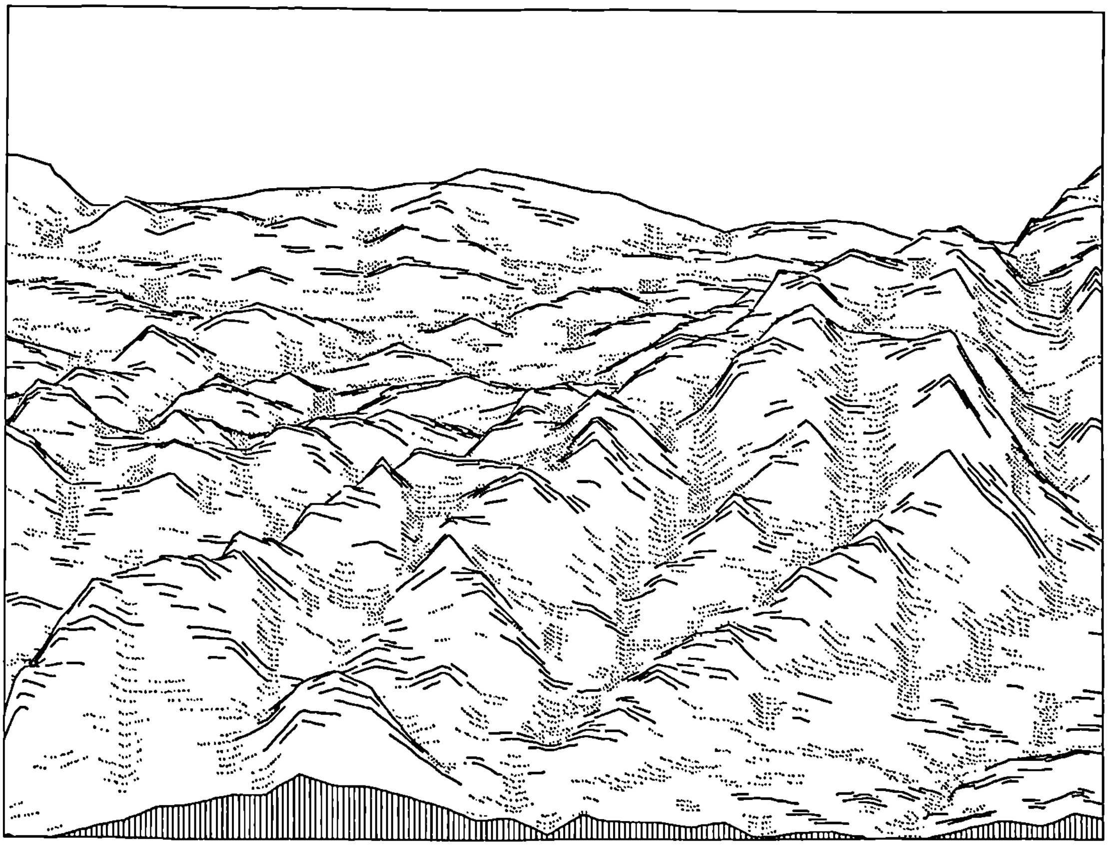


Figure 5.3(d): Sketch of 1:24,000 DEM from the right, using new sketching parameters.

Chapter 6

Conclusion

6.1 SUMMARY

An examination of techniques used in conventional cartography, aided by the development of a new taxonomy, identified a class of techniques which represent terrain pictorially. These include block diagrams, sketches which are often drawn as a preparatory stage in the production of a block diagram, and physiographic mapping methods which developed from the block diagram. Pictorial depiction of the landscape has of course also played a prominent role in the history of art.

The main trend of computer graphics is to produce images of reality with a photographic degree of realism, just as the drawing machines of centuries past were tools to help the artist accurately reproduce a scene. While some conventional cartographic techniques have been implemented on a computer, *e.g.* contours and profiles, three-dimensional images of terrain usually contain the full repertoire of photorealistic cues. Photorealism has its place; the creation of special effects in movies, advertising and training simulators are examples. In these cases there is a need for a high degree of photographic realism. However, there is another kind of realism "the realism of drawing" (Sasada, 1987). Over recent years the literature shows a growing interest in the simulation of artistic and illustrative techniques (Sasada, 1987; Dooley and Cohen, 1990; Saito and Takahashi, 1990; 5D Solutions, 1994; Hsu and Lee, 1994; Leister, 1994; Salisbury *et al.*, 1994; Winkenbach and Salesin, 1994).

This thesis described an original technique for automatically producing artistic sketches of DEMs. DEMs are widely available and are used for many purposes (*e.g.* visualisation, visibility analysis, planning, cut and fill problems *etc.*). The profile based sketching technique described in this thesis can be thought of as a two stage process:

1. Identify the form of the terrain.

   Line simplification algorithms are used in cartography to simplify complex two-dimensional lines such as coastlines, usually when a line is to be shown at a reduced scale. A line simplification algorithm is used to rate each cell in the DEM, by application to terrain profiles. This detects perceptually important cells which are termed "core cells".

   The most widely used line simplification algorithm is the Douglas-Peucker algorithm. However, two recent comparisons (Visvalingam and Whyatt, 1993; Visvalingam and Williamson, 1994) have shown Visvalingam's algorithm to be superior for caricatural generalisation. A comparison was carried out to determine which algorithm produced the best set of core cells for sketching. Visvalingam's algorithm was tested with effective area and perpendicular distance as metrics. Perpendicular distance is also the metric used by the Douglas-Peucker algorithm. The comparison considered:

   (a) the ability of the algorithms to simplify one-dimensional terrain profiles.

   (b) the resulting distribution of core cells across the DEM.

   (c) the sketches produced.

   It was concluded that Visvalingam's algorithm, with either metric produced superior results for sketching. It was therefore decided to use effective area.

2. Communicate the form of the terrain.

   The pencil strokes made by an artist are simulated by connecting strings of core cells on the same profile. These strings of core cells are then extended along the profile lines to form "profile-" or "p-strokes". Strings of core cells may be extended to either the right, the left or both while the length of extension may be:

   (a) none.

   (b) minimal (one extra cell).

   (c) full (up to and including the next cell of effective area zero or of opposite sign).

To simulate the varied strokes made by an artist four individual types of p-stroke were identified; +parallel, –parallel, +orthogonal and –orthogonal. Positive profile strokes describe convexities while negative profile strokes describe concavities. The symbolism, direction and length of extension can be set individually for each type of p-stroke while a user-specified tolerance controls the number of core cells selected.

Figures were presented using a vertical oblique projection. This allows the profiles that p-strokes follow to be separated to produce a map-like effect. This would not be possible with a perspective projection which causes distortion with depth.

The sketching technique was applied to a 1:10,000 Ordnance Survey DEM and a smaller scale 1:24,000 United States Geological Survey DEM. This produced promising results in both cases.

6.2 DISCUSSION

The proposed sketching technique is a simple one, using basic two-dimensional computer graphics. The most complex graphics technique used is the simple Painter's algorithm. Other computer graphics elements could be employed, such as a perspective transformation and, for smaller scale DEMs, depth cueing. Most of the techniques proposed by other researchers for automatically producing sketches and illustrations are based on extensions of complicated graphics techniques such as texture mapping and ray-tracing (Leister, 1994; Winkenbach and Salesin, 1994; 5D Solutions, 1994).

The growing interest in the simulation of artistic and illustrative techniques was noted in the previous section. The advantages of such techniques over photorealism include:

1. A sketch is an interpretation of a subject rather than a mechanical copy. It allows the abstraction of important elements in a scene which can be emphasised, clarified, simplified and exaggerated.

2. Superfluous detail which detracts from the purpose of the sketch can be omitted.

3. Sketches often possess a sense of vitality difficult to capture with photorealism (Winkenbach and Salesin, 1994).

4. It is easy to convey different levels of detail (Winkenbach and Salesin, 1994).

5. Ease of reproduction. A photocopier or laser printer is sufficient.

6. The economical lines of a sketch consume less storage.

7. The economy of a sketch also means there is less information to transmit (Pearson *et al.*, 1990; Pearson and Robinson, 1985).

The sketches produced have several advantages over a simple profile representation. Both can be aesthetically pleasing however, the major disadvantage of the profile representation is the obliterating effect which occurs when the profile lines come close together. The sketches overcome this problem providing a much clearer image which is suitable for the addition of landscape elements and/or area shading. The second advantage of the sketch is that many features which are "hidden" by surrounding detail in the profile representation are clearly visible. Also, the level of detail contained in a sketch can be easily varied by manipulation of the tolerances and sketching parameters. Conversely, the advantage of the profile representation is the ease with which it can be implemented.

The success of the sketching technique relies partly on Visvalingam's line generalisation algorithm for selecting geometrically important elements and partly on the methods used for visualising the results. A great deal of experimentation was needed to identify the "profile stroke" method described in this thesis and to abstract appropriate tolerances and symbolism. Our experience suggests that it is relatively easy to identify the convex form descriptors. However, we had a great deal of difficulty developing suitable symbolism for depicting the concave forms in a convincing manner.

While convexities and concavities have been associated with ridges and valleys for the sake of explanation, the method is not very intelligent at present. For example, it is clearly necessary to sketch valley bottoms and valley sides (both –orthogonals) somewhat differently. However, the effective areas are rich in information and there is scope for differentiating between various types of relief units. Thus, it looks as if this method may be refined to produce more effective field sketches and to identify surface specific features. Even as it stands, it picks out the main plateau behind Port Talbot, the summits on this plateau, the rivers which penetrate this upland and smaller features such as spurs and ledges on the hillside. The shape of the features are well conveyed.

Although the methods described in this thesis appear to be suitable for most features, they are not ideal; see for example figure 3.15(c) of Port Talbot which does not pick out clearly the ledge on the hillside. Nevertheless, it is quite clear that the output from this prototype system is superior to many manual sketches of terrain which appear in the cartographic and geographic literature. It is therefore believed that these ideas could contribute additional tools based on the traditional cartographic principles of selection, generalisation and symbolic representation.

Some views of the DEM are better suited than others to the sketching technique described here. For example, sketches of Port Talbot from the west seem to work better than those made from other directions. This is determined by the form and the ruggedness of the terrain which the DEM records. However, it is also the case in art and photography that some views are more picturesque than others. It is one of the skills of the artist or photographer to select such views.

This research has been mainly concerned with the problem of abstracting what needs to be shown. It has attempted to do this in an economical fashion by treating the profiles of a DEM independently. At present the drawing program draws all of the p-strokes using the Painter's algorithm though many of the p-strokes are not visible in the completed sketch. The sketch may be further generalised by removing some of the p-strokes and by dropping superfluous points within p-strokes. However, efficiency issues take second place to further development of sketching techniques, especially with regard to animation.

6.3 FUTURE WORK

There is a great deal of scope for future work:

1. The most urgent need for future work is the removal of current viewing limitations. This would allow sketches to be produced from any position. When this limitation is removed it will be possible to consider animation.

2. Sketches have so far been produced of 1:10,000 and 1:24,000 scale DEMs. In the future DEMs at a number of different scales should be sketched in order to draw further conclusions on the scale related nature of sketching.

3. This thesis has demonstrated that the proposed technique for sketching terrain is viable and shows promise. Now that this has been established the methods used by Sasada (1987) to generate views of distant mountain ranges could be implemented for comparison and possible assimilation.

4. Further experimentation may result in superior rules for extracting strings of core cells while there is also scope for experimenting with new p-stroke symbolism, for example the use of vertical lines to depict –parallel profile strokes. Alternatively, it would be interesting to try and enhance the expressiveness of the sketches shown in this thesis, using the extended vocabulary of lines proposed by Dooley and Cohen (1990), the hairy brush strokes of Strassmann (1986) or the skeletal strokes of Hsu and Lee (1994).

5. Currently, the sketching technique is concerned with portraying the form of the terrain with no regard for its character. "The character of the surface not covered with vegetation ranges from sand to ice, and from smooth rock to scree and talus," Robinson et al (1984, p.368). The only concession to character which is currently possible is the use of different base colours *e.g.* yellow for sand and white for ice. In the future, other ways of describing the character of the terrain could be investigated. For example, differences in character might be introduced by different stroke textures (Winkenbach and Salesin, 1994).

6. At present p-strokes are constrained to following the profile lines. While this method has some advantages the strokes of the human artist are drawn in many directions. Experimentation with such unconstrained strokes could initially be combined with the existing sketching procedure though ultimately this would result in a totally new sketching technique closer to that of a human artist.

7. It was described earlier how some researchers have attempted to identify features within DEMs. This thesis has shown that the information detected in the form of core cells is sufficient to produce a sketch where the features of the terrain can be identified by a human viewer. Progress in the field of cartographic generalisation may eventually reach a point where it is possible to dissect a DEM into its constituent features. This would allow the depiction of each type of feature in a way individually suited to them, as advocated by Lobeck (1924). However, this is clearly sometime in the future.

Items 1 - 4 are short term objectives while 5 and 6 are medium term. However, item 7 is still far beyond the state of the art of automated generalisation.

6.4 CONCLUSION

The focus of this highly exploratory project has been on the identification of core cells, proving that it is possible to extract the structure of a scene. While a topological model is not produced, geometric features are identified proving that this is a worthwhile method.

Despite the simplicity of the profile based technique, aesthetically pleasing sketches have been produced proving that it is possible to simplify terrain and depict it in a style that corresponds to that adopted by skilled cartographers and artists in the pre-computer age. These simple terrain sketches can stand on their own or can be used to touch up images of DEMs clothed with remotely sensed data. Area shading can be added to convey important themes, such as land use patterns, proposed developments, military operations and so on. My experience with grammar-based models also suggests that it should be possible to add simulated detail. Owing to a lack of time, this remains as future work.

The primary application of this technique is foreseen as static illustrations (due to current viewing limitations). Such illustrations would be ideal for inclusion in books, papers, newspapers (Ferris, 1993), tourist brochures and guide books. This technique could also be made available as a method of terrain representation in a GIS.

This thesis is the start of a programme of research which aims to supplement the cliches currently prevalent in the realm of digital cartography with the art forms of conventional cartography. This programme of research will benefit from multidisciplinary input; it is of interest to a variety of disciplines, including cartographers, geographers, geologists, the scientific visualisation community and psychologists, and several applications, such as the military, civil engineering, architecture, land use specialists, planners, tourism and the orienteering community.

References

5D Solutions, 1994, Personal communication, Southbank Technopark, 90 London Road, London, SE1 6LN.

Aerofilms Ltd, 1991, The Lake District from the Air, Barrie and Jenkins, 160pp.

Alpha, T. R. and Winter, R. E., 1971, "Quantitative Physiographic Method of Landform Portrayal", The Canadian Cartographer, 8 (2), 126 - 136.

Amanatides, J., 1987, "Realism in Computer Graphics: A Survey", IEEE Computer Graphics and Applications, 7 (1), 44 - 56.

Arnheim, R., 1976, "The Perception of Maps", The American Cartographer, 3, 5 - 10.

Arnheim, R., 1956, Art and Visual Perception: A Psychology of the Creative Eye, Faber and Faber, 408pp.

Arnold, D. B. and Duce, D. A., 1990, ISO Standards for Computer Graphics: The First Generation, Butterworths, 264.

Arthur, C., 1992, "Can Reality Move for You?", New Scientist, May 23, 22 - 28.

Attneave, F, 1954, "Some Informational Aspects of Visual Perception", Psychological Review, 61 (3), 183 - 193.

Ballard, D. H., 1981, "Strip Trees: A Hierarchical Representation for Curves", Communications of the ACM, 24 (5), 310 - 321.

Bagiana, F., 1993, "Tomorrow's Space: Journey to the Virtual Worlds", Computers and Graphics, 17 (6), 687 - 690.

Birch, T. W., 1964, Maps: Topographical and Statistical, Oxford University Press, London, 240pp.

Blinn, J. F., 1993, "A Trip Down the Graphics Pipeline: A Quarterly Report of SIGGRAPH-ACM, 12 (3), 286 - 292.

Bono, P. R., 1990, PC Graphics with GKS: Introduction to Graphics Standards (GKS, GKS-3D, PHIGS, CGI and CGM) and to Graphics Programming, Prentice-Hall International, 321pp.

Brandes, D., 1983, "Sources for Relief Representation", The Cartographic Journal, 20 (2), 87 - 94pp.

British Aerospace, 1993a, "GIS in the Electronic Cockpit", Mapping Awareness and GIS in Europe, 7 (4), 7 - 9.

British Aerospace, 1993b, "British Aerospace uses Silicon Graphics for Unique GIS Research", Iris UK, 2, 10 - 11.

Brivio, P. A. and Marini, D., 1993, "A Fractal Method for Digital Elevation Model Construction and its Application to a Mountain Region", Computer Graphics Forum, 12 (5), 297 - 309.

Brodlie, K. W., Carpenter, L. A., Earnshaw, R. A., Gallop, J. R., Hubbold, R. J., Mumford, A. M., Osland, C. D. and Quarendon, P. (eds.), 1992, Scientific Visualization: Techniques and Applications, Springer-Verlag, 284pp.

Brodlie, K. W., 1988, "Computer Graphics for Scientific Computing", School of Computer Studies: Research Report Series, The University of Leeds, Report 88.24, 17pp.

Brooks, W. D. and Pinzke, K. G., 1971, "A Computer Program for Three-Dimensional Presentation of Geographic Data", The Canadian Cartographer, 8 (2), 110 - 125pp.

Bryant, V. S. and Hughes, T. H., 1918, Map Work, Oxford, 174pp.

Burrough P. A., 1986, Principles of Geographical Information Systems for Land Resource Assessment, Oxford, 193pp.

Buttenfield, B. P. and McMaster, R. B. (eds.), 1991, Map Generalization: Making Rules for Knowledge Representation, Longman Scientific and Technical, 245pp.

Carmichael, L. D., 1969, "The Relief of Map Making", Cartographic Journal, 6 (1), 18 - 20pp.

Carter, J. R., 1984, Computer Mapping: Progress in the '80s, The Association of American Geographers, 86pp.

Catlow, D. R., 1986, "The Multi-Disciplinary Applications of DEMS", Proceedings of Auto Carto London, Volume 1: Hardware, Data Capture and Management Techniques, M. Blakemore (ed.), 447 - 454.

Chance, A, Newell, R. G. and Theriault, D. G., 1990, "An Object Oriented GIS - Issues and Solutions", Smallworld Technical Paper 7, 10pp.

Chen, Z-T. and Guevara, J. A., 1987, "Systematic Selection of Very Important Points (VIP) from Digital Terrain Model for Constructing Triangular Irregular Networks", Proceedings of Auto-Carto 8, Baltimore, Maryland, March 29 - April 3, Chrisman, N. R. (ed.), American Society for Photogrammetry and Remote Sensing and American Congress on Surveying and Mapping, 763pp.

Chen, Z-T. and Tobler, W. R., 1986, "Quadtree Representations of Digital Terrain", Proceedings of Auto Carto London, Volume 1: Hardware, Data Capture and Management Techniques, M. Blakemore (ed.), 475 - 484.

Cockshott, T., Patterson, J. and England, D., 1992, "Modelling the Texture of Paint", Eurographics '92, Computer Graphics Forum, 11 (3), C-218 - C-226.

Cohen, D. and Gotsman, C., 1994, "Photorealistic Terrain Imaging and Flight Simulation", IEEE Computer Graphics and Applications, 14 (2), 10 - 12.

Cohen, D. and Shaked, A., 1993, "Photo-Realistic Imaging of Digital Terrains", Eurographics '93, Computer Graphics Forum, 12 (3), C-363 - C-373.

Cole, A., 1992, Perspective, Dorling Kindersley, 64pp.

Collinson, A., 1993, "Cartographic Design Does Not Exist (and Never Has)!", The Bulletin of the Society of Cartographers, 27 (1), 3 - 6.

Coppock, J. T. and Anderson, E. K., 1987, "Editorial Review", International Journal of GIS, 1 (1), 3 - 11.

Cosgrove, D. E., 1993, The Palladian Landscape: Geographical Change and its Cultural Representations in Sixteenth Century Italy, Leicester University Press, 270pp.

Cuff, D. J. and Mattson, M. T., 1982, Thematic Maps: Their Design and Production, New York: Methuen, 169pp.

De Floriani, L., 1987, "Surface Representations Based on Triangular Grids", The Visual Computer, 3, 27 - 50.

De Floriani, L., Falcidieno, B., Nagy, G. and Pienovi, C., 1984, "A Hierarchical Structure for Surface Approximation", Computer and Graphics, 8 (2), 183 - 193.

De Floriani, L., Falcidieno, B. and Pienovi, C., 1983, "A Delauney-Based Method for Surface Approximation", Proceedings of Eurographics '83, 333 - 350.

Dettori, G. and Falcidieno, B., 1982, "An Algorithm for Selecting the Main Points on a Line", Computers and Geosciences, 8 (1), 3 - 10.

Deveau, T. J., 1985, "Reducing the Number of Points in a Plane Curve Representation", Proceedings of Auto Carto 7, Washington DC, 152 - 160.

Dickinson, G. C., 1969, Maps and Air Photographs, Edward Arnold Ltd., London, 286pp.

Dixon, A. R., 1994a, The Synthesis of Fractal Terrain and its Application to Flight and Space Simulation, Unpublished Ph. D. Thesis, The Department of Computer Science, The University of Hull, 103pp.

Dixon, A. R., Kirby, G. H. and Wills, D. P. M., 1994b, "A Data Structure for Artificial Terrain Generation", Computer Graphics Forum, 13 (1), 37 - 48.

Dixon, A. R., Kirby, G. H. and Wills, D. P. M., 1994c, "Towards Context Dependent Interpolation of Digital Elevation Models", Eurographics '94, Computer Graphics Forum, 13 (3), in press.

Dooley, D. and Cohen, F., 1990, "Automatic Illustration of 3D Geometric Models: Lines", Computer Graphics, 24, 77 - 82.

Douglas, D. H., 1993, "Least Cost Path in Geographic Information Systems", Research Note No. 61, Department of Geography, University of Ottawa, 22pp.

Douglas, D. H., 1986, "Experiments to Locate Ridges and Channels to Create a New Type of Digital Elevation Model", Cartographica, 23 (4), 29 - 61.

Douglas, D. H and Peucker, T. K., 1973, "Algorithms for the Reduction of the Number of Points Required to Represent a Digitised Line or its Caricature", The Canadian Cartographer, 10 (2), 112 - 122.

Dyer, D. S., 1990, "A Dataflow Toolkit for Visualization", IEEE Computer Graphics and Applications, 10 (4), 60 - 69.

Edwards, G., 1992, "Visualization: The Second Generation", Image Processing, 4 (2), 48 -53.

Ervin, S. M., 1993, "Landscape visualization with Emaps", IEEE Computer Graphics and Applications, 3, 28-33.

Ervin, S. M., 1992, "Visualizing n-Dimensional Implications of Two-Dimensional Design Decisions", Proceedings of IEEE Visualization Conference (Boston, Massachusetts), 356 - 360.

Environmental Systems Research Institute Inc. (ESRI), 1991, Surface Modelling with TIN (Revision 6.0), Arc/Info User's Guide.

Environmental Systems Research Institute Inc. (ESRI), 1990, Understanding GIS: The Arc/Info Method, Arc/Info User's Guide.

Evans, B. M., 1987, "View from Practice", Computer-Aided Design, 19 (4), 203 - 210.

Falcidieno, B. and Pienovi, C., 1990, "A Feature-Based Approach to Terrain Surface Approximation", Proceedings of the 4th International Symposium on Spatial Data Handling (Zurich, Switzerland), Volume 1, 190 - 199.

Falcidieno, B. and Spagnuolo, M., 1991, "A New Method for the Characterisation of Topographic Surfaces", International Journal of Geographical Information Systems, 5 (4), 397 - 412.

Falcidieno, B. and Spagnuolo, M., 1990a, "Automatic Recognition of Topographic Features for Digital Surface Modelling", Proceedings of the 4th International Symposium on Spatial Data Handling (Zurich, Switzerland), Volume 1, 35 - 44.

Falcidieno, B. and Spagnuolo, M., 1990b, "Characterisation of Topographic Surfaces", Proceedings of Eurographics '90, 287 - 298.

Falk, S., 1989, "Three-Dimensional Modelling and Piero Della Francesca's Use of Linear Perspective", Computers and Graphics, 13 (3), 345 - 347.

Ferris, K., 1993, "Black and White and Read All Over: The Constraints and Opportunities of Monochrome Cartography in Newspapers", The Cartographic Journal, 30 (2), 123 - 128.

The Fine Art Society, 1911, Catalogue of an Exhibition of Early Chinese Paintings from the Collection of A. W. Bahr, The Fine Art Society, 12pp.

Fisher, P., Dykes, J. and Wood, J., 1993, "Map Design and Visualization", The Cartographic Journal, 30 (2), 136 - 142.

Foley, J., Van Dam, A., Feiner, S. and Hughes, J., 1990, Computer Graphics: Principles and Practice (2nd edition), Addison-Wesley, 1174pp.

Fournier, A., Fussel, D. and Carpenter, L., 1982, "Computer Rendering of Stochastic Models", CACM, 25 (6), 371 - 384.

Fowler, R. J. and Little, J. J., 1979, "Automatic Extraction of Irregular Network Digital Terrain Models", Computer Graphics: A Quarterly Report of SIGGRAPH-ACM, 13 (3), 199 - 207.

Frank, A. U., Palmer, B. and Robinson, V. B., 1986, "Formal Methods for Accurate Definition of Some Fundamental Terms in Physical Geography", Proceedings 2nd International Symposium on Spatial Data Handling, Seattle, Washington, 583 - 599.

Frenkel, K. A., 1988, "The Art and Science of Visualising Data", Communications of the ACM, 31 (2), 111 - 121.

Friedell, M. and Kochhar, S., 1991, "Design and Modelling with Schema Grammars", Journal of Visual Languages and Computing, 2, 247 - 273.

Friedell, M. and Schulmann, J. L., 1990, "Constrained, Grammar-Directed Generation of Landscapes", Graphics Interface '90, 244 - 251.

Friedhoff, R. M. and Benzon, W, 1989, The Second Computer Revolution: Visualization, W. H. Freeman and Company, 215pp.

Gaman, W. A. and Giovinazzo, W. A., 1991, PHIGS by Example, Springer, 218pp.

Gardner, G. Y., 1985, "Visual Simulation of Clouds", Computer Graphics: A Quarterly Report of SIGGRAPH-ACM, 19 (3), 297-303.

Gardner, G. Y., 1984, "Simulation of Natural Scenes Using Textured Quadric Surfaces", Computer Graphics: A Quarterly Report of SIGGRAPH-ACM, 18 (3), 11 - 20.

Gargantini, I., 1982, "An Effective Way to Represent Quadtrees", Communications of the ACM, 25 (12), 905 - 910.

Gelberg, L. M. and Stephenson, T. P., 1987, "Supercomputing and Graphics in the Earth and Planetary Science", IEEE Computer Graphics and Applications, 7 (7), 26 - 33.

Glassner, A. S. (ed.), 1989, An Introduction to Ray Tracing, Academic Press: London, 329pp.

Gombrich, E. H. J., 1960, Art and Illusion: A Study in the Psychology of Pictorial Representation, Pantheon Books, 466pp.

Gouraud, H., 1971, "Continuous Shading of Curved Surfaces", IEEE Transactions on Computers, C-20 (6), 623 - 629.

Groom, J. and Kemp, Z., 1994, "Generic Multimedia Facilities in Geographic Information Systems", Proceedings of the GIS Research UK 1994 Conference, 11 - 13th April, 1994, University of Leicester, 359 - 368.

Haber, R. B. and McNabb, D. A., 1990, "Visualisation Idioms: A Conceptual Model for Scientific Visualisation Systems", in Neilson, G. M. and Shriver, B. D. (eds.), Visualisation in Scientific Computing, 74 - 93.

Haeberli, P., 1990, "Paint by Numbers: Abstract Image Representations", Computer Graphics, 24 (4), 207 - 214.

Hall, W. and Simmons, D., 1992, "An Open Model for Hypermedia and Its Applications to Geographical Information Systems", Eurographics '92, Computer Graphics Forum, 11 (3), C-1 - C-7.

Haralick, R. M., Campbell, J. B. and Wang, S., 1985, "Automatic Inference of Elevation and Drainage Models from a Satellite Image", Proceedings of the IEEE, 73 (6), 1040 - 1053.

Haralick, R. M., Watson, L. T. and Laffey, T. J., 1983, "The Topographic Primal Sketch", The International Journal of Robotics Research, 2 (1), 50 - 72.

Harley, J. B., 1975, Ordnance Survey Maps: A Descriptive Manual, Southampton: Ordnance Survey, 200pp.

Heller, M., 1990, "Triangulation Algorithms for Adaptive Terrain Modelling", Proceedings of the 4th International Symposium on Spatial Data Handling (Zurich, Switzerland), Volume 1, 163 - 174.

Hinks, A. R., 1933, Maps and Survey, Cambridge University Press, 283pp.

HMSO, 1987, "Handling Geographic Information", Report of the Committee of Enquiry chaired by Lord Chorley, 208pp.

Hopgood, F. R. A. and Duce, D. A., 1991, A Primer for PHIGS, John Wiley and Sons Ltd., 298pp.

Hopgood, F. R. A., 1986, Introduction to the Graphical Kernel System (GKS), London: Academic Press, 250pp.

Howard, T. L. J., 1991, A Practical Introduction to PHIGS and PHIGS PLUS, Addison-Wesley, 339pp.

Hsu, S. C. and Lee, I. H. H., 1994, "Drawing and Animation Using Skeletal Strokes", Proceedings of SIGGRAPH '94, 109 - 118.

Hubbold, R. J. and Hewitt, W. T., 1988, "GKS-3D and PHIGS: Theory and Practice", Eurographics Technical Report, 60pp.

Imhof, E., 1982, Cartographic Relief Presentation, Steward, H. J. (ed.), Walter de Gruyter, 389pp.

Jenks, G. F., 1981, "Lines, Computers and Human Frailties", Annals of the Association of American Geographers, 71 (1), 1 - 10.

Jenson, S. K. and Domingue, J. O., 1988, "Extracting Topographic Structure from Digital Elevation Data for Geographic Information System Analysis", Photogrammetric Engineering and Remote Sensing, 54, 1593 - 1600.

Jenson, S. K. and Trautwein, C. M., 1987, "Methods and Applications in Surface Depression Analysis", Proceedings of Auto-Carto 8, Baltimore, Maryland, March 29 - April 3, Crisman, N. R. (ed.), American Society for Photogrammetry and Remote Sensing and American Congress on Surveying and Mapping, 137 - 144.

Jones, C. B., Kidner, D. B. and Ware, M., 1994, "The Implicit Triangulated Irregular Network and Multiscale Spatial Databases", The Computer Journal, 37 (1).

Jones, Y., 1974, "Aspects of Relief Portrayal on 19th Century British Military Maps", Cartographic Journal, 11 (1), 19 - 33.

Kaneda, K., Kato, F., Nakamae, E., Nishita, T., Tanaka, H. and Noguchi, T., 1989, "Three Dimensional Terrain Modelling and Display for Environmental Assessment", Computer Graphics, 23 (3), 207 - 214.

Kelley, A. D., Malin, M. C. and Nielson, G. M., 1988, "Terrain Simulation Using a Model of Stream Erosion", Computer Graphics: A Quarterly Report of SIGGRAPH-ACM, 22 (4), 263 - 268.

Kingslake, R, 1986, An Introductory Course in Computer Graphics, Chartwell-Bratt, 144pp.

Kraak, M. J., 1988, Computer-Assisted Cartographical Three-Dimensional Imaging Techniques, Delft University Press, 175pp.

Laflin, S., 1987, Two-Dimensional Computer Graphics, Chartwell-Bratt, 85pp.

Lang, L., 1993, "Terrain Modelling", Computer Graphics World, 16 (9), 23 - 28.

Lang, T, 1969, "Rules for Robot Draughtsmen", Geographical magazine, 42, 50 - 51.

Lansdown, J., 1990, "Understanding the Digital Image", Images and Understanding: Thoughts About Images, Ideas About Understanding, Barlow, H., Blakemore, C. and Weston-Smith, M. (eds.), Cambridge University Press, 227 - 234.

Laurel, B., Strickland, R. and Tow, R., 1994, "Placeholder: Landscape and Narrative in Virtual Environments", Computer Graphics, 28 (2), 118 - 126.

Lawrence, G. R. P., 1971, Cartographic Methods, Methuen and Company, London, 162pp.

Lee, J., 1991, "Comparison of Existing Methods for Building Triangular Irregular Network Models of Terrain from Grid Digital Elevation Models", International Journal of Geographical Information Systems, 5 (3), 267 - 285.

Leister, W., 1994, "Computer Generated Copper Plates", Computer Graphics Forum, 13 (1), 69 - 78.

Lobeck, A. K., 1924, Block Diagrams and Other Graphic Methods used in Geology and Geography, John Wiley and Sons, 206pp.

Maling, D. H., 1973, Co-ordinate Systems and Map Projections, Philip, 255pp.

Mandelbrot, B. B., 1982, The Fractal Geometry of Nature, W. H. Freeman and Co., 460pp.

Marino, J. S., 1979, "Identification of Characteristic Points Along Naturally Occurring Lines: An Empirical Study", Canadian Cartographer, 16 (1), 70 - 80.

Mark, D. M., 1984, "Automated Detection of Drainage Networks from Digital Elevation Models", Cartographica, 21 (3), 168 - 178.

McCormack, J. E., Gahegan, M. N., Roberts, S. A., Hogg, J. and Hoyle, B. S., 1993, "Feature-based Derivation of Drainage Networks", International Journal of Geographical Information Systems, 7 (3), 263 - 279.

McCormick, B. H., DeFanti, T. A. and Brown, M. D. (eds.), 1987, "Visualisation in Scientific Computing", ACM SIGGRAPH Computer Graphics, 21 (6).

McKim, R. H., 1972, Experiences in Visual Thinking, Wadsworth Publishing, 171pp.

McLaren, R. A. and Kennie, T. J. M., 1989, "Visualisation of Digital Terrain Models: Techniques and Applications", in Three Dimensional Applications in GIS, Raper, J. (ed.), Taylor and Francis, 79 - 98.

McMaster, R. B., 1986, "A Statistical Analysis of Mathematical Measures for Linear Simplification", American Cartographer, 13 (2), 103 - 117.

Miller, G.S.P., 1986, "The Definition and Rendering of Terrain Maps", Computer Graphics: A Quarterly Report of SIGGRAPH-ACM, 20 (4), 39 - 45.

Milne, P. H., 1992, "Digital Ground Modelling", Mapping Awareness and GIS in Europe, 6 (3), 33 - 36.

Moellering, H., 1990, "3-D Stereoscopic Surface Exploration in Interactive Real Time", Proceedings of the 4th International Symposium on Spatial Data Handling (Zurich, Switzerland), Volume 1, 381 - 392.

Monkhouse, F. J. and Wilkinson, H. R., 1976, Maps and Diagrams: Their Compilation and Construction, 3rd edition, Methuen, 522pp.

Monmonier, M. S., 1986, "Towards a Practicable Model of Cartographic Generalisation", Proceedings Auto Carto London (ICA, 1986), Blakemore, M. (ed.), 257 - 266.

Morrison, J. L., 1975, "Map Generalisation: Theory, Practice and Economics", Proceedings of Auto Carto 2, 99 - 112.

Muller, J. C., 1987, "Optimum Point Density and Compaction Rates for the Representation of Geographic Lines", Proceedings Auto Carto 8, Chrisman, N. R. (ed.), 221 - 230.

Musgrave, F. K., Kolb, C. E. and Mace, R. S., 1989, "The Synthesis and Rendering of Eroded Fractal Terrains", Computer Graphics: A Quarterly Report of SIGGRAPH-ACM, 23 (3), 41 - 50.

Nakamae, E., Harada, K. and Ishizaki, T., 1986, "A Montage Method: The Overlaying of the Computer Generated Images onto a Background Photograph", Computer Graphics: A Quarterly Report of SIGGRAPH-ACM, 20 (4), 207 - 214.

Oberlander, T. M., 1969, "Annals Commentary", Annals of the Association of American Geographers, 59 (3), 600 - 606.

Oberlander, T. M., 1968, "A Critical Appraisal of the Inclined Contour Technique of Surface Representation", Annals of the Association of American Geographers, 58 (4), 802 - 813.

Opheim, H., 1982, "Smoothing a Digitised Curve by Data Reduction Methods", Proceedings of Eurographics '81, 127 - 135.

Oppenheimer, P., 1986, "Real Time Design and Animation of Fractal Plants and Trees", Computer Graphics: A Quarterly Report of SIGGRAPH-ACM, 20 (4), 55 - 64.

Palmer, B., 1984, "Symbolic Feature Analysis and Expert Systems", Proceedings International Symposium on Spatial Data Handling, 465 - 478.

Parslow, R., 1987, "A New Direction for Computer Graphics", Computer Bulletin, September, 22 - 25 and 31.

Peachey, D. R., 1985, "Solid Texturing of Complex Surfaces", Computer Graphics: A Quarterly Report of SIGGRAPH-ACM, 19 (3), 279 - 286.

Pearson, D., Hanna, E. and Martinez, K., 1990, "Computer-Generated Cartoons", Images and Understanding: Thoughts About Images, Ideas About Understanding, Barlow, H., Blakemore, C. and Weston-Smith, M. (eds.), Cambridge University Press, 46 - 60.

Pearson, D. E. and Robinson, J. A., 1985, "Visual Communication at Very Low Data Rates", Proceedings of the IEEE, 73 (4), 795 - 812.

Peitgen, H-O. and Saupe, D. (eds.), 1988, The Science of Fractal Images, Springer-Verlag, 312pp.

Perlin, K. and Hoffert, E., 1989, "Hypertexture", Computer Graphics: A Quarterly Report of SIGGRAPH-ACM, 23 (3), 253 - 262.

Perlin, K., 1985, "An Image Synthesiser", Computer Graphics: A Quarterly Report of SIGGRAPH-ACM, 19 (3), 287 - 296.

Petrie, G. and Kennie, T. J. M., 1987, "Terrain Modelling in Surveying and Civil Engineering", Computer-Aided Design, 19 (4), 171 - 187.

Peucker, T. K., Fowler, R. J., Little, J. J. and Mark, D. M., 1978, "The Triangulated Irregular Network", in Proceedings of the DTM Symposium, American Society of Photogrammetry - American Congress on Survey and Mapping, St Louis, Missouri, 516 - 540.

Peucker, T. K., 1975, "A Theory of the Cartographic Line", Proceedings of Auto Carto II, Reston, Virginia, 508 - 518.

Peucker, T. K. and Chrisman, N., 1975, "Cartographic Data Structures", American Cartographer, 2 (1), 55 - 69.

Peucker, T. K. and Douglas, D. H., 1975, "Detection of Surface-Specific Points by Local Parallel Processing of Discrete Terrain Elevation Data", Computer Graphics and Image Processing, 4, 375 - 387.

Phong, B. T., 1975, "Illumination for Computer Generated Pictures", Communications of the ACM, 18 (6), 311 - 317.

Phong, B. T., 1973, Illumination for Computer Generated Images, Unpublished Ph.D. Thesis, The Department of Computer Science, University of Utah.

Plastock, R. A. and Kalley, G., 1986, "Chapter 7: Mathematics of Projection", in Theory and Problems of Computer Graphics, Schaum's Outline Series, McGraw-Hill, 127 - 132.

Quinnell, R. A., 1993, "Software Simplifies Virtual-World Design", EDN, November 25, 47 - 54.

Raisz, E., 1938, General Cartography, McGraw-Hill, New York, 370pp.

Raisz, E., 1931, "The Physiographic Method of Representing Scenery on Maps", Geographical Review, 21 (2), 297 - 304pp.

Rasure, J. and Young, M., 1992, "Open Environment for Image Processing and Software Development", Proceedings of 1992 SPIE/IS&T Symposium on Electronic Imaging, 1659.

Reeves, W. T. and Blau, R., 1985, "Approximate and Probabilistic Algorithms for Shading and Rendering Structured Particle Systems", Computer Graphics: A Quarterly Report of SIGGRAPH-ACM, 19 (3), 313 - 322.

Reeves, W. T., 1983, "Particle Systems - A Technique for Modelling a Class of Fuzzy Objects", Computer Graphics: A Quarterly Report of SIGGRAPH-ACM, 17 (3), 359 - 376.

Ridd, M. K., 1963, "Proportional Relief Landform Map", Annals of the Association of American Geographers, 53 (4), 569 - 576.

Roberge, J., 1985, "A Data Reduction Algorithm for Planar Curves", Computer Vision, Graphics and Image Processing, 29, 168 - 195.

Robinson, A. H., Sale, R. D., Morrision, J. L. and Muehrcke, P. C., 1984, Elements of Cartography (5th edition), John Wiley and Sons, 543pp.

Robinson, A. H. and Thrower, N. J., 1969, "Annals Commentary", Annals of the Association of American Geographers, 59 (3), 600 - 606.

Robinson, A. H. and Thrower, N. J. W., 1957, "A New Method of Terrain Representation", Geographical Review, 47 (4), 507 - 520pp.

Rogers, D. F., 1988, Procedural Elements for Computer Graphics, McGraw-Hill, 433pp.

Saito, T. and Takahashi, T., 1990, "Comprehensible Rendering of 3-D Shapes", Computer Graphics, 24 (4), 197 - 206.

Salisbury, M. P., Anderson, S. E., Barzel, R. and Salesin, D. H., 1994, "Interactive Pen-and-Ink Illustration", Proceedings SIGGRAPH '94, 101 - 105.

Samet, H., 1984, "The Quadtree and Related Hierarchical Data Structures", ACM Computing Surveys, 16 (2), 187 - 260.

Sasada, T. T., 1987, "Drawing Natural Scenery by Computer Graphics", Computer-Aided Design, 19 (4), 212 - 218.

Schaal, H., 1988, "Computer Graphical Treatments of Perspective Pictures", Computers and Graphics, 12 (1), 15 - 31.

Scott, L., 1969, "Early Experience in the Photomapping Technique", Cartographic Journal, 6 (2), 108 - 113pp.

Segall, M. H., Campbell, D. T. and Herskovits, M. J., 1966, The Influence of Culture on Visual Perception, Bobbs-Merrill, 268pp.

Selley, G. L. C., 1991, Trees and Woods Image Generation System, Unpublished Ph. D. Thesis, Department of Graphic Design and Communication, Coventry School of Art and Design, Coventry Polytechnic, 127pp.

Shu, N. C., 1988, Visual Programming, Van Nostrand Reinhold Company, 315pp.

Skidmore, A. K., 1990, "Terrain Position as Mapped from a Gridded Digital Elevation Model", International Journal of Geographical Information Systems, 4 (1), 33 - 49.

Smith, A. R., 1984, "Plants, Fractals, and Formal Languages", Computer Graphics: A Quarterly Report of SIGGRAPH-ACM, 18 (3), 1 - 10.

Stacy, J. R., 1958, "Terrain Diagrams in Isometric Projection - Simplified", Annals of the Association of American Geographers, 48 (3), 232 - 236.

Stiny, G. and Mitchell, W. J., 1980, "The Grammar of Paradise: on the Generation of Mughul Gardens", Environment and Planning B: Planning and Design, 7, 209 - 226.

Stiny, G. and Mitchell, W. J., 1978, "The Palladian Grammar", Environment and Planning B: Planning and Design, 5, 5 - 18.

Stone, R. J., 1993, "Reality - Who Needs It?", IEE Review, November, 243 - 246.

Strassman, S., 1987, "Hairy Brushes", Computer Graphics: A Quarterly Report of SIGGRAPH-ACM, 20 (4), 225 - 232.

SUN Microsystems, 1991, Sun PHIGS 2.0 Programming Guide, Sun Microsystems (California).

SUN Microsystems, 1986, Sun GKS Reference Manual, Sun Microsystems (California).

Tanaka, K., 1950, "The Relief Contour Method of Representing Topography on Maps", Geographical Review, 40 (3), 444 - 456pp.

Tanaka, K., 1932, "The Orthographical Relief Method of Representing Hill Features on a Topographical Map", Geographical Journal, 79 (3), 214 - 219.

Thapa, K., 1988, "Automatic Line Generalisation using Zero Crossings", Photogrammetric Engineering and Remote Sensing, 54 (4), 511 - 517.

Thiemann, R., 1989, "Visualisation of Digital Terrain Data", Proceedings of Eurographics '89, 173 - 195.

Tribe, A., 1990, "Towards the Automated Recognition of Landforms (Valley Heads) from Digital Elevation Models", Proceedings of the 4th International Symposium on Spatial Data Handling (Zurich, Switzerland), Volume 1, 45 - 52.

Turnbull, W. M. and Gourlay, I., 1987, "Visual Impact Analysis: A Case Study of a Computer-based System", Computer-Aided Design, 19 (4), 197 - 202.

Upson, C., Faulhaber Jr., T., Kamins, D., Laidlaw, D., Schlegel, D., Vroom, J., Gurwitz, R. and van Dam, A., 1989, "The Application Visualization System: A Computational Environment for Scientific Visualization", IEEE Computer Graphics and Applications, 9 (4), 30 - 42.

Van Horn, E. K., 1985, "Generalising Cartographic Data Bases", Proceedings of Auto Carto 7, 532 - 540.

Van Zuylen, L., 1969, "Production of Photomaps", Cartographic Journal, 6 (2), 92 - 102pp.

Visvalingam M., 1994, "Visualisation in GIS, Cartography and ViSC", in Visualisation in Geographical Information Systems, Hearnshaw, H. and Unwin, D. J. (eds.), John Wiley and Sons Ltd., 18 - 25.

Visvalingam M. and Williamson P. J., 1994, "Generalising Roads on Large-Scale Maps: A Comparison of Two Algorithms", Cartographic Information Systems Research Group Discussion Paper 13, University of Hull.

Visvalingam, M. and Whyatt, J. D., 1993, "Line Generalization by Repeated Elimination of the Smallest Area", The Cartographic Journal, 30 (1), 46 - 51.

Visvalingam, M., 1991, "Visualisation, VISC and Scientific Insight", Cartographic Information Systems Research Group Discussion Paper 9, The University of Hull, 21pp.

Visvalingam, M. and Whyatt, J. D., 1991, "Cartographic Algorithms: Problems of Implementation and Evaluation and the Impact of Digitising Errors", Computer Graphics Forum, 10 (3), 225 - 235.

Visvalingam, M., 1990, "Trends and Concerns in Digital Cartography", Computer Aided Design, 22 (3), 115 - 130.

Visvalingam, M. and Whyatt, J. D., 1990, "The Douglas-Peucker Algorithm for Line Simplification: Re-evaluation through Visualisation", Computer Graphics Forum, 9 (3), 213 - 228.

Voss, R., 1985, "Random Fractal Forgeries", Fundamental Algorithms for Computer Graphics, Earnshaw, R. A. (ed.), Springer-Verlag, Berlin, 805 - 835.

Wainwright, A. and Brabbs, D., 1991, Wainwright's Favourite Lakeland Mountains, Michael Joseph, 216pp.

Wainwright, A., 1973, A Coast to Coast Walk (St. Bees Head to Robin Hood's Bay): A Pictorial Guide, Westmorland Gazette, 168pp.

Walton, J., 1993, "Now You See It - Interactive Visualization of Large Datasets", NAG Technical Report TR4/93, 14pp.

White, E. R., 1983, "Perceptual Evaluation of Line Generalisation Algorithms", Unpublished Masters Thesis, University of Oklahoma.

Whitted, T., 1980, "An Improved Illumination Model for Shaded Display", Communications of the ACM, 23 (6), 343 - 349.

Whyatt, J. D., 1991, Visualisation and Re-evaluation of Line Simplification Algorithms, Unpublished Ph. D. Thesis, The Department of Computer Science, The University of Hull, 259pp.

Whyatt, J. D. and Wade, P. R., 1988, "The Douglas-Peucker Line Simplification Algorithm", Bulletin of The Society of University Cartographers, 22 (1), 17 - 25.

Willats, J., 1990, "The Draughtsman's Contract: How an Artist Creates an Image", Images and Understanding: Thoughts About Images, Ideas About Understanding, Barlow, H., Blakemore, C. and Weston-Smith, M. (eds.), Cambridge University Press, 235 - 254.

Williams, L., 1983, "Pyramidal Parametrics", Computer Graphics: A Quarterly Report of SIGGRAPH-ACM, 17 (3), 1 - 11.

Winkenbach, G. and Salesin, D. H., 1994, "Computer-Generated Pen-and-Ink Illustration", Proceedings of SIGGRAPH '94, 91 - 100.

Winterbotham, H. S. L., 1939, A Key to Maps (2nd edition), Blackie and Son Limited, 214pp.

Wolff, R. S. and Yaeger, L., 1993, Visualization of Natural Phenomena, Springer-Verlag, 374pp.

Yoeli, P., 1967, "The Mechanisation of Analytical Hill Shading", The Cartographic Journal, 4 (2), 82 - 88.

Appendix A

Types of System

The aim of this appendix is to provide examples of the terrain visualisation techniques offered by different kinds of system. The four main categories of software which can produce terrain visualisations are presented below. Each category is illustrated by one or more example systems. Other types of system which could potentially be used are CAD (Computer Aided Design) systems, which are usually used to design objects such as machine parts, and paint systems. Paint systems allow the creation of two-dimensional images by methods that are analogous to the artist's use of brush and paint and also include image processing algorithms to allow image manipulation (Friedhoff and Benzon, 1989). With paint systems the ratio of artistic skill to mathematics is greatly increased as is the amount of manual effort necessary. This appendix also describes why computer graphics standards were chosen for use in this research project.

A.1 GIS

The Chorley Report defines Geographical Information Systems (GIS) as systems for "capturing, storing, checking, integrating, manipulating, analysing and displaying data which are spatially referenced to the Earth," (HMSO, 1987). Coppock and Anderson (1987) describe GIS as "a rapidly developing field lying at the intersection of many disciplines - among them cartography, computing, geography, photogrammetry, remote sensing, statistics, surveying and other disciplines concerned with handling and analysing spatially referenced data." The production of maps and terrain visualisation is only part of the functionality of a GIS.

Arc/Info is a widely used GIS. In Arc/Info graphical output is produced by the "Arcplot" program. Arc/Info can be used to produce many different types of map (see Appendix E in ESRI (1990) for a selection of sample maps). However, only the facilities available for the visualisation of terrain are described here. Regular grid data, referred to as a "lattice" in Arc/Info, can be used as can irregularly spaced data. The TIN program (ESRI, 1991) creates TINs using Delauney triangulation. In most cases the visualisation of a TIN involves its automatic conversion to a lattice through the use of interpolation.

A number of methods are provided for two-dimensional terrain visualisation. A lattice can be visualised as a pseudo-coloured grid while a TIN can be visualised as a wireframe or with shaded triangles. Two-dimensional contouring and analytical hill shading can be applied to both lattices and TINs. For three-dimensional visualisation sets of profiles parallel to the X or Y axis may be drawn and the spacing between profiles can be set. Both sets of profiles may be combined to form a mesh or fishnet which is draped over the terrain. The sets of profiles forming the mesh/fishnet may alternatively be drawn diagonally. Other three-dimensional surface views are produced by draping two-dimensional visualisations over the terrain surface. Three-dimensional contouring is performed by draping the set of two-dimensional contours over the terrain. Hill shading is produced in the same way and similarly a satellite image could be draped over the terrain as could other two-dimensional images. A three-dimensional image of a TIN, shown as a wiremesh, is also achieved by draping. Methods may be combined, for example hill shading may be draped over the terrain followed by the draping of a set of contour lines. Point and vector data may also be draped.

Other examples of GIS are SPANS, GRASS and the object-oriented SmallWorld GIS (Chance *et al.*, 1990).

A.2 TURNKEY VISUALISATION SYSTEMS

Turnkey visualisation systems are characterised by attractive user interfaces, ease of use and the speed at which results can be obtained. However, in general such systems cannot be modified or extended and often only provide part of the solution a user requires (Brodlie *et al*, 1992). Unimap 2000 is such a system. Unimap is part of the UNIversal RASter system (UNIRAS). UNIRAS software can be used for the presentation and visualisation of a wide range of data. UNIRAS consists of a Fortran library containing more than 450 subroutines and a set of interactive programs that use this library. Unimap is a system for spatial data visualisation. Other UNIRAS programs exist for drawing graphs (Unigraph) and for editing pictures (Uniedit).

Unimap can handle both irregularly spaced and regular grid data though most methods of visualisation available can only be used with the latter. For this reason several interpolation methods are provided to convert irregularly spaced data into a regular grid.

The only visualisation method applicable solely to irregularly spaced data is the two-dimensional "dot map" which shows the position of each point. A "grid map" can be produced from both types of data. When regular grid data is used each square of the grid is coloured depending on altitude. With irregularly spaced data only squares which data points fall in are coloured. Regular grid data is required for "line" and "contour" maps. A "line map" shows contour lines on a plain background while a "contour map" produces layer shading. Three-dimensional views can be produced of "grid", "line" and "contour" maps. A three-dimensional "grid" map corresponds to the three-dimensional histogram method and is the only three-dimensional method which can also be used for irregularly spaced data. Figure A.1 shows the Unimap system and this method of visualisation.

Three-dimensional views utilise perspective, hidden line removal and may be viewed from any position. It is possible with such views to determine how dramatic, on a scale of one to ten, are the effects of perspective. Unimap can also produce oblique projections. The projection usually appears on the top face of the box which surrounds a three-dimensional visualisation.

Unimap also allows the production of four-dimensional maps. This is where the first three variables determine the form of a surface and another, fourth variable, determines its colour. For example the fourth variable might show temperature via pseudo-colouring. Maps may be labelled, titled, accompanied by a key and have appropriate axes. One of the predefined colour palettes may be selected and can be modified or a user defined palette may be used.

While UNIRAS software is currently based on the non-standard UNIRAS library they have indicated a commitment to base future products on PHIGS+ (Brodlie, 1988).

Other turnkey visualisation systems include NCSA tools, PV-WAVE and Data Visualiser (Brodlie *et al.*, 1992).

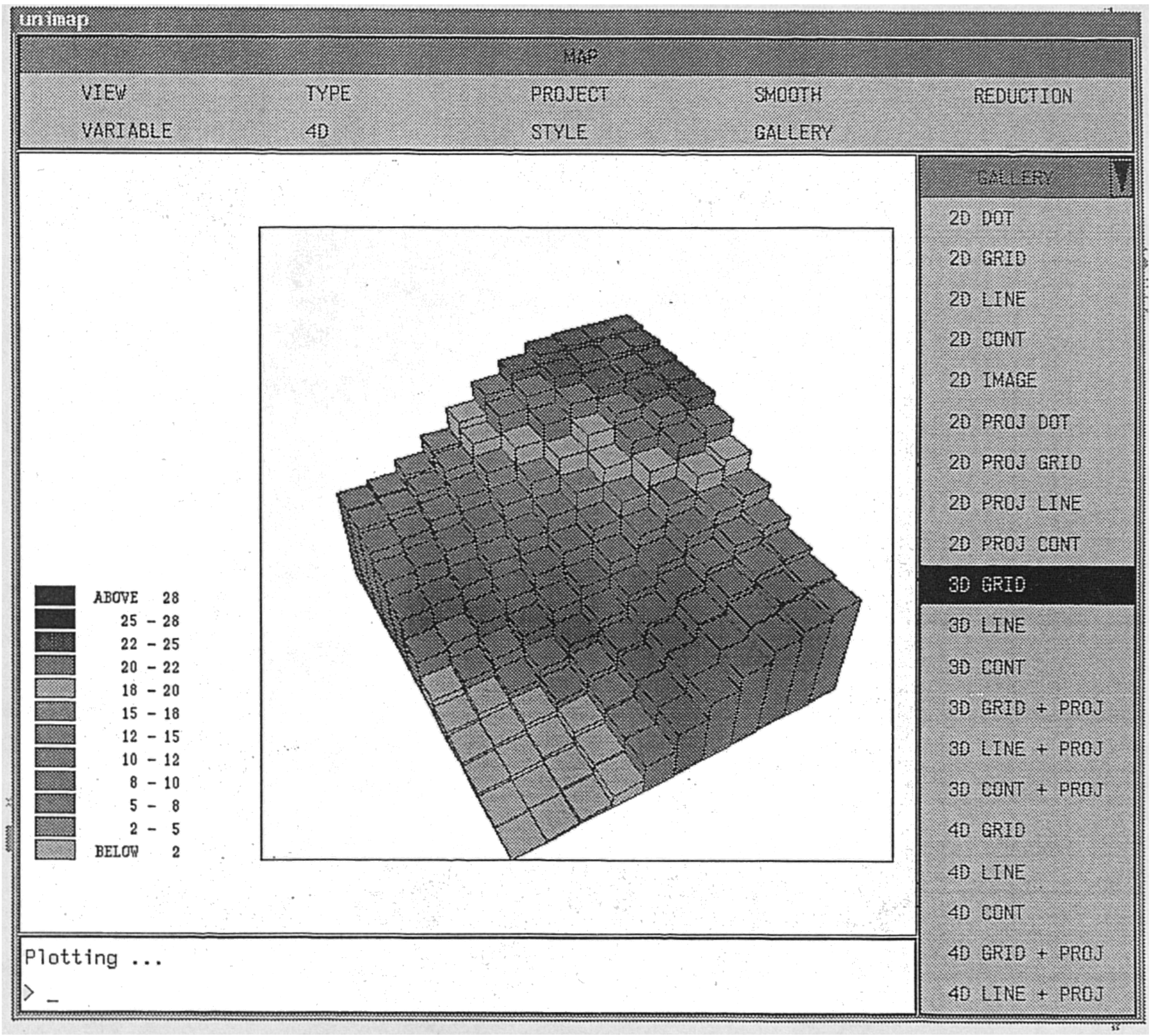


Figure A.1: The Unimap System.

A.3 APPLICATION BUILDER VISUALISATION SYSTEMS

The current trend in visualisation systems is the application builder. This type of system allows users from different fields to easily and quickly design visualisation programs suitable for their own needs through the use of a visual programming language (Shu, 1988). Users do not require traditional programming skills in order to be able to use a system like this. A dataflow paradigm is used. "In this approach, the user interactively creates the application in the form of a network of modules. Each module is a software routine that performs a specific function on its input data, and produces some output. The network controls the way in which the data flows between modules - *i.e.* how the output from one module is the input to another. A module will usually perform a substantial amount of data processing, which means that ... typical networks will only contain a small number of modules," (Walton, 1993). "New applications can be prototyped very quickly by connecting modules in different ways," (Brodlie *et al.*, 1992). Application builders are extendable. If no module exists to perform a required task a module can be written and added to the system. Existing modules can also be replaced by user-written ones. However, the writing of modules may be a non-trivial task requiring a great deal of knowledge about the application builder visualisation system.

Khoros is an application builder written at the University of New Mexico and is available in the public domain. Figure A.2 shows a typical Khoros screen. Khoros was used in the early stages of the research to visualise terrain extracts in three dimensions. The visual programming environment in Khoros is called "Cantata" and the small boxes which represent each module in the visual programming language are termed "glyphs". Each glyph has three small icons at the top. The leftmost one is used to delete the glyph, the middle one brings up a form where information is entered to instantiate the glyph, and the rightmost icon is used to turn the glyph on or off. Khoros uses its own internal file format called "viff" (Visualisation / Image File Format). For more detailed information on the Khoros visualisation system see Rasure and Young (1992) or the Khoros manual.

The module used for display was "xprism3". Xprism3 offers several different methods of display; 3D, scatter, impulse, mesh, colour mesh, surface, horizon, contour 2D and contour 3D. The axes can be changed and labels added, plots can be titled and with large extracts subsets of the data can be viewed.

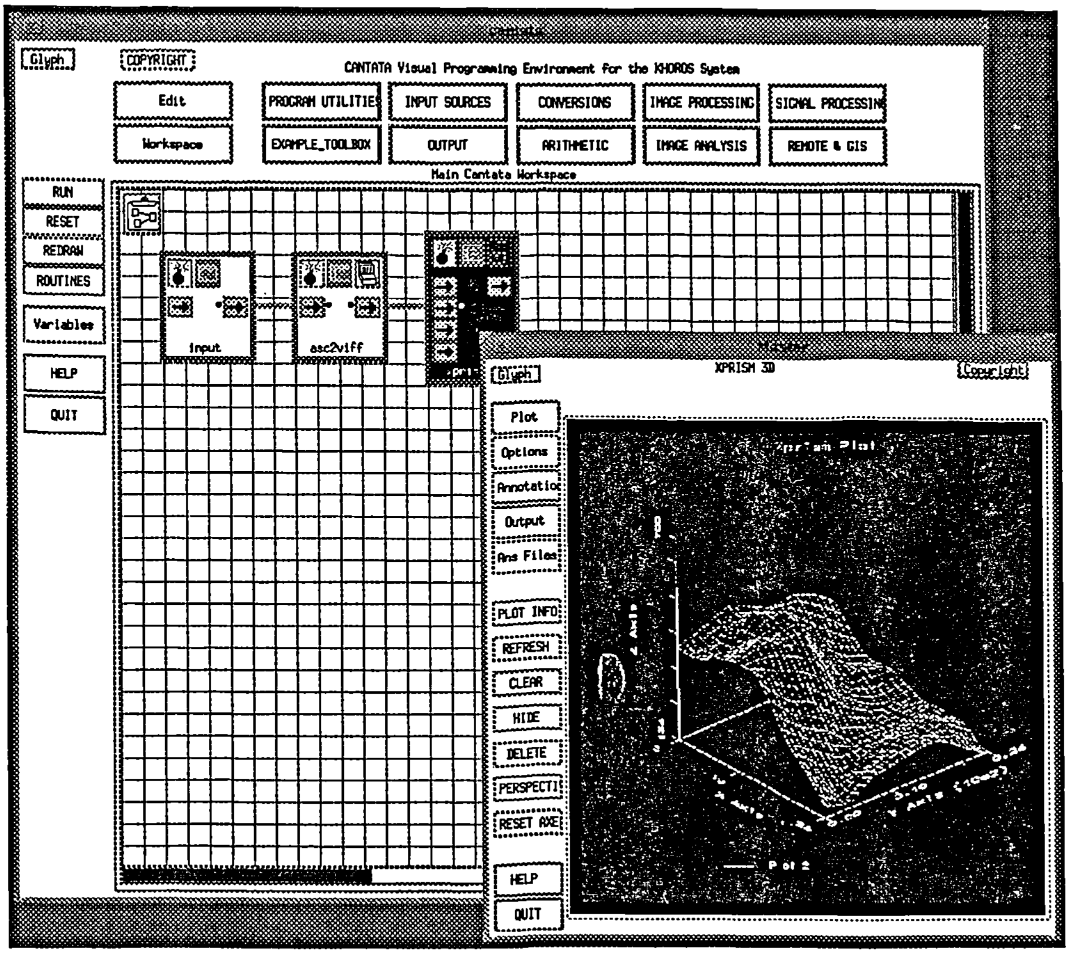


Figure A.2: The Khoros visualisation system.

Khoros is an application builder written at the University of New Mexico and is available in the public domain. Figure A.2 shows a typical Khoros screen. Khoros was used in the early stages of the research to visualise terrain extracts in three dimensions. The visual programming environment in Khoros is called "Cantata" and the small boxes which represent each module in the visual programming language are termed "glyphs". Each glyph has three small icons at the top. The leftmost one is used to delete the glyph, the middle one brings up a form where information is entered to instantiate the glyph, and the rightmost icon is used to turn the glyph on or off. Khoros uses its own internal file format called "viff" (Visualisation / Image File Format). For more detailed information on the Khoros visualisation system see Rasure and Young (1992) or the Khoros manual.

Xprism3 also allows the extract to be viewed from any position.

Other application builder visualisation systems include AVS (Upson *et al.*, 1989), Iris Explorer (Edwards, 1992) and apE (Dyer, 1990).

Application builders are still relatively new and are only now starting to mature. They do however offer great potential as they appear to offer all the flexibility and extensibility of the subroutine libraries with the ease of use of the turnkey systems. Many new developments are expected in this form of product in the next few years (Brodlie *et al*, 1992).

A.4 COMPUTER GRAPHICS STANDARDS

Another means for producing terrain representations is through the use of computer graphics standards. A graphics standard provides a library of graphics subroutines which can be called by an application program to perform tasks such as drawing lines, filling areas, changing colours, *etc.* These routines are used in application programs through other standards called language bindings. These define how the functions are called from a particular language, such as C, Fortran, Pascal or ADA. The purpose of a computer graphics standard is to ensure the portability of software across different platforms. There are many graphics libraries which are not standards such as GL, UNIRAS and the NAG graphics library. The previous systems described are at a higher level of abstraction and could be built on top of graphics standards.

A number of graphics standards exist. These are GKS, GKS-3D, PHIGS, CGM and CGI (Arnold and Duce, 1990). The first three of these are for the production of computer graphics. The CGM (Computer Graphics Metafile) standard allows the storage of pictures for later use or transfer to another system. The CGI (Computer Graphics Interface) standard provides a standard interface between the device-independent and device-dependent parts of an implementation (Brodlie, 1988).

GKS became the world's first international computer graphics standard in 1985 having taken over ten years of development (Arnold and Duce, 1990) GKS provides only rudimentary two-dimensional graphics. However, GKS can still be used to produce images which have a three-dimensional effect but this must be due to the efforts of the programmer. The advantage of GKS is its simplicity and ease of use.

GKS-3D is an extension of GKS, designed to provide similar functions but for three dimensions. PHIGS is another standard for the production of three-dimensional graphics. It is also modelled on GKS but is more elaborate than GKS-3D. For many applications GKS-3D is relatively straightforward to use, but its limitations become apparent when more complex displays are required. "In contrast, PHIGS permits graphical data to be hierarchically structured. It is targeted at high-performance displays and workstations and caters for dynamic picture editing and display. This, however, makes it more difficult to use," (Hubbold and Hewitt, 1988).

GKS-3D and PHIGS do not provide facilities for generating complex shaded images. However, PHIGS has been extended with a set of features for modern, pseudo-realistic rendering of objects on raster displays; this extension is called PHIGS PLUS (where PLUS is an acronym for Plus Lumiere Und Surfaces - some authors actually use the plus sign and write "PHIGS+" instead). PHIGS PLUS enhances PHIGS by providing: primitives for lighting models; shading of surfaces; depth cueing; primitives for defining curves and surfaces; additional control of colour specification and interpretation (Howard, 1991). "The fact that PHIGS+ has such extensions explains why a number of manufacturers are emphasising their support for it rather than for GKS-3D," (Hubbold and Hewitt, 1988). However, this increased functionality brings increased complexity.

Foley *et al.* (1990) believes that PHIGS will have "much more influence on interactive 3D graphics than will GKS-3D". Brodlie (1988) states that relatively few implementations of GKS-3D are expected, chiefly because the US graphics community has put its weight behind PHIGS. Hubbold and Hewitt (1988) confirm this - "several manufacturers have chosen to by-pass GKS-3D and go straight to PHIGS for 3-D graphics".

The advantage of graphics libraries is their flexibility and direct control but they suffer from the disadvantages of the large amount of time invested in writing and supporting code (Brodlie *et al.*, 1992). The flexibility provides means for experimentation and prototyping.

A.5 SYSTEMS USED IN THIS PROJECT

Turnkey visualisation systems cannot be modified or extended. They are limited to a fixed set of visualisation techniques which excludes them from use in a research project of this nature. This problem is remedied by application builder visualisation systems which allow new modules to be added. However, in the past, when this research was began, it was felt that such products were too immature and the writing of modules too difficult. Over the past few years such systems have developed making them the most attractive of the alternatives presented here because they facilitate experimentation through rapid prototyping. The creation of new modules is made easier in systems such as Iris Explorer where special features are provided to aid in this task. The sketching pipeline shown in figure 3.2 could be implemented in such a system as a visual program containing a number of custom written modules. New modules can also be written for GIS such as Arc/Info but these systems do not provide the quick prototyping capabilities of application builder visualisation systems. However, the technique of producing artistic sketches described in this thesis could be added to future GIS as an additional method of terrain representation.

Graphics libraries were used to conduct this research because of the flexibility and direct control which they allow. Two graphics standards were used; GKS, the Graphical Kernel System, (Hopgood, 1986; Bono, 1990) and PHIGS, the Programmer's Hierarchical Interactive Graphics Standard, (Hopgood and Duce, 1991; Gaman and Giovinazzo, 1991). SunGKS (SUN Microsystems, 1986) was the implementation of GKS used. SunPhigs (SUN Microsystems, 1991) was the PHIGS implementation used. SunPhigs also provides PHIGS PLUS functionality. A C language binding was used with both standards.

Appendix B

Test Data

B.1 INITIAL TESTING

The feasibility of the sketching technique described in this thesis was initially tested using several very small (10 x 10) DEMs containing artificial data. Figure B.1 shows some of these while figure B.2 shows the corresponding sketches. Testing then progressed to using increasingly larger extracts of real terrain data.

B.2 THE PORT TALBOT DEM

The Ordnance Survey of Great Britain release sample data for a 5km x 5km area around Port Talbot, Wales. This data consists of a regular grid DEM and a set of contour lines. Only a quarter of this dataset was used because the rest is relatively flat. Details of this DEM are shown in table B.1.

Ordnance Survey 1:10,000 contour data has a 5m interval (10m in mountainous areas) and is used for DEM creation.

B.3 THE WEST POINT DEM

The other DEM is part of a larger United States Geological Survey (USGS) 7.5 minute DEM which models the terrain around West Point, New York. An interesting area containing features at different scales was selected from the full DEM. Details of this DEM are shown in table B.2.

100	100	200	300	400	400	300	200	100	100
100	100	200	300	400	400	300	200	100	100
100	100	200	300	400	400	300	200	100	100
100	100	200	300	400	400	300	200	100	100
100	100	200	300	400	400	300	200	100	100
100	100	200	300	400	400	300	200	100	100
100	100	200	300	400	400	300	200	100	100
100	100	200	300	400	400	300	200	100	100
100	100	200	300	400	400	300	200	100	100
100	100	200	300	400	400	300	200	100	100

(a)

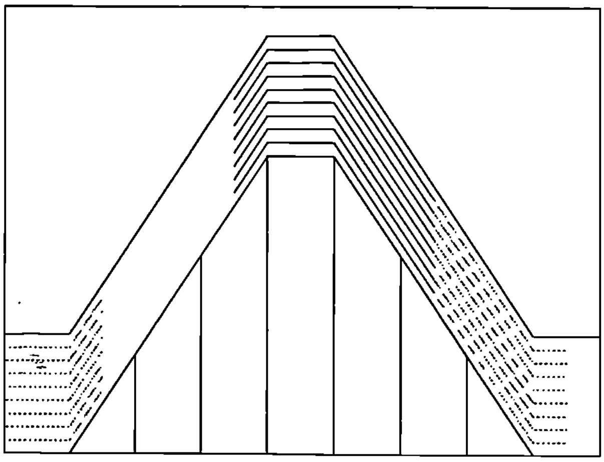
400	400	300	200	100	100	100	100	100	100
300	400	400	300	200	100	100	100	100	100
200	300	400	400	300	200	100	100	100	100
100	200	300	400	400	300	200	100	100	100
100	100	200	300	400	400	300	200	100	100
100	100	100	200	300	400	400	300	200	100
100	100	100	100	200	300	400	400	300	200
100	100	100	100	100	200	300	400	400	300
100	100	100	100	100	100	200	300	400	400
100	100	100	100	100	100	100	200	300	400

(b)

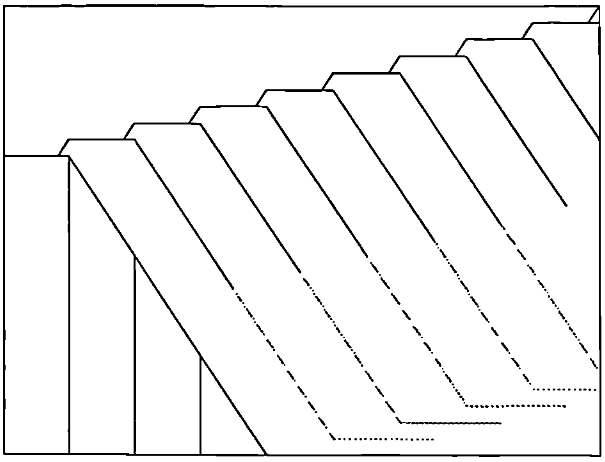
300	300	300	300	300	300	300	300	300	300
300	200	200	200	200	200	200	200	200	300
300	200	100	100	100	100	100	100	200	300
300	200	100	300	300	300	300	100	200	300
300	200	100	300	400	400	300	100	200	300
300	200	100	300	400	400	300	100	200	300
300	200	100	300	300	300	300	100	200	300
300	200	100	100	100	100	100	100	200	300
300	200	200	200	200	200	200	200	200	300
300	300	300	300	300	300	300	300	300	300

(c)

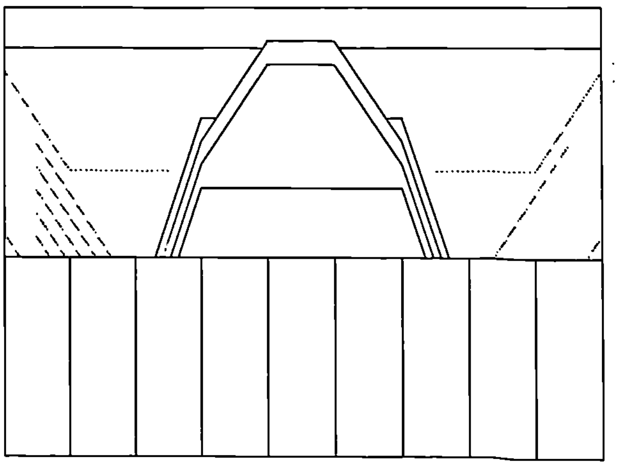
Figure B.1: Small artificial DEMs: (a) a ridge running parallel to line of sight; (b) a ridge running diagonally across the DEM; (c) a crater with a plateau rising in its centre



(a)



(b)



(c)

Figure B.2: Sketches of small artificial DEMs: (a) a ridge running parallel to line of sight; (b) a ridge running diagonally across the DEM; (c) a crater with a plateau rising in its centre

Port Talbot DEM	
size	250 x 250
scale	1 : 10,000
grid spacing	10m
vertical resolution	10cm
maximum elevation	255.9m
minimum elevation	4.2m

Table B.1: Statistics for Ordnance Survey DEM.

West Point DEM	
size	201 x 201
scale	1 : 24,000
grid spacing	30m
vertical resolution	1m
maximum elevation	492.0m
minimum elevation	0.0m

Table B.2: Statistics for United States Geological Survey DEM.

In orthophotomapping it is necessary to generate elevations to remove parallax effects. USGS DEMs are created in this way, as a "by-product of an orthophotomapping program" Mark (1984, p.170).

B.4 A TERRAIN PROFILE

The terrain profile used in chapter 4 is taken from the 1:24,000 USGS West Point DEM. It consists of 302 points which are 30m apart. The maximum elevation is 463.0m and the minimum elevation is 0.0m.

Appendix C

The Variation of Sketch Parameters

C.1 THE EXTENSION RULES

In section 3.3.1.3 three rules for extending strings of core cells were described. These were:

1. no further extension.
2. add one additional cell to give minimally extended strokes.
3. extend each string by adding cells up to and including the next cell of effective area zero or of opposite sign. This gives fully extended strokes.

Figure E.1 shows sketches of the Port Talbot DEM, viewed from the west. Only +parallel profile strokes are drawn, using a tolerance of 1000 for core cell selection. (a) - (c) illustrate each of the rules.

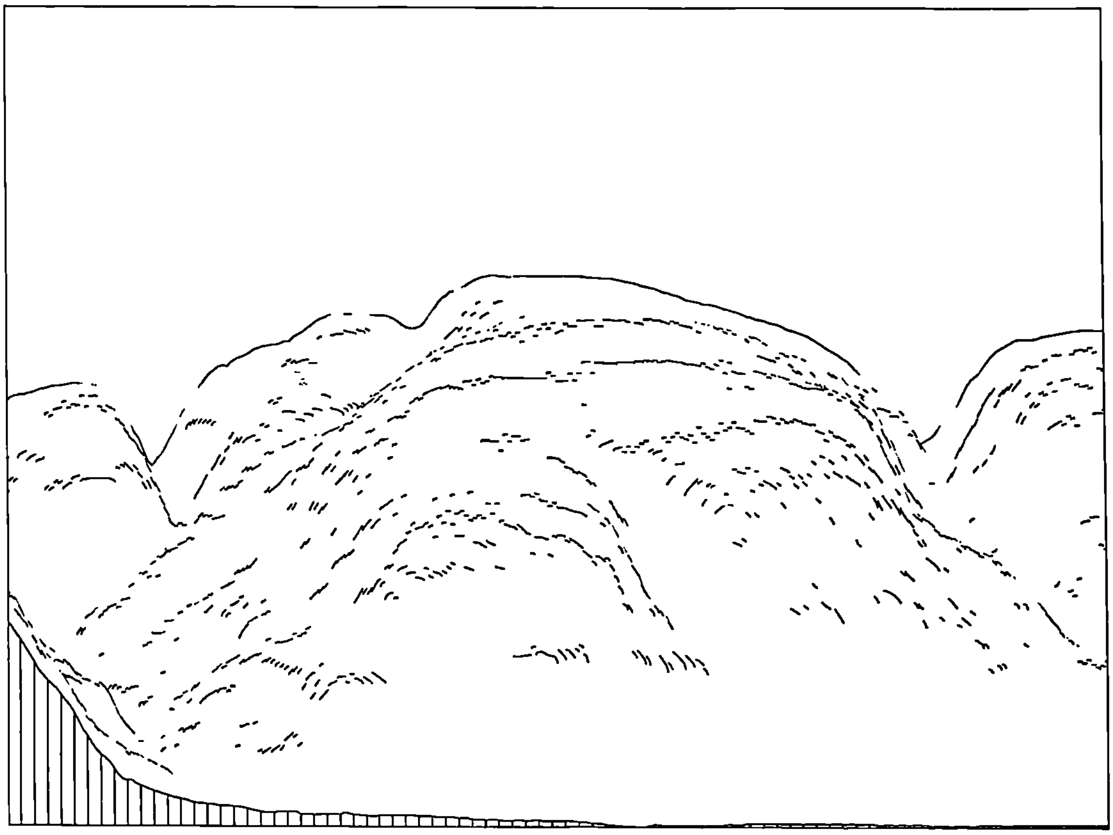


Figure C.1(a) No extension to either side.

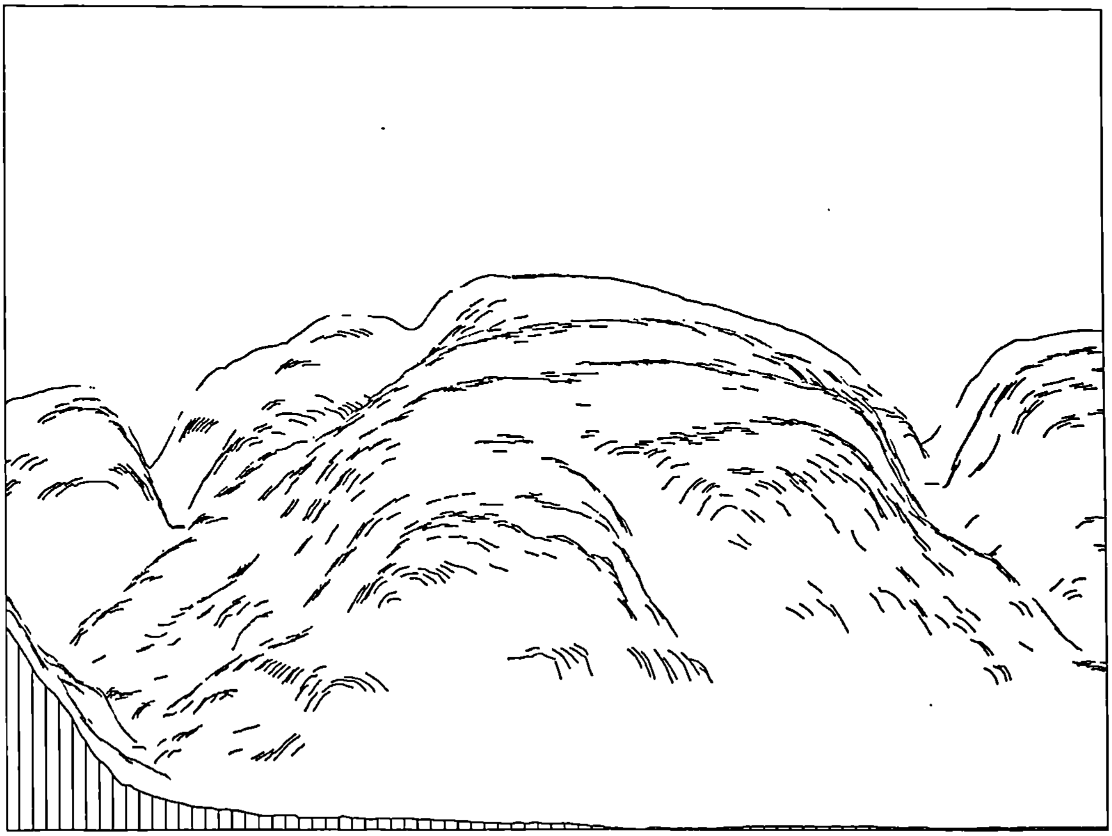


Figure C.1(b) Minimal extension to the right and left.

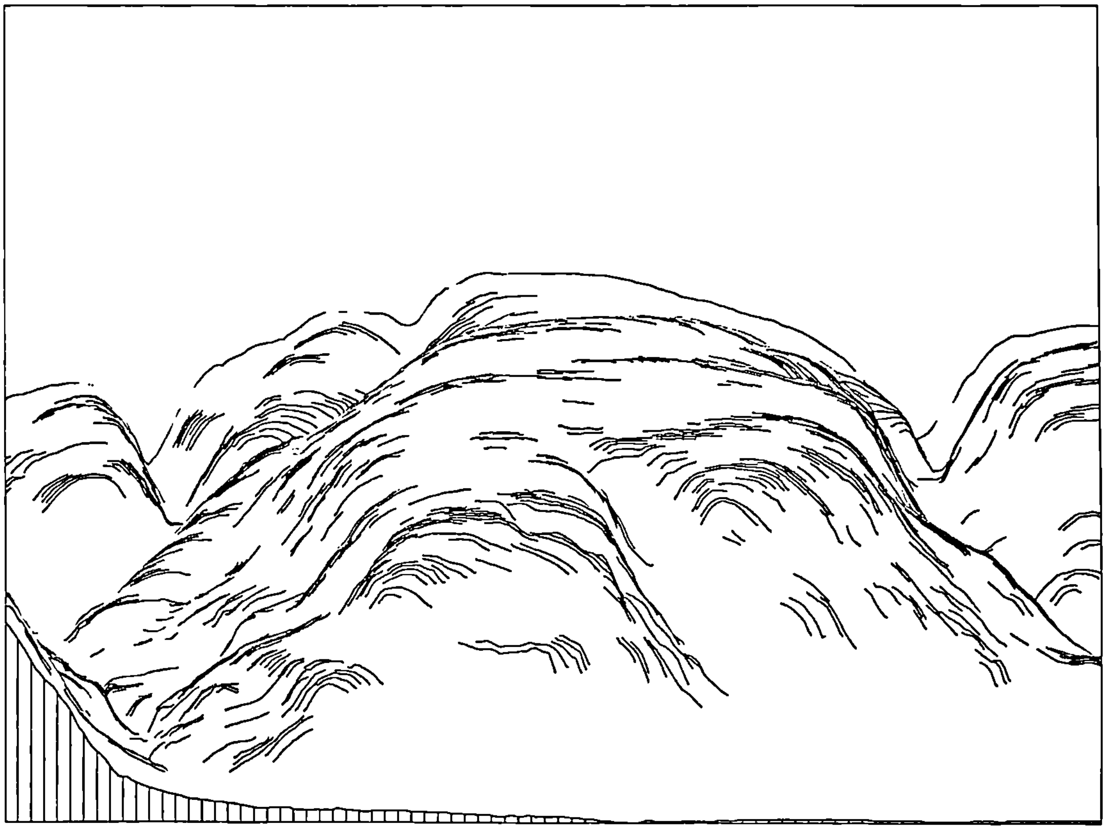


Figure C.1(c) Full extension to the right and left.

C.2 DIRECTION OF EXTENSION

Strings of core cells can be extended to either the left, the right or in both directions (see section 3.3.1.3). This section provides examples of extending strings of core cells in these directions however, to make the effects more easily visible the orthogonal profile strokes have been extended fully. The other sketching parameters are as shown in table 4.3.

In Figure E.2 orthogonal p-strokes are extended in the directions shown in table 4.3. In figure E.3 the directions have been reversed while in figure E.4 orthogonal p-strokes are extended in both directions.

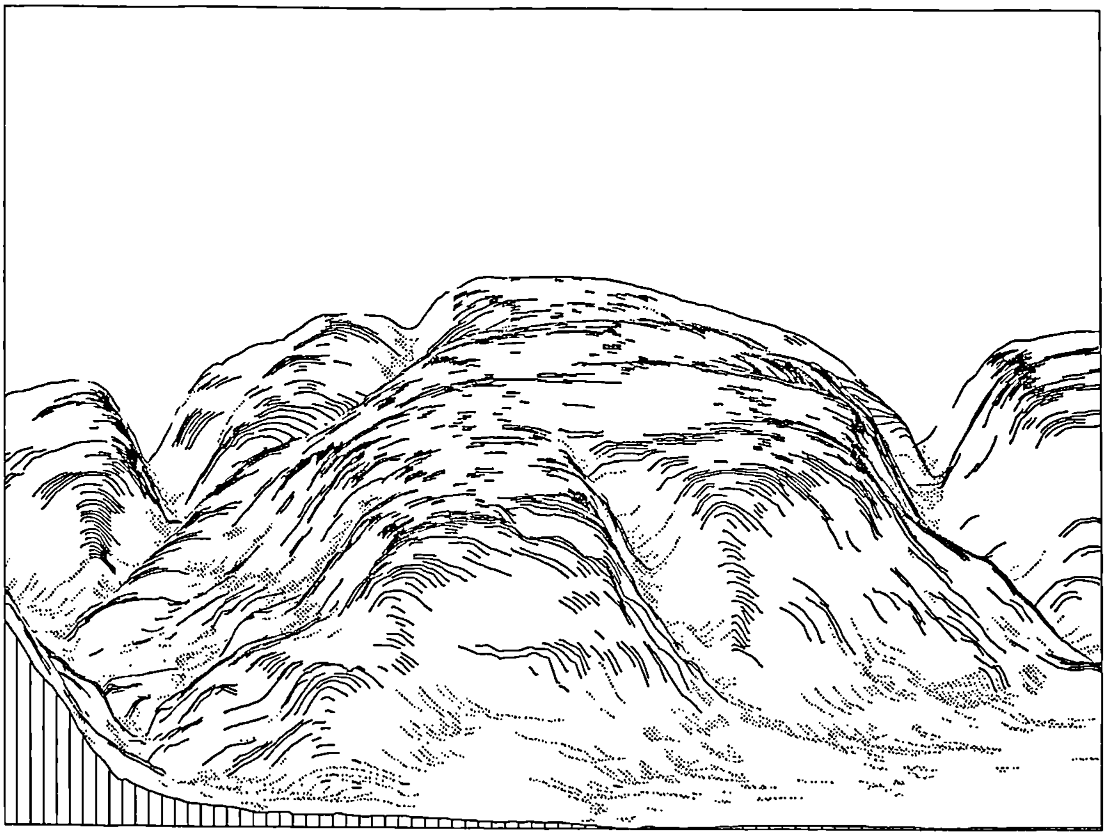


Figure C.2(a): Sketch of Port Talbot DEM from the west, +orthogonal p-strokes fully extended to the right and -orthogonal p-strokes fully extended to the left.

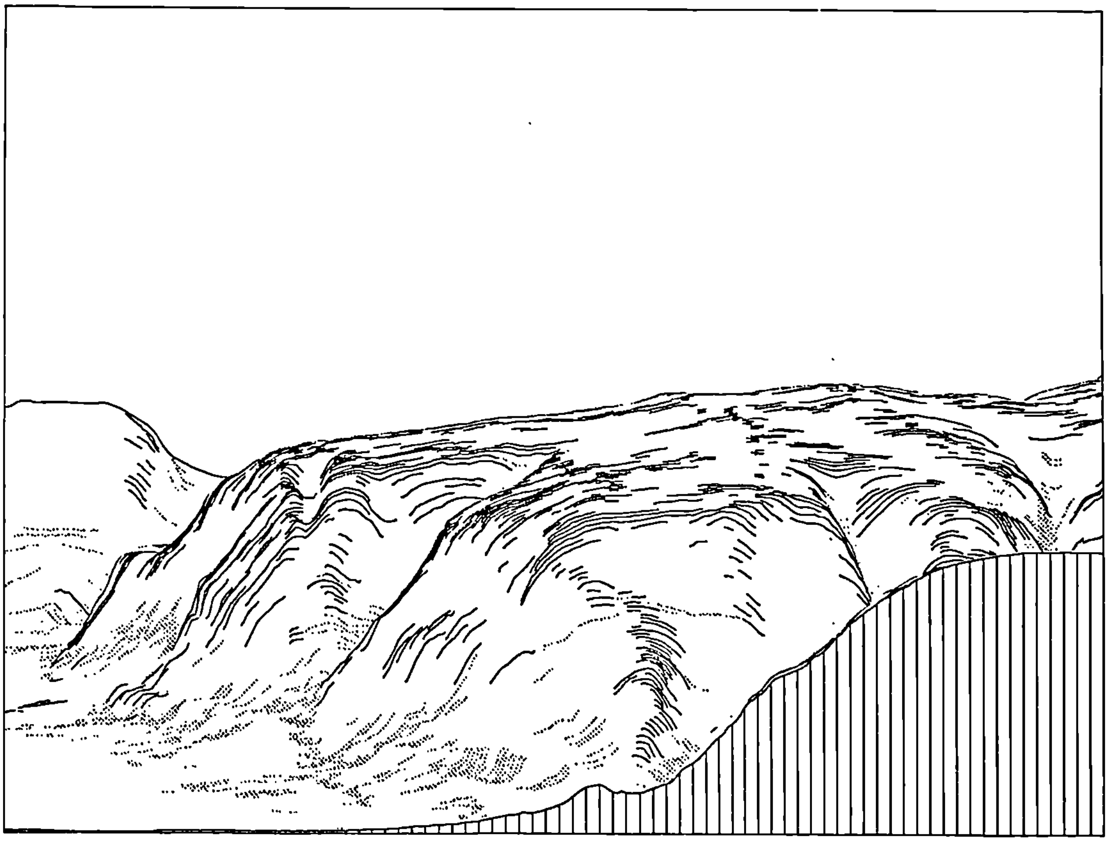


Figure C.2(b): Port Talbot DEM viewed from the south, +orthogonal p-strokes fully extended to the right and -orthogonal p-strokes fully extended to the left.

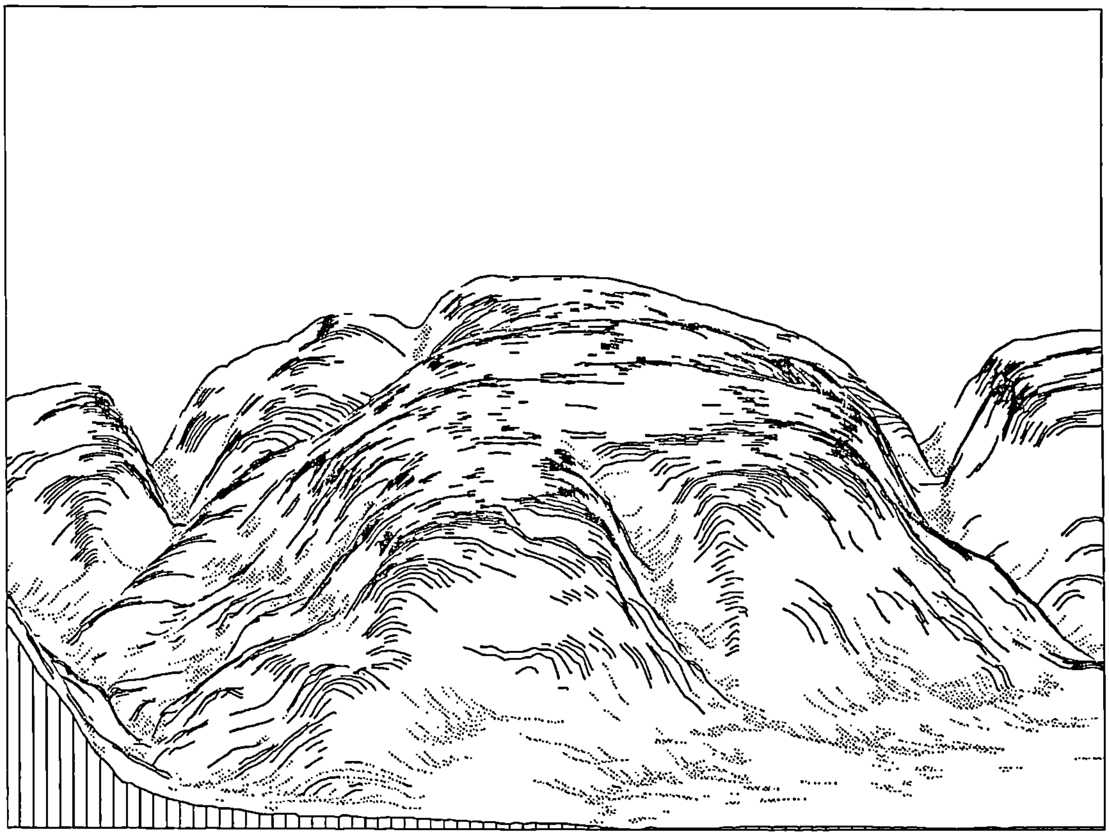


Figure C.3(a): Sketch of Port Talbot DEM from the west, +orthogonal p-strokes fully extended to the left and -orthogonal p-strokes fully extended to the right.

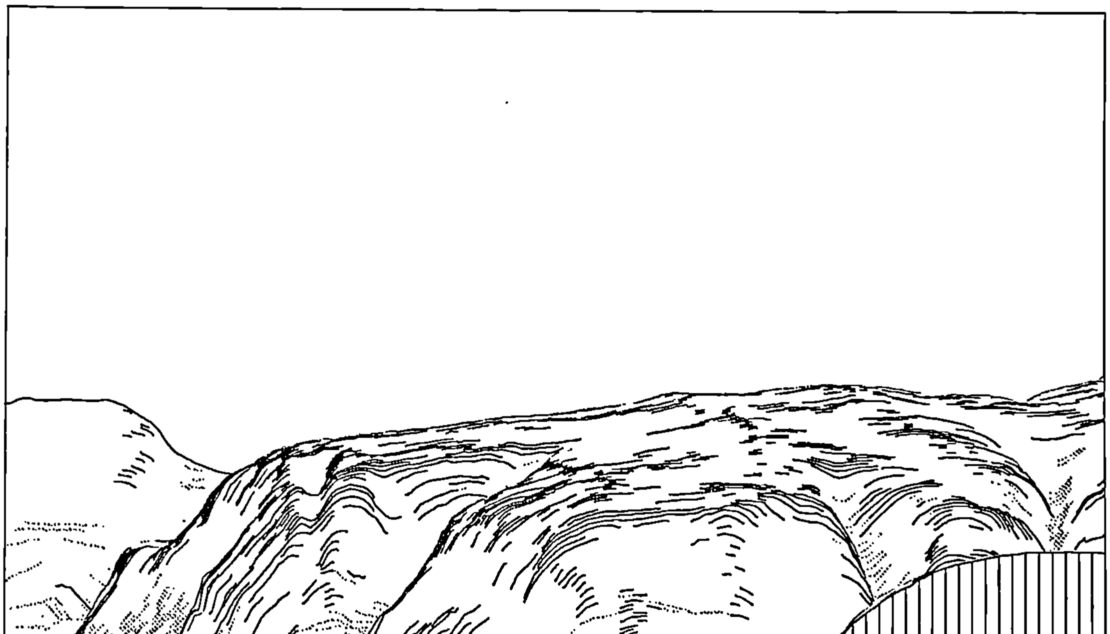


Figure C.3(b): Port Talbot DEM viewed from the south, +orthogonal p-strokes fully extended to the left and -orthogonal p-strokes fully extended to the right.

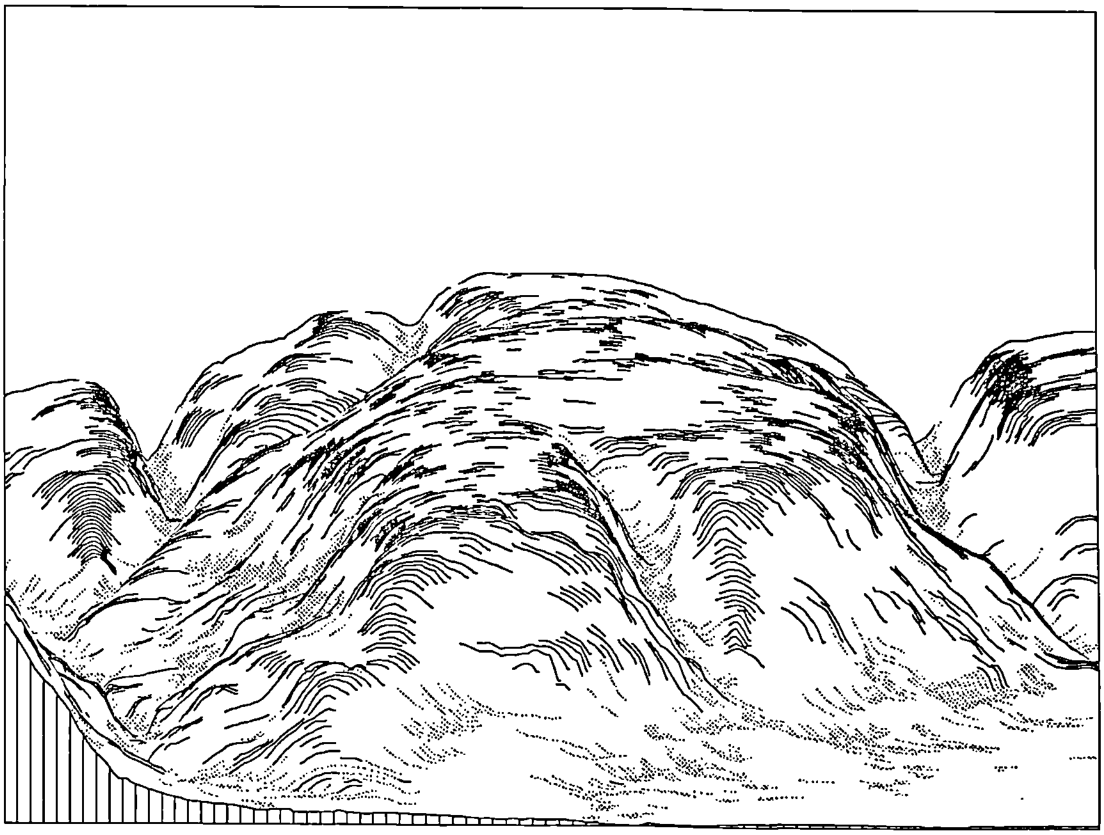


Figure C.4(a): Sketch of Port Talbot DEM from the west, orthogonal p-strokes fully extended to right and left.

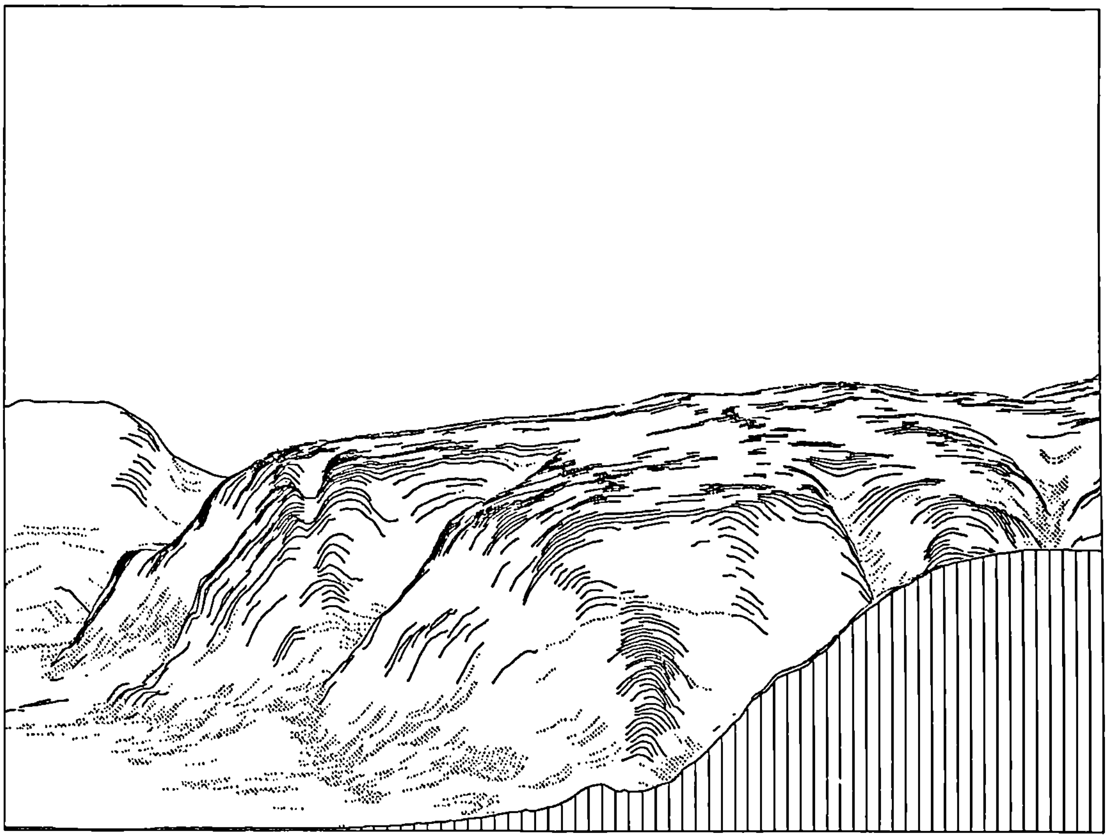


Figure C.4(b): Port Talbot DEM viewed from the south, orthogonal p-strokes fully extended to right and left.

C.3 PROFILE STROKE SYMBOLISM

The sketching parameters in table 4.3 differentiate between positive and negative profile strokes by using different symbolism. While this is desirable (see section 3.3.2) sketches can be produced using the same symbolism for each type of p-stroke. Figure E.5(a) uses solid black lines for all of the p-strokes.

Figure E.5(b) - (d) shows the use of an alternative p-stroke symbolism. So far all p-strokes have been represented by polylines which followed the terrain profiles however, the new symbolism consists of rows of short vertical lines. In (b) - (d) this symbolism is used for –parallel p-strokes which indicate convexities perpendicular to the viewer. This alternative symbolism allows the distinction of types of convexity and can improve the depiction of terrain form.

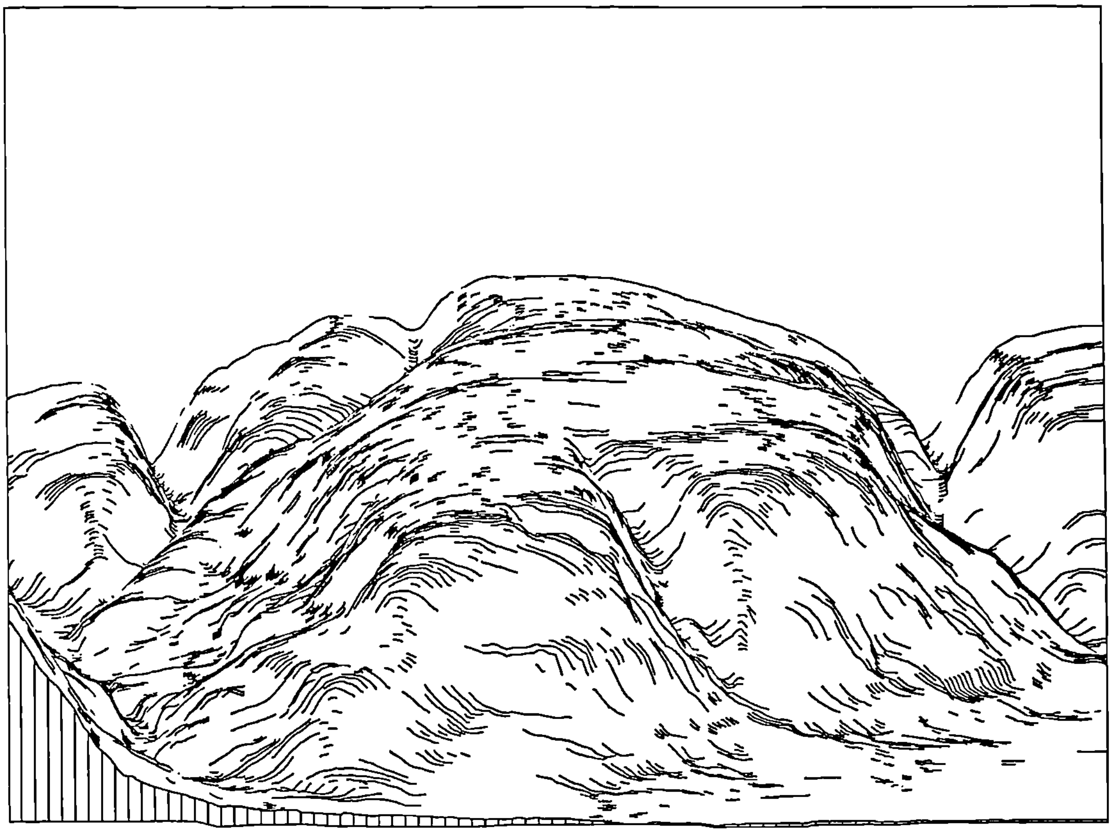


Figure C.5(a) All p-strokes are solid black lines.

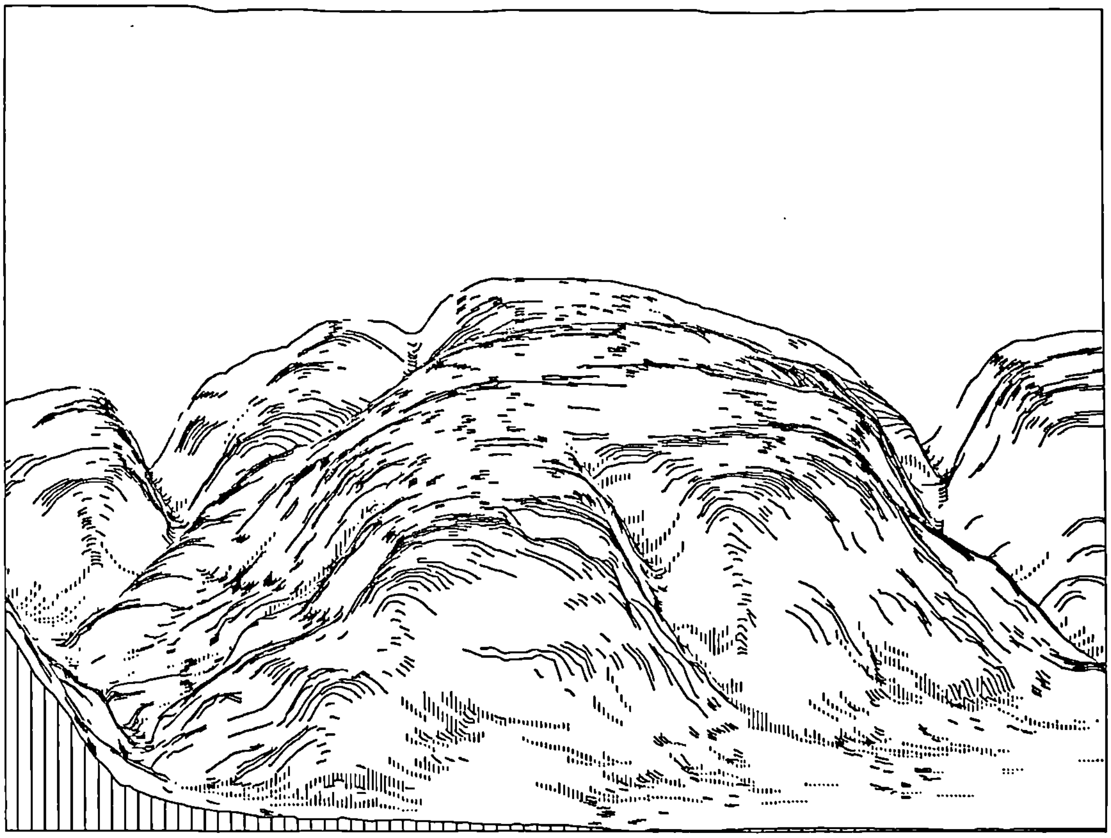


Figure C.5(b): Sketch of Port Talbot DEM from the west, –parallel p-strokes symbolised by vertical lines.

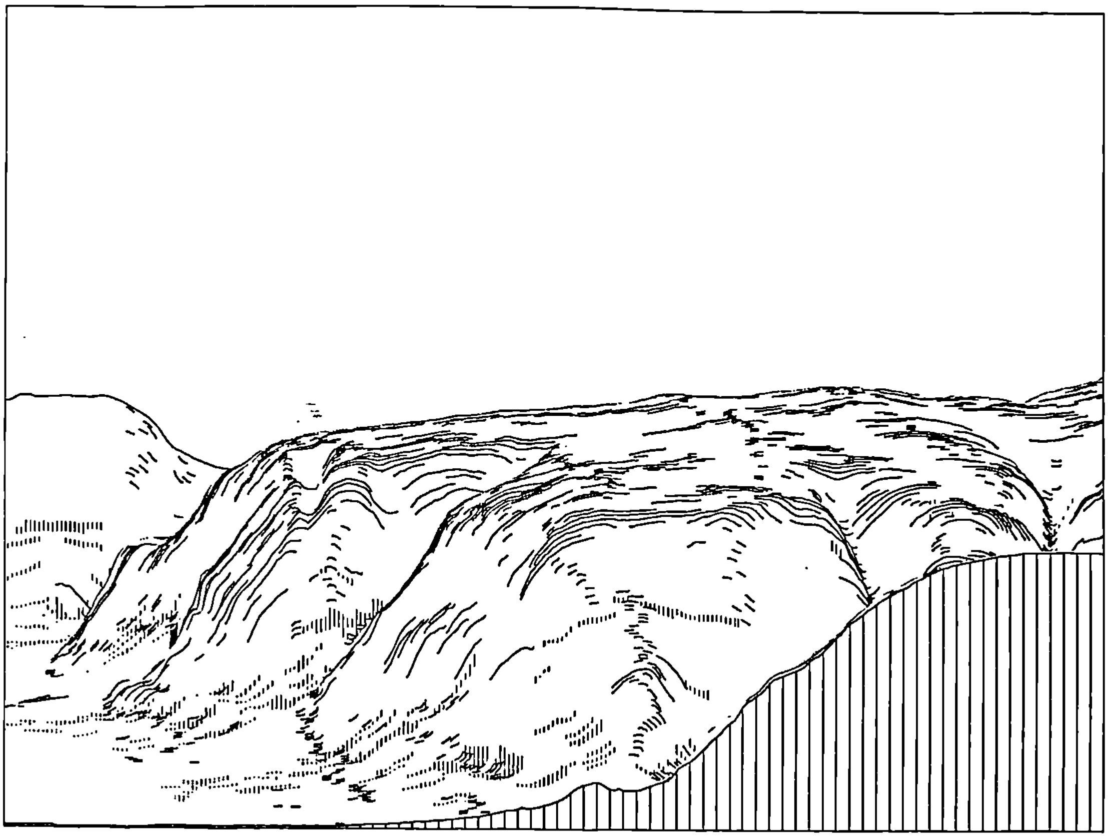


Figure C.5(c): Port Talbot DEM viewed from the south, –parallel p-strokes symbolised by vertical lines.

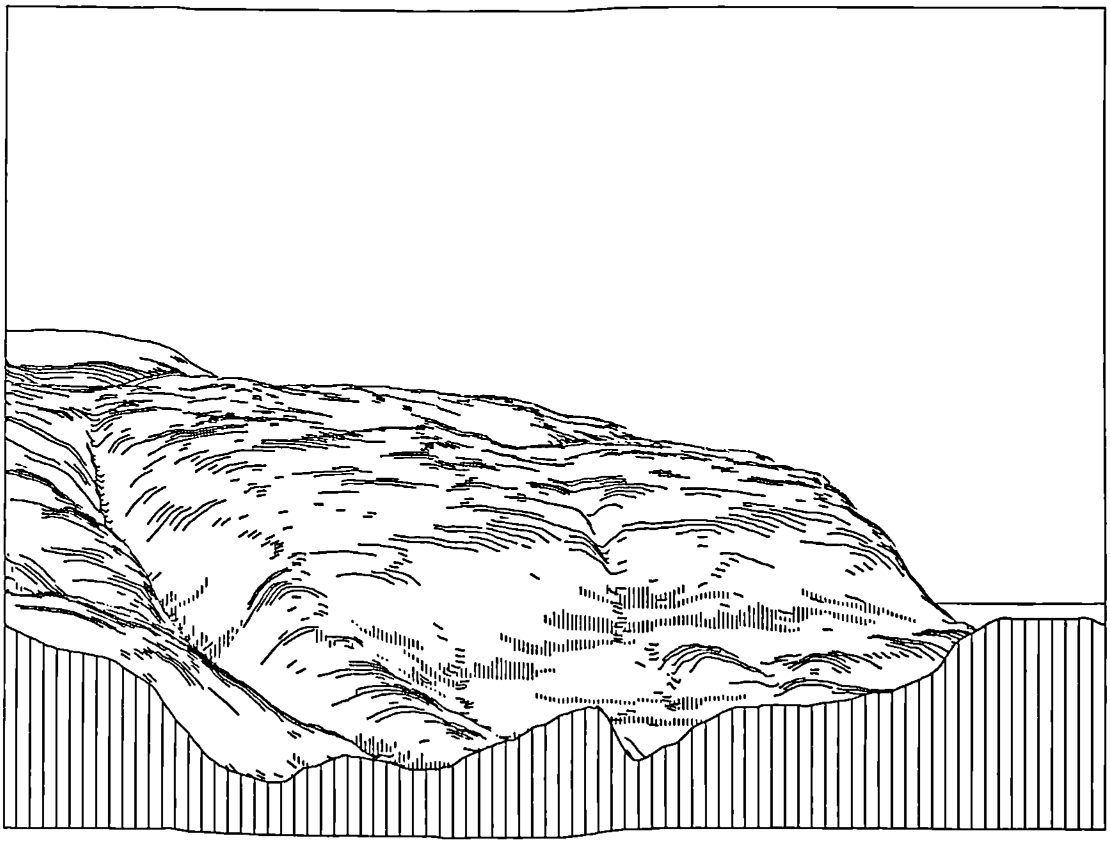


Figure C.5(d): Port Talbot DEM viewed from the north, –parallel p-strokes symbolised by vertical lines.

C.4 TOLERANCE VARIATION

Figure E.6 shows the effect of varying the tolerances used for core cell selection. The sketching parameters used for both of these sketches are shown in table 4.3 while table E.1 contains the tolerance values and corresponding number of core cells selected.

User-Specified Tolerance Values				
	Figure E.2(a)		Figure E.2(b)	
	Tolerance	Core Cells	Tolerance	Core Cells
+parallel	5000	786	200	3151
+orthogonal	20000	233	800	1166
-orthogonal	20000	239	800	1141
-parallel	20000	411	800	1510

Table C.1: User-specified tolerances control the number of core cells selected.

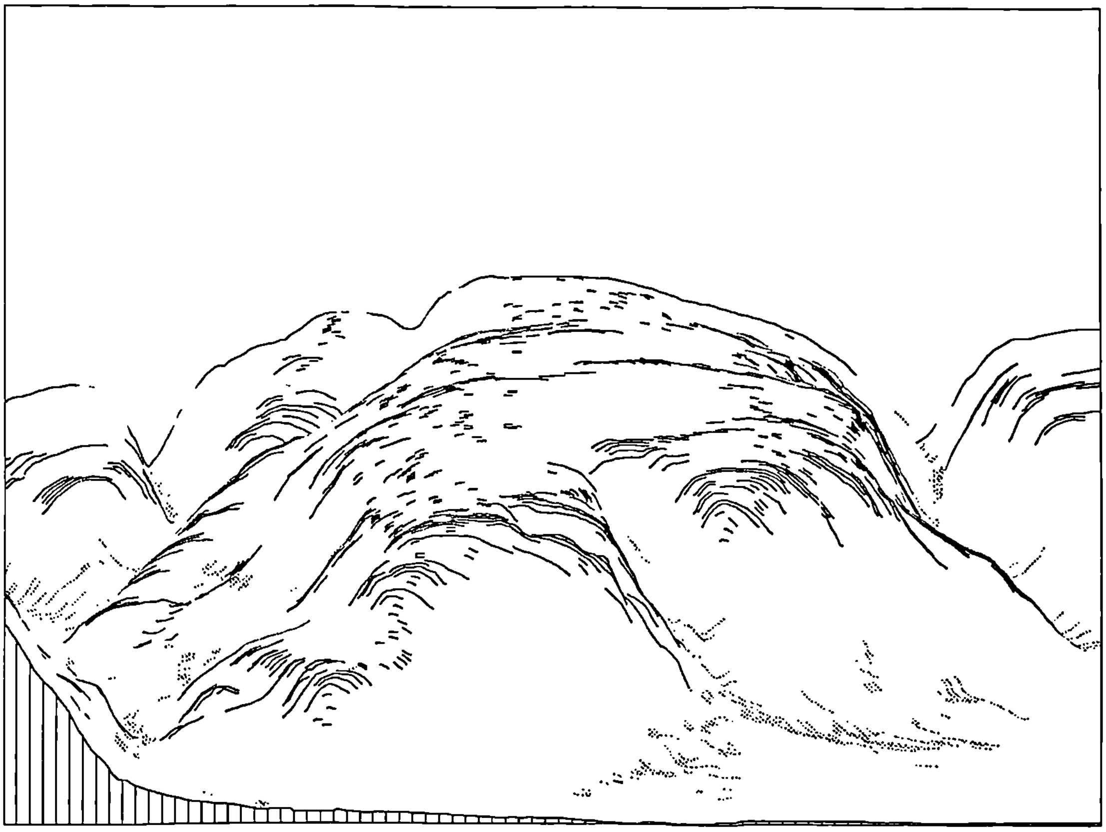


Figure C.6(a) Increasing user-specified tolerance values.

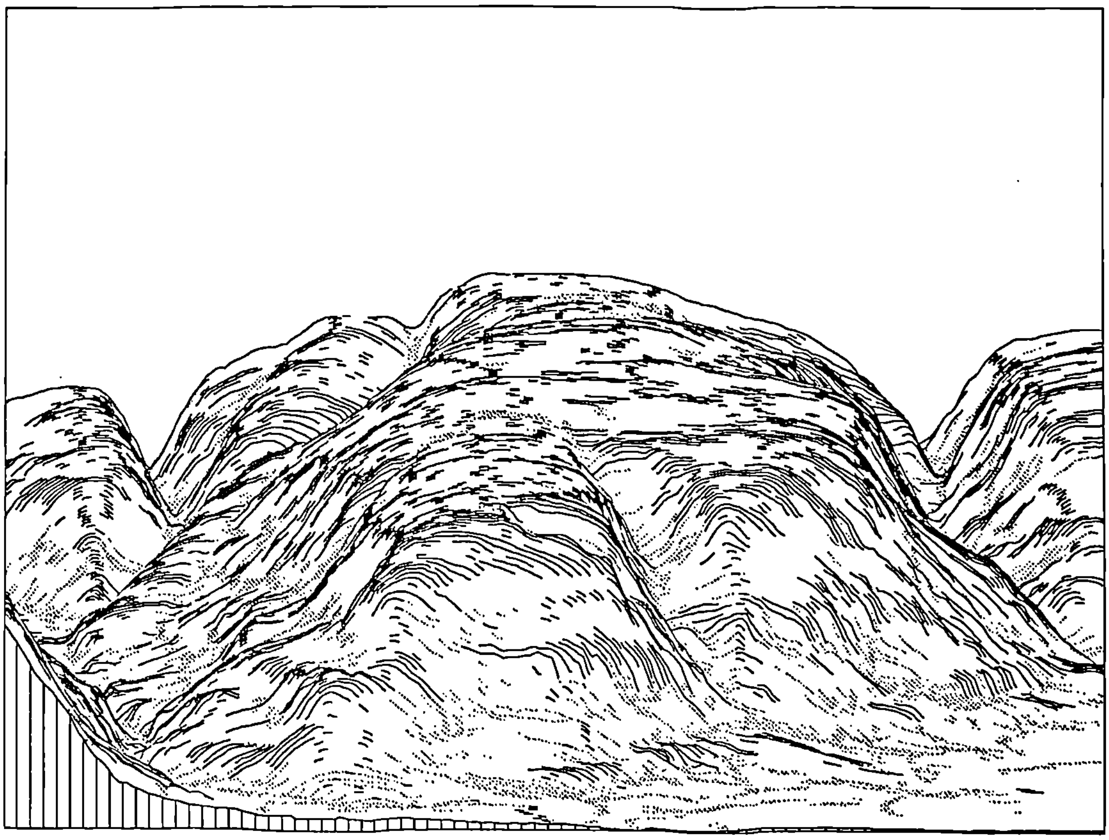


Figure C.6(b) Decreasing user-specified tolerance values.

C.5 PROFILE SEPARATION

Figure E.7 shows the effect of varying the separation between terrain profiles. Because a vertical oblique projection is used, a large profile separation gives the impression of a sketch made from a high point of view and vice versa. As previously noted, a very large separation produces a map-like effect.

Figure E.7 shows several sketches of the Port Talbot DEM with different profile separations, drawn with the sketching parameters shown in table 4.3. Previous figures showing the Port Talbot DEM used a profile separation of 2m while those showing the West Point DEM, in chapter 5, used a profile separation of 15m.

Figure E.8 shows a sketch of the Port Talbot DEM from the east. Usually, a view from this direction is obscured by highland close to the viewer but by using a separation of 10m the hidden terrain is revealed.

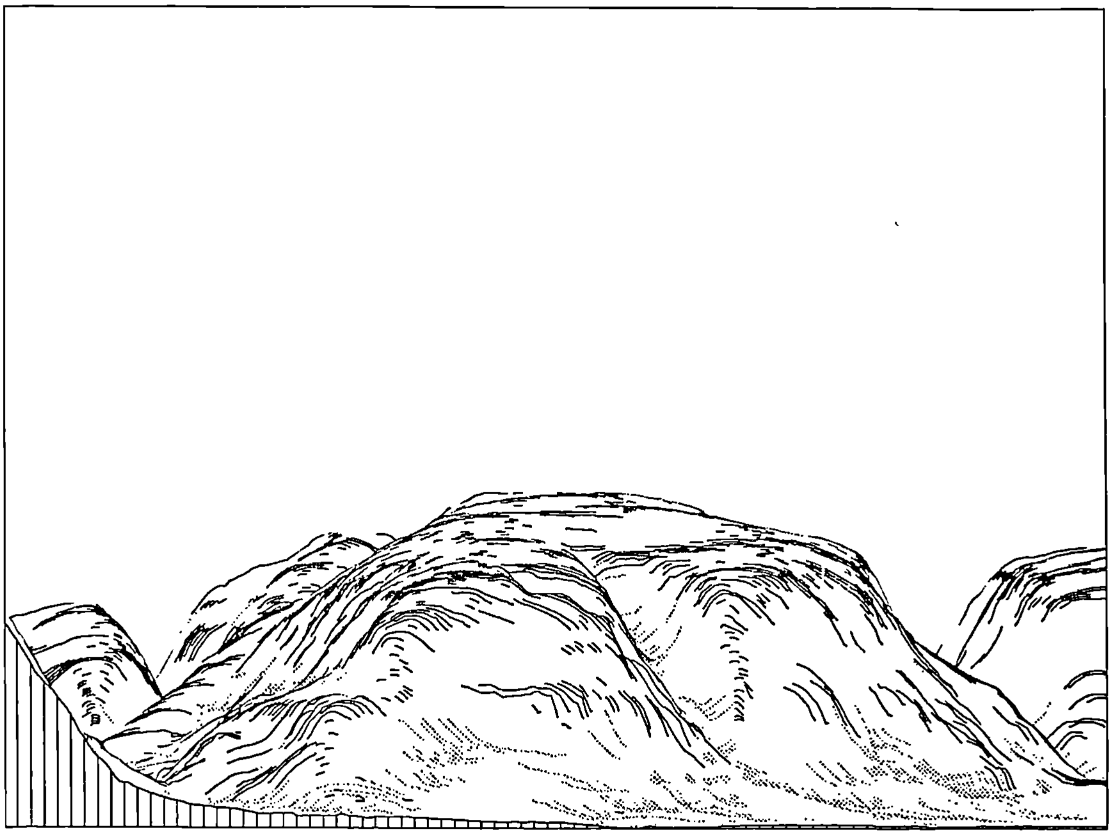


Figure C.7(a): Sketch of Port Talbot DEM, from the west, with a profile separation of 0m.

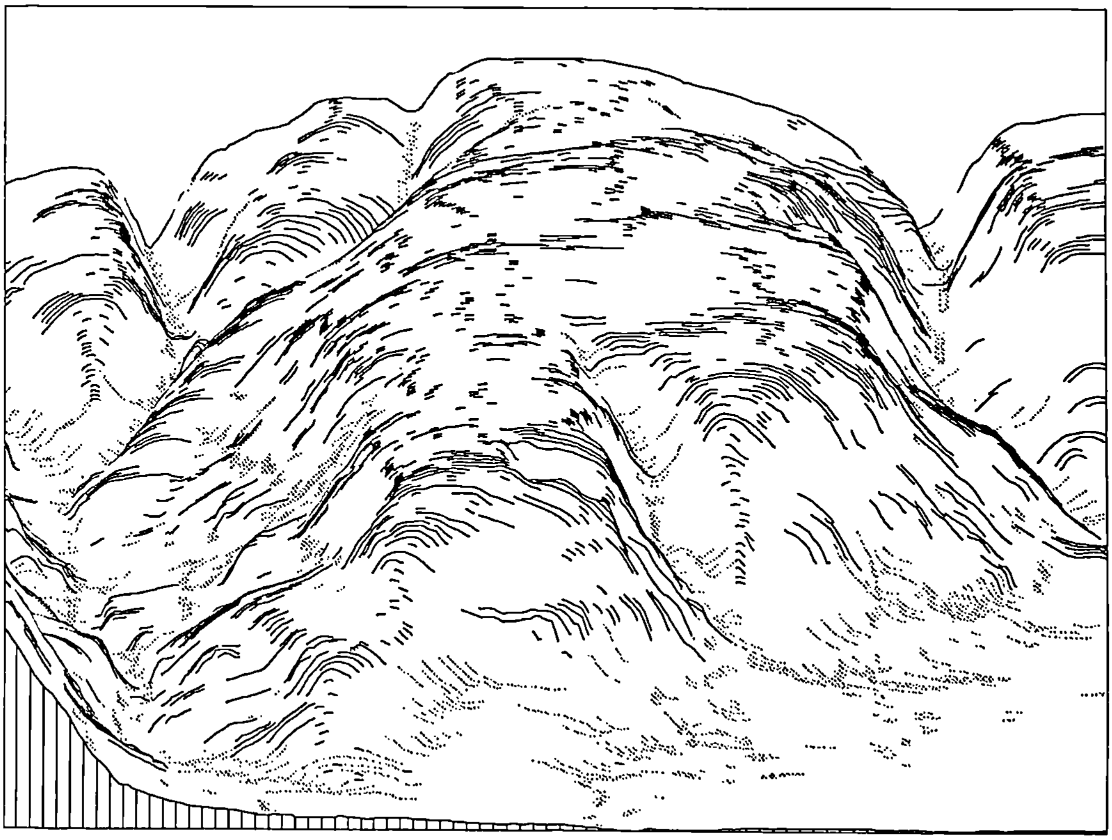


Figure C.7(b): Sketch of Port Talbot DEM, from the west, with a profile separation of 4m.

Figure C.7(c): Sketch of Port Talbot DEM, from the west, with a profile separation of 6m.

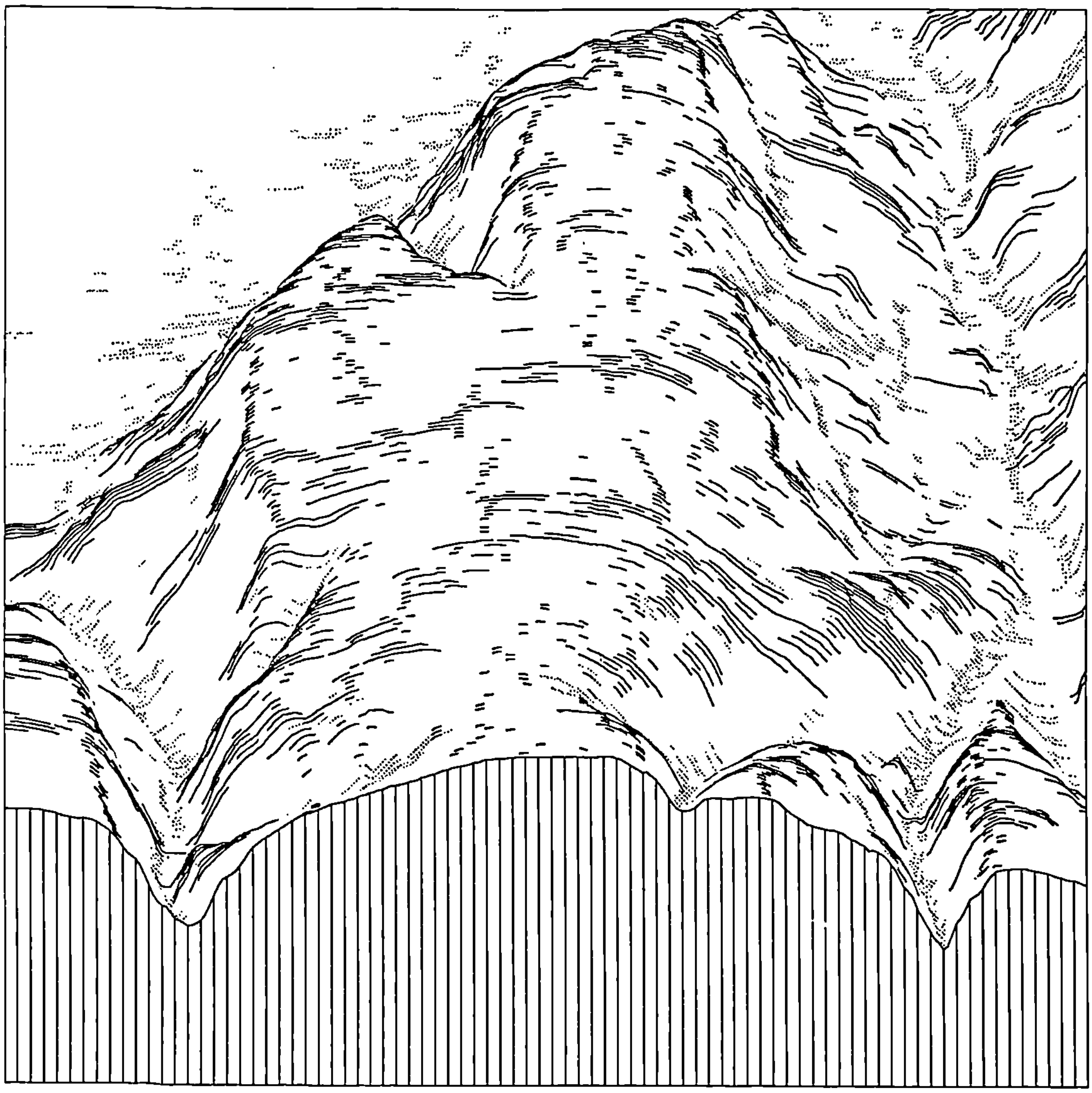


Figure C.8: Sketch of Port Talbot DEM, from the east, with a profile separation of 10m.

E.6 VERTICAL EXAGGERATION

Vertical exaggeration was discussed in section 3.3.1.3. Figure E.9 shows the effect of varying vertical exaggeration. Previous figures for both the Port Talbot and West Point DEMs used a vertical exaggeration of times three. Figure E.9 uses the sketching parameters shown in table 4.3. (a) shows the terrain without any vertical exaggeration while (b) shows an over exaggerated terrain (seven times). Clearly, neither of these is appropriate.

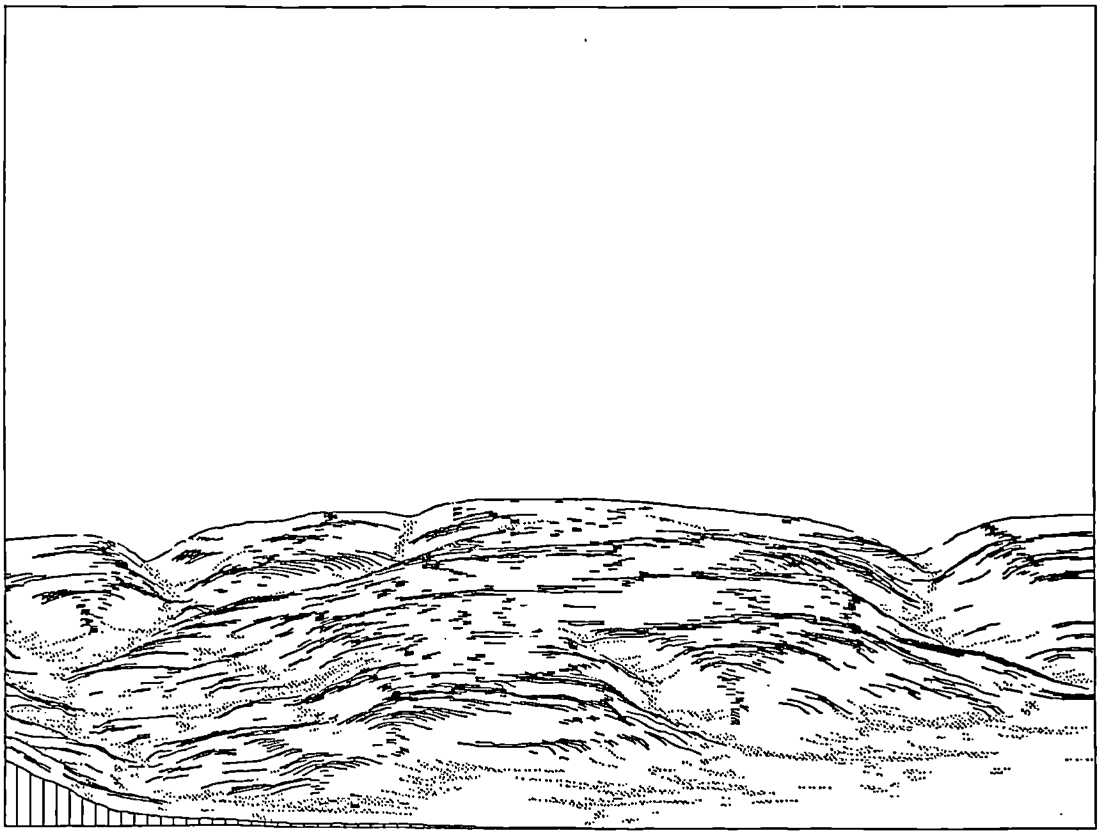


Figure C.9(a) No vertical exaggeration (x1).

Figure C.9(b) Too much vertical exaggeration (x7).