6 Visualisation of High Resolution DEMs for Landform Mapping

6.1 Introduction

With the increased availability of digital elevation models (DEM) in areas with detailed topographic maps and the promise of SRTM data, DEMs are set to become a valuable source of topographic data for the glacial researcher. National mapping programmes are producing DEMs, often with a pixel resolution of 10m and height accuracy of ±1.0m. These have been created from either surveyed contour data or directly from aerial photography using digital analytical plotters. Air and space borne SAR systems are another major data source for the creation of DEMs, with, for example, the Landmap project (Kitmitto *et al*, 2000) providing complete DEM coverage of the United Kingdom and Ireland.

Glacial mapping from DEMs has been briefly touched upon by Lidmar-Bergström *et al* (1991) who used relief shading to visually display landforms, whilst Chapter 5 utilised them for providing control data for the production of a morphological map of "truth". For linear landforms Lidmar-Bergström *et al* (1991) state that they can be less visible when shaded from a limited sector, although they become more visible through a small change in light source azimuth. They created two, broadly orthogonal shaded DEMs for viewing glacial landforms, but only used one for mapping. They did not discuss the implications of how relief shading could be implemented within a broad mapping programme without the bias they had mentioned or how shape can change for those landforms that are not purely linear when viewed under different light source azimuths.

Through the production of the morphological map for this research, the same azimuth biasing as illustrated for the satellite imagery, was encountered. The morphological map was created by break of slope mapping from two illumination azimuths, however this is time consuming and not a viable option

for regional scale landform mapping. Consequently this chapter explores a variety of methods for visualising DEM data with the aim of reducing bias', and quantitatively assesses their suitability.

6.2 Mapping Approaches

The human eye is particularly good at perceiving subtle greyscale changes in an image (Estes *et al*, 1983) and therefore the creation of an image through the use of shading to highlight topographic variation has been a popular method to map landforms from DEMs (also see §5.2.2 and Appendix 1). The main variables controlling visualisation include the illumination azimuth, illumination elevation and vertical scale. Linear landforms are particularly sensitive to variations in the first of these, such that systematic bias may be introduced in the representation of landforms. Different methods for visualising DEM data have therefore been explored.

The different approaches explored are listed and discussed below:

1. RELIEF SHADING

a. Orthogonal Illumination Directions (Figures 6.1a and 6.2a)

This method requires the creation of at least two relief shaded images from a DEM, parallel and orthogonal to the principal lineament direction. This arrangement should allow the visualisation of all landforms on the image.

2. Combined Viewing

a. False Colour Composite (Figure 6.3)

Remote sensing software typically allow the colour co-visualisation of up to three images through the use of the red, green and blue colours on a computer monitor. In this method two relief shaded images were created as in method (1), and assigned to a different monitor colour (i.e. image 1 is viewed as blue and image 2 as green). This has the effect of colouring areas of the image that appear in only one, or both, images.

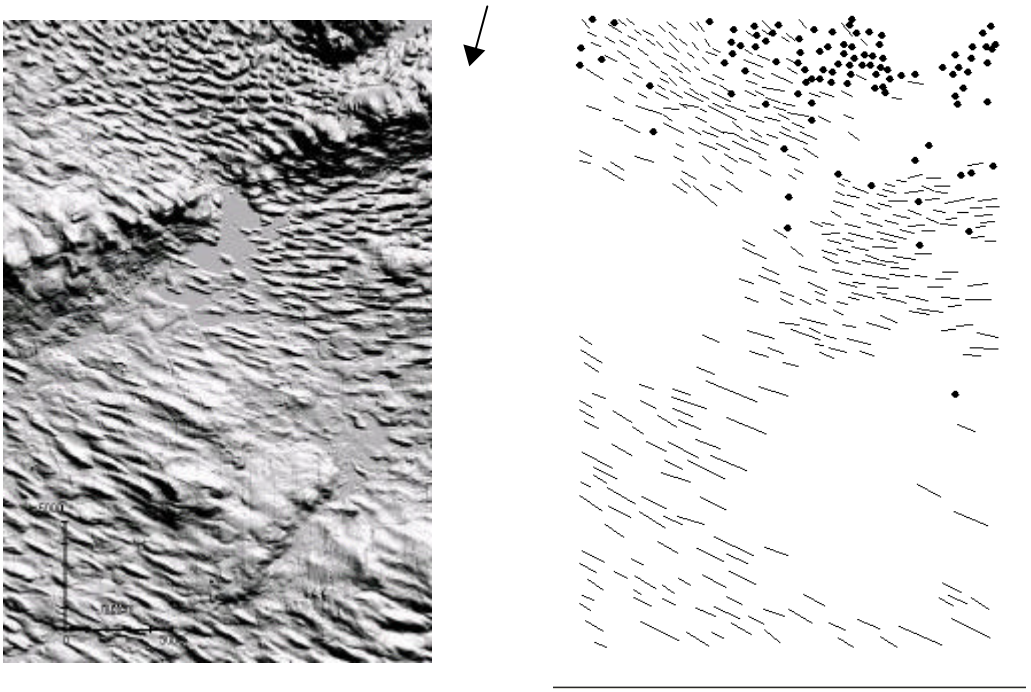


Figure 6.1 a and b Relief shaded DEM of Lough Gara, Ireland, (left) using an illumination azimuth orthogonal to the principal lineament orientation and glacial landforms mapped (right) from this image (lineaments represented as lines and hillocks points). Illuminated from 20º (© Irish Ordnance Survey).

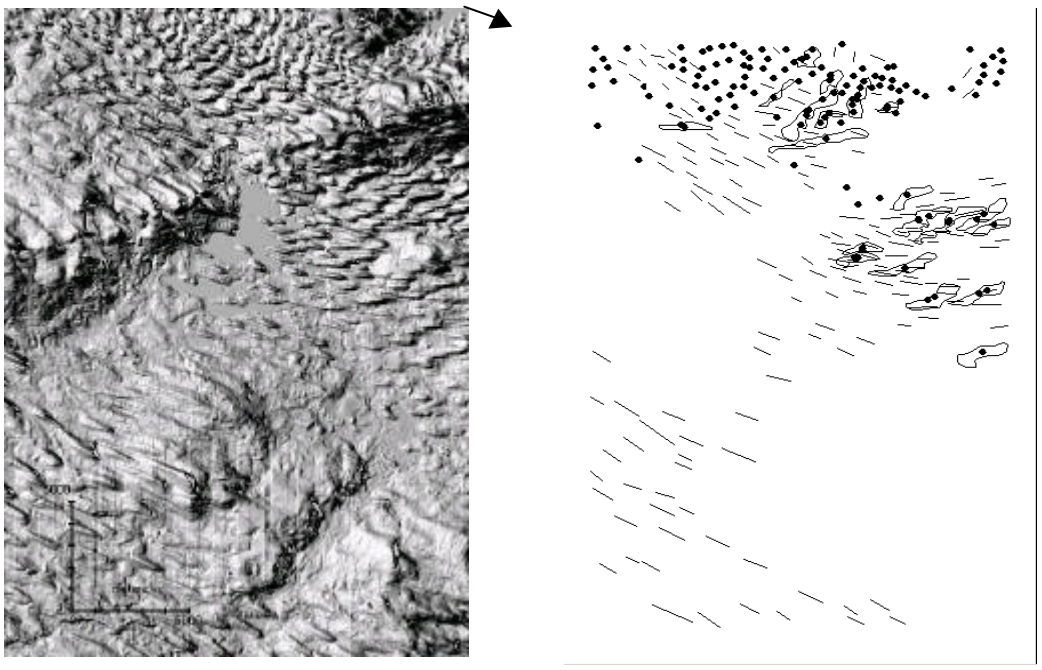


Figure 6.2a and b Relief shaded DEM of Lough Gara, Ireland, (left) using an illumination azimuth parallel to the principal lineament orientation and glacial landforms mapped (right) from this image (lineaments represented as lines and hillocks points). Illuminated from 290º (© Irish Ordnance Survey).

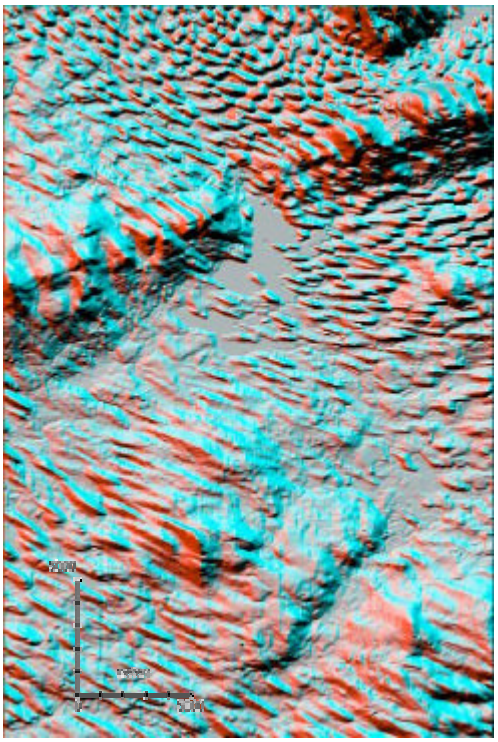


Figure 6.3 False colour composite co-visualisation of Lough Gara, Ireland, from a DEM, relief shaded parallel and orthogonal to the dominant lineament direction. The parallel image is coloured in green/blue and the orthogonal image in red (© Irish Ordnance Survey).

b. Statistical Analysis (Figure 6.4)

Geographic Information Systems (GIS) allow the exploration of differences and similarities between images using a variety of statistical methods. These can be used to isolate and emphasise traits or features from 2 or more input images. Methods include addition, subtraction, minimum, maximum and mean between different images. A log transform can also be used to emphasise low elevation detail (e.g. Guzzetti and Reichenbach, 1994), however this is relative within the study area (i.e. a global operator) and does not highlight smaller, localised, elevation variations (i.e. lineaments).

A common method applied in remote sensing is Principal Components Analysis, or PCA, which aims to describe the different image bands with new orthogonal axes. Essentially it compresses the multiple components (images) of the original data and creates a new set of axes along the line of maximum data variance. Once the pixels have been resampled onto their new co-ordinate system, they then contain more information that any other single band in the original data (Figure 6.5).

c. Combination Viewing (Figure 6.5)

Remote sensing software can load several images, *layered* on top of each other. It is possible to fade or flicker between these layers to facilitate a visual comparison; this technique can be used to jointly map two alternatively shaded DEMs as described in point (1).

d. Dynamic Illumination Variability (accompanying animated GIF file)

The orthogonal and parallel images introduced above illustrate two discrete views of the variability in landform representation within the continuous range from 0°-360°. Disc 1 provides an example of Dynamic Illumination Variability whereby the terrain is viewed using a constantly changing illumination azimuth. This provides a full, visual, depiction of landform representation change with azimuth.

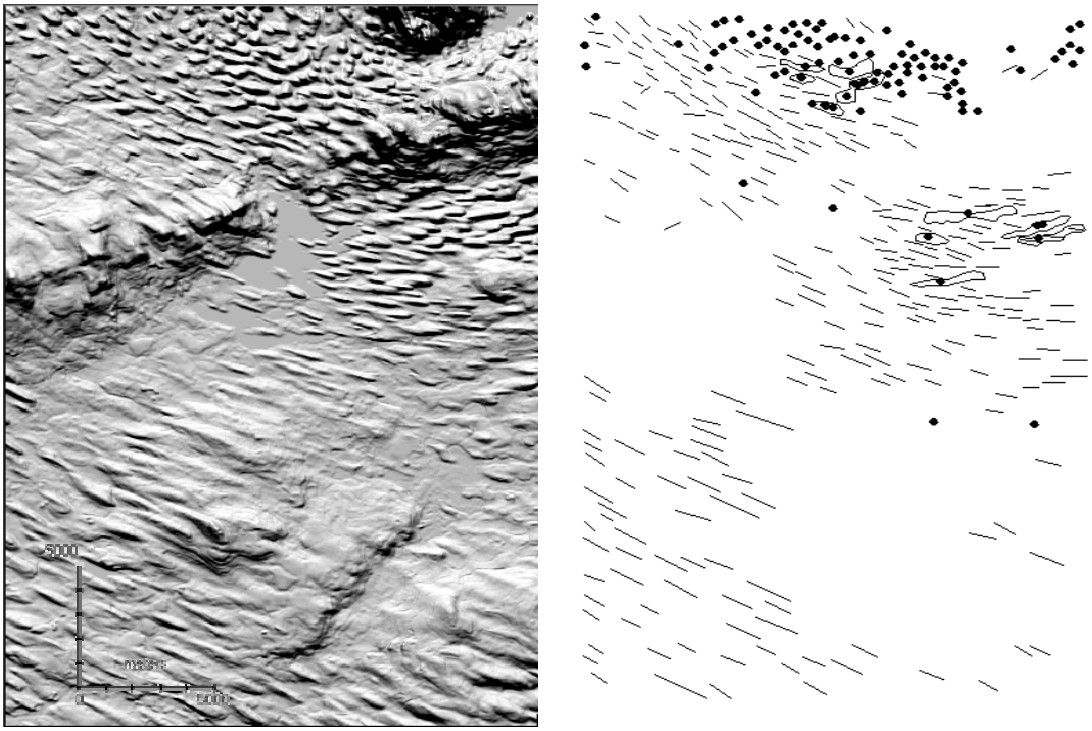


Figure 6.4 a and b Principal Component 1 of Lough Gara, Ireland, (left) produced from a DEM relief shaded parallel and orthogonal to the dominant lineament direction and glacial landforms mapped (right) from this image (lineaments are lines and hillocks points; © Irish Ordnance Survey).

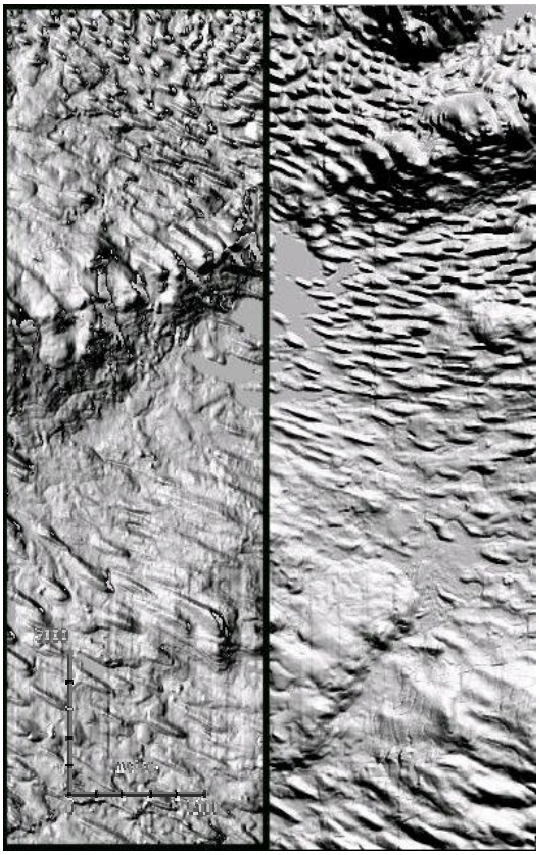


Figure 6.5 Combination Viewing of Lough Gara, Ireland, (left) produced from a DEM relief shaded parallel and orthogonal to the dominant lineament direction. The rectangle outlines the border between the combined images. In this approach it is possible for software to repetitively flip between the two image types whilst on-screen mapping is performed (© Irish Ordnance Survey).

3. Surface Derivatives

a. Gradient (Figure 6.6a)

Lineaments are topographically distinct as a result of their elevation difference from the surrounding terrain, which is a function of changes in surface gradient. Lineaments can therefore be highlighted by calculating gradient across a whole image. The brightness of each pixel is directly related to slope angle so that bright areas are flat and dark areas are steep.

b. Slope Curvature (Figure 6.7a)

Gradient alone cannot be developed to identify lineaments. Rather it is the change in gradient (i.e. curvature) that makes lineaments topographically distinctive, particularly in cross-section. Gradient changes from flat at the base, moderate up its sides and flat again on the top. Consequently curvature shows rapid changes at the base and the top (i.e. the concave slope at the base and the convex slope at the summit). Figure 6.7a shows that when this is calculated across a region, outlines and ridges are clearly discernible and not only are they highlighted but they are also normalised for elevation and, as the image is not illuminated, there is no azimuth bias. This is a major advantage.

4. 3D Viewing

a. Perspective Viewing (Figure 6.8b)

As a DEM provides elevation data, it is possible to overlay it with thematic information (e.g. map or satellite image) which can then be distorted with respect to elevation. This is typically used to view a landscape obliquely and generate “fly-bys”. This system is essentially the same as flight simulator software and allows a detailed examination of the landscape. Software is being developed that allows direct digitising from such imagery as a 2D or 3D GIS layer, however at present, this is not possible. In addition the process is time consuming and so does not lend itself to rapid mapping.

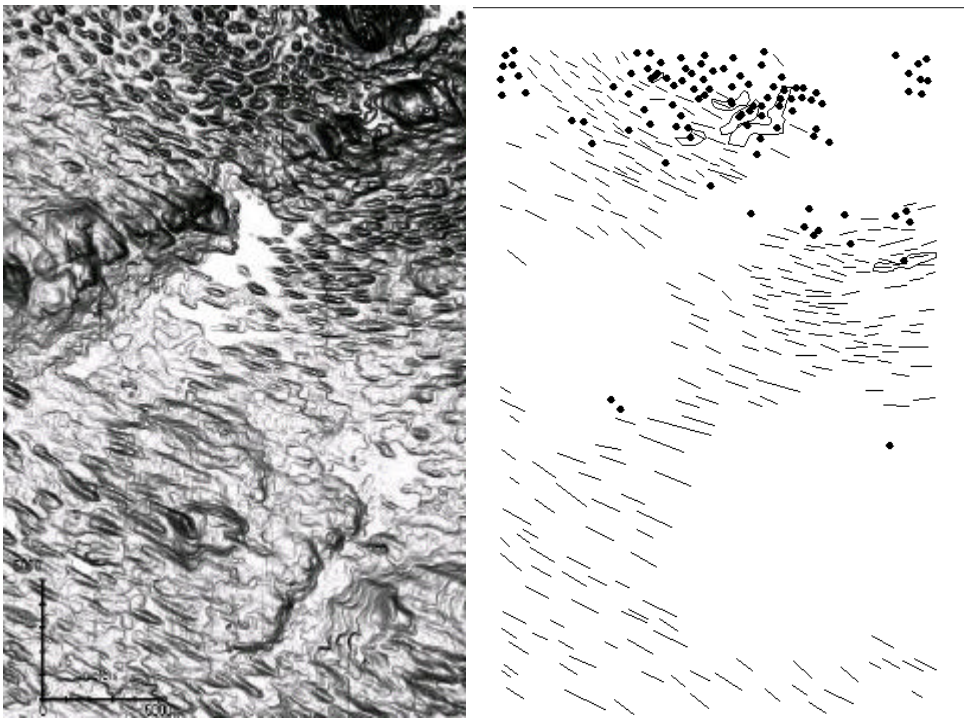


Fig 6.6 a and b An image showing gradient of Lough Gara, Ireland, (left) and glacial landforms mapped (right) from this image (lineaments represented as lines and hillocks points; © Irish Ordnance Survey).

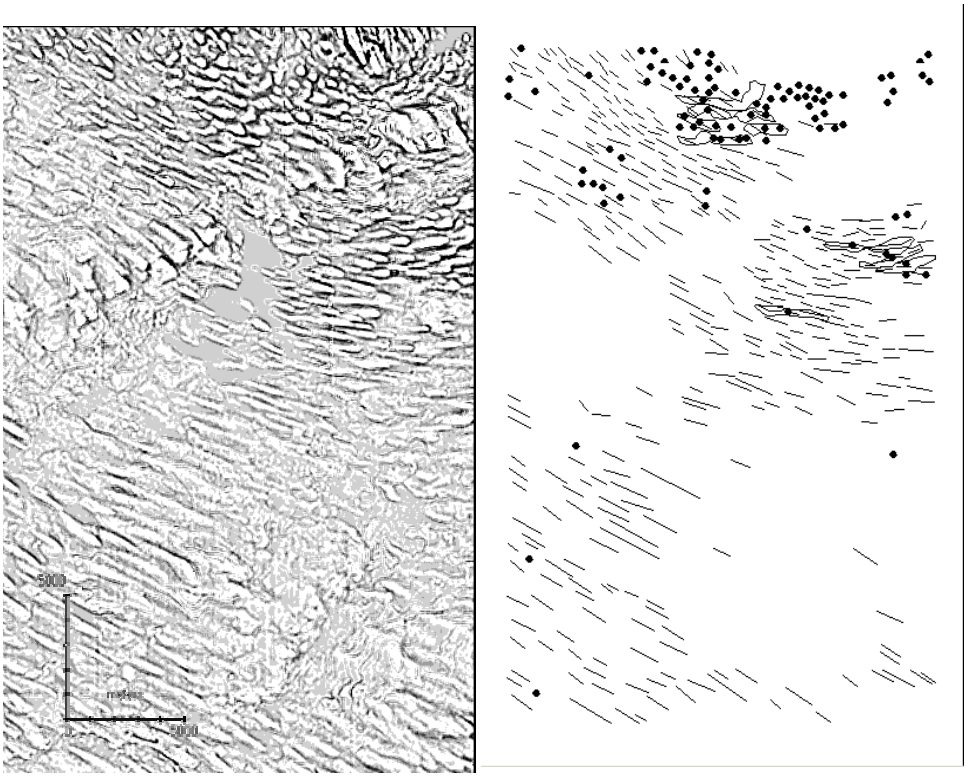


Figure 6.7 a and b An image showing Profile Curvature of Lough Gara, Ireland, (left) and glacial landforms mapped (right) from this image (lineaments are lines and hillocks points; © Irish Ordnance Survey).

b. Stereo Viewing (Figure 6.8a)

An anaglyph or stereo-pair image can be created from a DEM or stereo aerial photos and then overlaid with thematic data (as above). The DEM or aerial photo data is used to introduce parallax effects into the resultant image making it viewable as a 3-dimensional scene either as an anaglyph image (Figure 6.8a) or by using 3D viewing goggles. This system is essentially an entirely digital photogrammetry workstation. Like photogrammetry, digitising is possible. It is also possible to perform stereo perspective viewing and “fly-bys”, with the same caveats noted above.

5. Localised Spatial Enhancement

Traditional image contrast techniques are applied to a whole image and so operate globally. As a result many lineaments remain hidden as, although they are *locally* distinct, globally they are not. The following techniques are designed to apply locally based contrast enhancements to an image.

a. Adaptive Filtering (Figure 6.9a)

Adaptive filtering uses locally derived linear stretches to provide contrast enhancements. The input image is partitioned into windows, and the transformation parameters are calculated for each pixel as a linear interpolation of the stretch parameters for adjoining blocks. Fahnestock and Schowengerdt (1983) discuss this in more detail.

In this method (termed *local contrast stretch*) a simple, locally based, contrast enhancement is applied to each individual pixel, over a 3 by 3 window. Local topographic variations are selectively enhanced, using the following method, which is based upon 8bit data and therefore scaled to 256 data values:

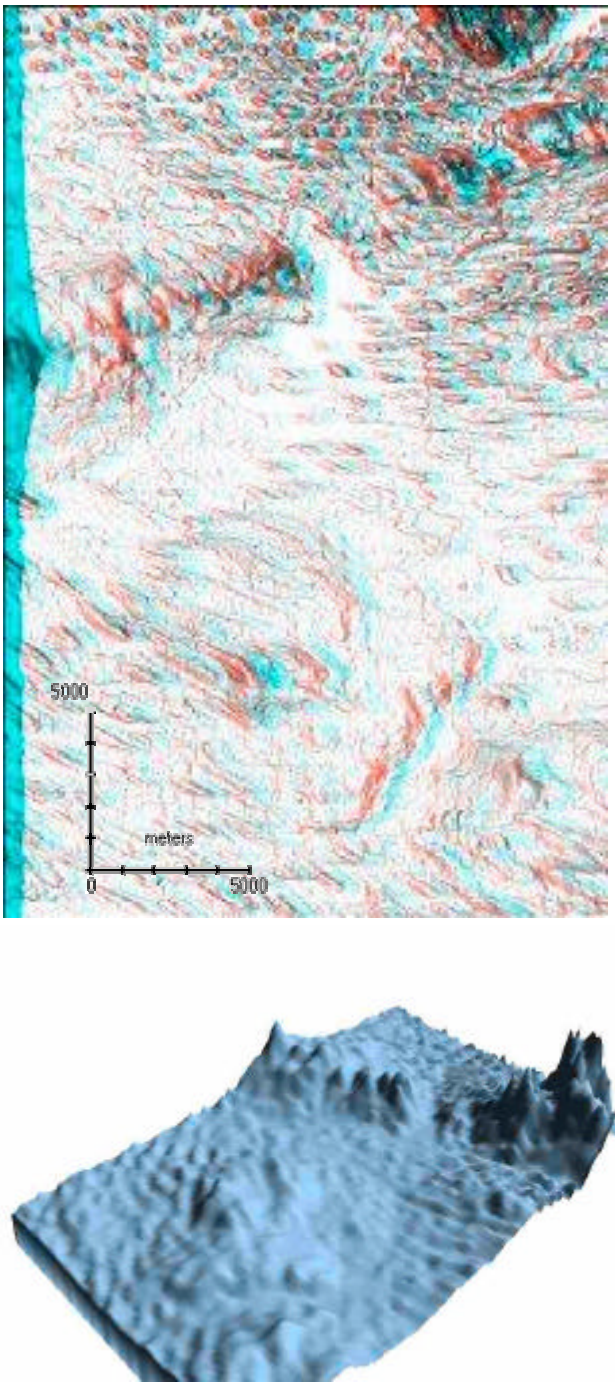


Figure 6.8a and b a. Anaglyph image created from a gradient map (please use attached glasses). b. Perspective view of Lough Gara, Ireland (© Irish Ordnance Survey).

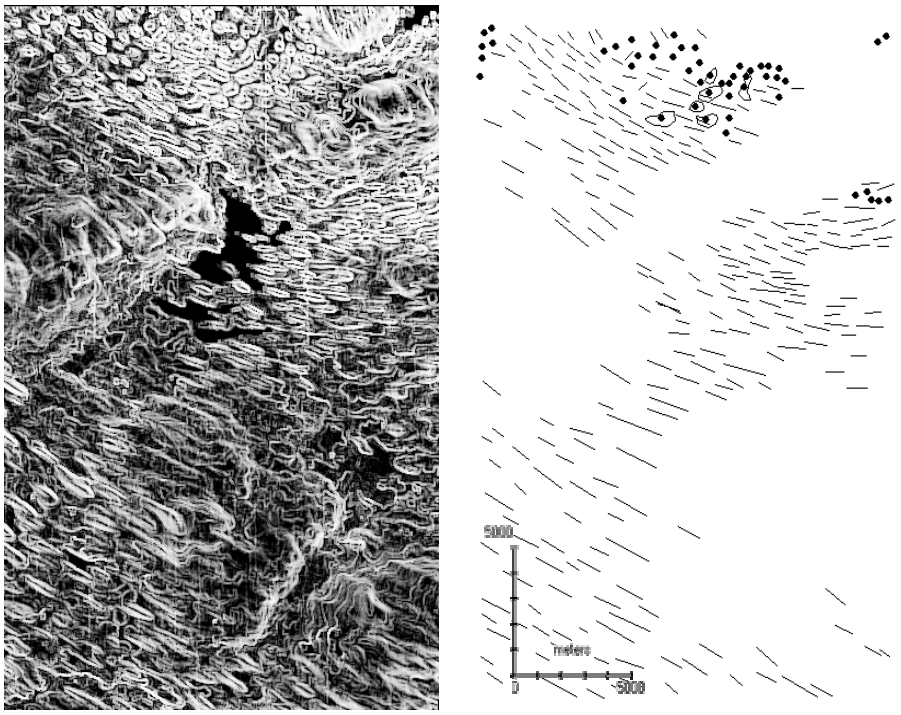


Figure 6.9 a and b Local contrast enhancements applied to the image of Lough Gara, Ireland, (left) and glacial landforms mapped (right) from this image (lineaments are lines and hillocks points; © Irish Ordnance Survey).

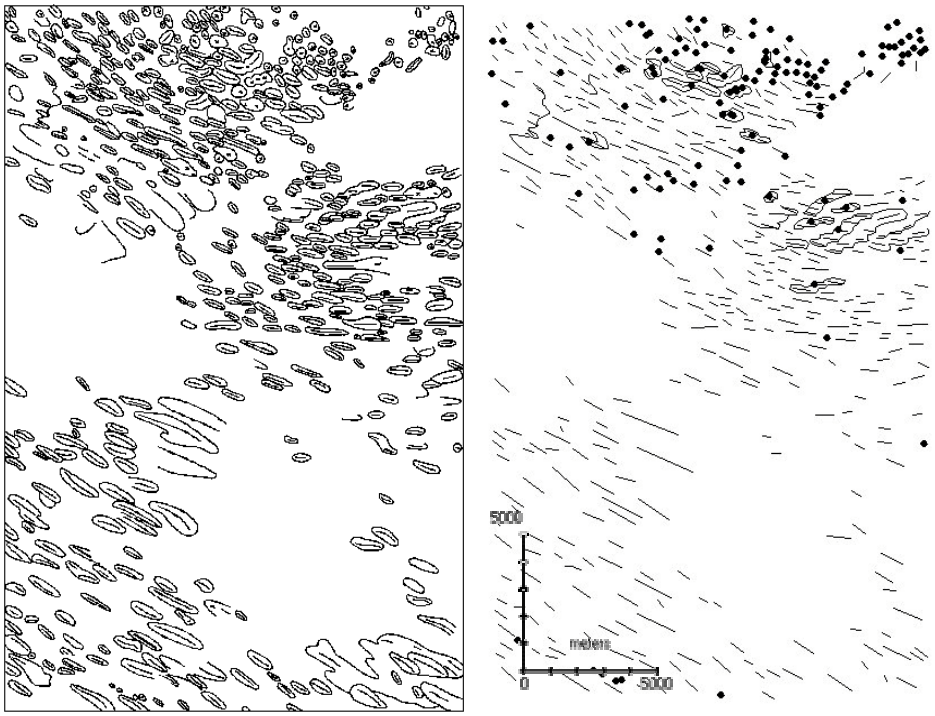


Figure 6.10 a and b Morphological map (truth) of all resolvable lineaments produced from the DEM of Lough Gara, Ireland (left) and the generalised lineament map derived from it (right).

$$x_{out} = y_{\min} - x_{in} . \frac{y_{\max} - y_{\min}}{256}$$

where

x_{out} is the output pixel value

x_{in} is the input pixel value

y_{min} is the minimum pixel value within the moving window

y_{max} is the maximum pixel value within the moving window

Figure 6.9a illustrates this approach using a 401x601 window.

b. Texture Filter

Texture filtering has traditionally been used to selectively highlight textural elements within VIR/IR imagery, although low pass, high pass and edge detection filters are more commonly used. These techniques have become prominent with the popularity of radar data. Textural information within gridded elevation data is typified by small, apparently random, changes in elevation. For lineaments these are spatially correlated so that texture filtering can highlight them. Irons and Peterson (1981) discuss optimised texture filters for a variety of different applications.

6.3 Method

In order to provide a comparative analysis of different DEM visualisation methods, a drumlinised area from the Lough Gara region of the Republic of Ireland was selected. This is the same region that was used in Chapter 5 for assessing the problems in mapping glacial lineaments from satellite imagery. The DEM was created by the Irish Ordnance Survey using high resolution (1:40,000) stereo aerial photography at a spatial resolution of 50m. They used *direct terrain extraction* to generate the DEM data values. In this method the aerial photography is scanned into the system and a stereo model generated. This is then used to calculate elevation using regularly spaced grid sampling. This moderate resolution DEM is able to resolve individual drumlins, although

cross-cutting patterns and smaller forms are difficult to distinguish. A brief discussion of this data can be found in §5.2.2.

The above 9 methods were initially assessed in order to disregard any that were unsuitable. The *False Colour Composite* method was unsatisfactory as the variation in colour distracted the eye from the underlying terrain making mapping difficult. *Combination Viewing* and *Dynamic Illumination Variability* were useful as interpretative tools and as a means of highlighting the azimuth bias, however there is currently no easy method by which mapping can take place using these techniques. The *3D Viewing* techniques allowed viewing in stereo, however the technical requirements and mapping difficulties are such that it is currently inappropriate for widespread landform mapping. Finally, of the local contrast enhancements the *texture filter* produced results similar to *slope curvature* and was therefore not considered. All processing, unless otherwise specified, was performed using Erdas Imagine™.

The remaining 5 methods were selected for testing:

1. **Relief shading** - in order to reproduce the variability introduced by alternate relief shading azimuths, three new images were created, relief shaded *orthogonal* (20º), *parallel* (290º) and *intermediate* (335º) to the principal lineament direction (290º). Increasing the amount of vertical exaggeration helped better visualise the landforms, however individual results will depend upon the method of relief shading implemented by the software in use.
2. **Overhead Illumination** - this was created in the same way as *relief shading*, except using a solar elevation of 90º.
3. **Principal Components Analysis (PCA)** – a standard PCA method was used, utilising the *parallel* and *orthogonal* relief shaded images.
4. **Slope Curvature** – this was calculated in ARC/INFO, which has been implemented using the method of Zevenbergen and Thorne (1987). A 3 by 3 low pass filter, followed by a histogram stretch using a low number of bins (less than 10 in this instance) was effective for visual highlighting. A standard deviation stretch using a value of 0.2 was also useful. The low pass has the effect of softening the contrast within the image which makes viewing easier. Both the standard deviation and histogram stretches

essentially highlight the extreme values within the image, providing good delineation of lineament outline or crest.

5. **Local Contrast Stretching** – the local contrast stretch performs a standard linear contrast stretch over a localised region as described above. The region (or locale) is pre-defined using a set window size and is dependent upon the resolution of the DEM and the dimensions of landforms that are being studied. A variety of different window sizes were explored and a 3 by 3 window was found to give the best results.

To allow absolute inter-comparison (see below) a measure of the landforms that are actually present within the terrain is needed. The morphological map (simply referred to as *truth*) created for the satellite image comparisons in Chapter 5 was used for this purpose (Figure 6.10a; see §5.2.1). This was compiled from break of slope mapping using multiple illumination azimuths and checked using stereo aerial photography (see §5.3.2 for further discussion).

The investigation then involved mapping all landforms present within the images produced by the five selected visualisation methods. Mapping was performed by one observer and observer variability is assumed to be minimal through consistency produced by this. To check for this, the orthogonal relief shaded image was mapped again at a later date and used as a set of control data. The results in §6.4 discuss this further. Simple line geometry was used for digitising lineaments, with polygons for spatially larger landforms and points for local summits in hummocky terrain.

The above images, and the lineaments mapped from them, are initially visually assessed through descriptive inter-image comparisons (§6.4.1). A comparison of the number of lineaments mapped, their orientation, length and coincidence is also provided (§6.4.2). Coincidence was assessed visually to account for errors by observer mis-digitisation.

6.4 Results

This section presents the qualitative and quantitative results of the image comparisons. The qualitative section provides a description of both the images

and the landforms mapped from them for each mapping approach, whilst the quantitative section presents summary statistics for mapped landforms.

6.4.1 Visual Image Inter-Comparisons

1. Truth Data (Figure 6.10a/b)

The morphological map shows a strong trend of lineaments oriented NW-SE, with longer lineaments in the southern area. A spread of lineaments oriented E-W is also noticeable. There is a strong concentration of hummocky terrain in the northern part of the map, with a few hummocky forms elsewhere. The northern half of the map also contains transverse ridges, often with lineaments overlying them. This map is taken to be the most accurate representation of the landforms present (i.e. “truth”) against which the other images are tested.

2. Orthogonal Illumination (Figure 6.1a/b)

The orthogonal illumination azimuth produces a detailed representation of the longer lineaments in the southern half of the image. It also revealed a large number of smaller, densely packed, lineaments in the northern and eastern parts of the image. The eastern area shows a change in lineament orientation from broadly SE to ENE, with these latter forms having a lower elongation ratio (i.e. fatter). The northern area also exhibits some of these “fatter” forms, including some circular hill forms generically termed “hillocks”. The topographic maps for the area suggest a thin drape of till over the southern area, a conclusion supported by the dominant bedrock ridge running NE to SW and in the extreme NE area. Note the irregular looking ridge in the SW corner which is actually a river terrace.

Mapping confirmed the existence of the dominant set of NW-SE orientated lineaments, with shorter forms in the northern and eastern areas. The ENE-SSW oriented lineaments in the eastern area and “hillocks” in the northern area were also identifiable and therefore mapped.

3. Parallel Illumination (Figure 6.2a/b)

The parallel illumination azimuth dramatically dampens the effect of all lineaments that were strongly represented in Figure 6.1a. This effect is particularly well demonstrated in the southern part of the image; many landforms are still visible, but their outline is indistinct and often represented as cuspate forms. Similar effects are apparent in eastern and northern parts of the image. However it is the “fatter” forms from the previous image that have dramatically changed shape and orientation. The eastern part of the image depicts composite lineaments making up larger, transverse, NE-SW trending landforms, termed transverse ridges. This effect is repeated in the northern part of the image, although the circular “hillocks” are still evident.

The mapping confirmed the visual appraisal. There were far fewer lineaments mapped, however there are a greater number of “hillocks” in the northern area and the addition of transverse ridges in the northern and eastern areas.

4. Intermediate Illumination (Figure 6.11a/b)

The intermediate illumination azimuth looks very similar to Figure 6.1a, although strongly represented landforms from that image are now less distinct. The transverse ridges in the eastern area (Figure 6.2a) are not evident, although their presence can be hinted at when compared to Figure 6.2a.

Mapping results appear very similar to those for Figure 6.1b, with a large number of lineaments oriented NW-SE. Again there are a number of “hillocks” in the northern area and an arc of lineaments in the eastern area.

5. Principal Components Analysis (PCA) (Figure 6.5a/b)

The PCA image would be expected to contain the essential elements of both input image (i.e. *parallel* and *orthogonal* relief shaded images), however the transverse ridges shown in Figure 6.5a are subtle such that an inexperienced observer would not identify them. Strongly represented landforms from Figure 6.1a are subdued and, in some cases, omitted, however the transverse ridges in the northern and eastern areas are visible although not as distinct as in Figure 6.2a.

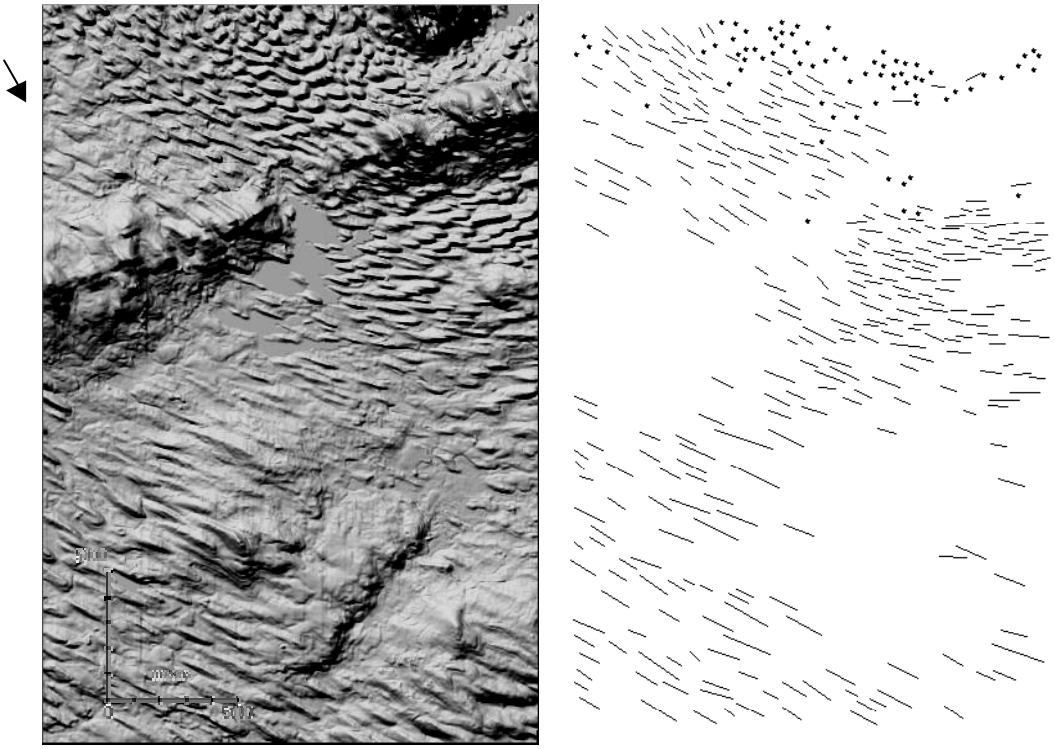


Figure 6.11a and b Relief shaded DEM of Lough Gara, Ireland, (left) using an illumination azimuth at 45º to the principal lineament orientation and glacial landforms mapped (right) from this image (lineaments represented as lines and hillocks points; © Irish Ordnance Survey).

Mapping clearly identified the strong NE-SW alignment of lineaments and the presence of some of the transverse ridges. There are also a large number of “hillocks” mapped in the northern area.

6. Gradient (Figure 6.6a/b)

Using overhead relief shading, initial viewing is favourable with distinctive shading of the landforms produced. Lineaments are clearly delimited and easy to map, again showing the predominance of fewer, longer, lineaments in the southern portion of the image, with smaller, narrower landforms in the NW. However the transverse landforms in the eastern area are less distinct, although, as with the *Intermediate Illumination*, their presence can be discerned when compared to the *Parallel Illumination*.

Mapping results are similar to both the *Parallel* and *Intermediate* illuminations showing the main NW-SE lineament trend, the arc of lineaments in the east and hillocks in the north.

7. Slope Curvature (Figure 6.7a/b)

The lack of azimuth bias in calculating curvature is clear and was therefore a good approach for mapping lineaments. There are hints of transverse ridges in the eastern and northern areas, however this is not visually strong and might be considered noise. The mapping results largely bear out the description above; there are fewer lineaments mapped when compared to other methods, however the same basic trends are still visible.

8. Local Contrast Stretch (Figure 6.9a/b)

Initial viewing appears confused, but close inspection of the image shows that many lineaments are clearly outlined, again highlighting the dominance of NE-SW oriented lineaments, as well as many hillocks in the north. Transverse landforms are not clearly outlined although a small number have been mapped in the north of the image.

6.4.2 Analysis of Landform Detectability

The quantitative results were gathered from image inter-comparisons carried out in the method described above. These results fall into three main sections discussing mapped landform totals, lineament length and orientation and inter-image lineament coincidence. The control data are discussed separately in §6.4.2.4.

Landform totals and lineament length/orientation are broad global measures that can be usefully used to compare and contrast the landforms mapped from the different visualisation methods. The former assesses completeness in terms of number of landforms, whist the second assesses the degree of similarity through descriptive statistics. It is also appropriate to consider locational similarity of mapped landforms and this is achieved by considering the degree of coincidence in lineament mapping between the different mapped data and truth.

Landform Totals (Table 6.1)

The simplest descriptive term is the total number of landforms mapped when compared to the total number of landforms present, so providing a measure of completeness for the lineaments mapped from a specific dataset. The *truth* shows a total of 442 lineaments mapped, with only *Slope Curvature* (361) and *Orthogonal Illumination* (374) having similar landform totals. *Intermediate Illumination* has a slightly lower mapped lineament total (338), whilst the *PCA* (271), *Parallel Illumination* (203), *Local Contrast Stretch* (267) and *Overhead Illumination* (273) are significantly lower. Total lineament length also provides a surrogate measure for number of lineaments, however it also normalises for segmentation of lineaments. This highlights that *truth* has a greater number of shorter lineaments. In this instance *Slope Curvature* and *Orthogonal* and *Intermediate Illumination* have greater total lengths. However it also highlights the low values of *Overhead Illumination*, *PCA* and *Parallel Illumination*.

Landform	Lineament	Hillock	Ridge	Total Lineament Length (km)
Slope Curvature	361	84	10	297
PCA	271	89	10	218
Orthogonal Illumination	371	101	0	289
Parallel Illumination	176	120	20	146
Intermediate Illumination	330	75	0	146
Local Contrast Stretch	267	45	0	234
Overhead Illumination	273	102	0	218
Truth	**442**	**109**	**25**	**263**
Control (Orthogonal Illumination)	382	117	0	260

Table 6.1 Total number of lineaments, hillocks and ridges mapped from the different visualisation methods. Total lineament length is also included.

The number of hillocks mapped are similar between all the visualisation methods, except *Local Contrast Stretch* which is substantially lower, whilst *Slope Curvature*, *PCA* and *Intermediate Illumination*, have slightly lower numbers mapped than for the other methods.

Finally, totals for number of transverse ridges mapped is variable with the *Intermediate Illumination*, *Orthogonal Illumination*, *Local Contrast Stretch* and *Overhead Illumination* having had none mapped. Some ridges were mapped on *Parallel Illumination, Slope Curvature* and *PCA*, with *Parallel Illumination* mapping nearly as many ridges as *Truth*.

In summary, *Orthogonal*, *Parallel* and *Overhead* are the best methods to identify lineaments, ridges and hillocks, respectively. However, *Curvature* data performs very well at identifying lineaments and satisfactorily for hillocks and ridges. The *Parallel Illumination* data performs well at identifying hillocks and ridges, but poorly for lineaments. The remaining images have different strengths and weaknesses but are unable to match the performance of the above two.

Lineament Length and Orientation

In addition to mapped landform totals, which provide an overview of the completeness of different visualisation methods, it is also appropriate to review lineament length (Table 6.2) and orientation (Table 6.3). These allow us to assess any differences in the characteristics of the landforms being mapped between approaches.

	Min	Max	Mean	Standard Deviation
Orthogonal Illumination	307	2604	780	352
Parallel Illumination	354	2136	829	292
Intermediate Illumination	317	2602	843	363
Local Contrast Stretch	381	2760	887	382
Overhead Illumination	326	3026	851	350
PCA	332	2340	806	323
Slope Curvature	285	3063	827	381
Truth	**172**	**2758**	**595**	**331**
Control (Orthogonal Illumination)	347	2584	798	338

Table 6.2 Minimum, Maximum, Mean and Standard Deviation calculations for **lineament length** (in metres) from the different visualisation methods.

The results for lineament length show consistency between visualisation methods with the minimum and maximum values similar. In comparison to truth, Overhead Illumination and Slope Curvature have slightly higher maximum values, whilst Parallel Illumination has a slightly lower value. The mean is consistently higher for all methods. The previous section has already demonstrated that there are more lineaments mapped in Truth and, generally these tend to be shorter (and hence the smaller minimum value).

The results for lineament orientation are more varied, a reflection of the azimuth bias present in the relief shaded images. The greatest variation in the northmost value comes from Parallel Illumination and Overhead Illumination, with relatively north and south values respectively. The southmost values are similar, although

truth has the most northerly value. The vector mean and vector strength are all similar, bar the vector strength for Parallel Illumination and Truth which tend to be lower, a reflection of their extreme values.

	Min	Max	Vector Mean	Vector Strength
Orthogonal Illumination	51.3	142.8	111.7	0.974
Parallel Illumination	13.4	147.5	109.0	0.948
Intermediate Illumination	61.0	149.8	111.0	0.976
Local Contrast Stretch	45.0	149.9	111.6	0.971
Overhead Illumination	71.6	147.5	111.3	0.970
PCA	50.7	145.3	111.1	0.971
Slope Curvature	34.7	147.0	113.3	0.972
Truth	**39.6**	**160.6**	**115.7**	**0.954**
Control (Orthogonal Illumination)	22.3	155.0	112.0	0.973

Table 6.3 Minimum, Maximum, Vector Mean and Standard Deviation calculations for **lineament orientation** (in º) from the different visualisation methods.

Inter-image Lineament Coincidence (Table 6.4)

Coincidence was assessed visually with lineaments required to be within approximately 200m of each other and not deviate by more than 15º, although consideration was given to a greater deviation due to azimuth biasing if the lineaments were crossing. Visual assessment was selected as the optimum method as consideration could be given to any deviations as a result of poor digitising. The results for coincidence between all the different visualisation methods is given in Table 6.4. The table also includes a comparison with the control data set.

To help visualise these comparisons, Figures 6.12 and 6.13 provide overlays of the four main methods (Slope Curvature, Gradient, PCA and Local Contrast Stretch) with truth. As each individually relief shaded image (parallel, intermediate and orthogonal) suffers from azimuth biasing, it is not necessary to visually appraise lineament coincidence between these.

	Slope Curvature	*PCA*	*Orthogonal Illumination*	*Parallel Illumination*	*Intermediate Illumination*	*Local Contrast Stretch*	*Overhead Illumination*	*Truth*	*Control (Orthogonal Illumination*
Slope Curvature		63	60	64	60	81	81	45	
PCA	74		71	68	71	68	71	53	
Orthogonal Illumination	87	85		66	81	84	86	64	87
Parallel Illumination	52	45	40		40	52	52	33	
Intermediate Illumination	87	87	84	72		80	81	61	
Local Contrast Stretch	64	70	60	69	64		78	53	
Overhead Illumination	61	72	63	70	65	80		50	
Truth	79	83	88	80	81	82	81		
Control (Orthogonal Illumination)			79						

Table 6.4 Coincidence of landforms using different visualisation methods, expressed as a percentage of the total number of lineaments mapped. For example, 85% of lineaments mapped from the PCA image were coincident with those mapped from the Orthogonal Illumination image.

Figure 6.12
a Overlay of lineaments and hillocks mapped from Local Contrast Stretch (blue) and Truth imagery (red).

b Overlay of lineaments and hillocks mapped from Curvature (blue) and Truth imagery (red).

Figure 6.13
a Overlay of lineaments and hillocks mapped from PCA and Truth imagery.

b Overlay of lineaments and hillocks mapped from Gradient and Truth imagery.

In assessing the results displayed in Table 6.4 it is most appropriate to review coincidence with truth (greyed). The penultimate column shows the degree of *locational completeness*. This depicts the lineaments mapped by truth which are locationally coincident with the different mapping methods. The Orthogonal and Intermediate Illumination perform better than the other methods and Parallel Illumination performs noticeably worse.

The penultimate row highlights what can be considered an *error rate*. This depicts the lineaments mapped by the different methods which are locationally coincident with truth. Given truth is considered our complete dataset we would expect these values to be high and, indeed, all of them are approximately 80%. The following section further discusses mapping error by considering the control data set.

Control Data

In order to test for variations in the ability and consistency of the operator a control dataset was created. This involved re-mapping landforms represented on the *Orthogonal Illumination*. Chapter 4 highlighted the poor results that have been obtained in assessing the reproducibility of lineament mapping *between* individual operators, however the emphasis is on reproducibility by a single individual. This is important in terms of assessing the results and conclusions drawn from them, as well as showing that individuals can consistently map over large areas.

A qualitative comparison of the control data shows a strong visual consistency (Figure 6.14), with a small number of localised inconsistencies. In terms of landform totals (Table 6.1) there is very close agreement between the two datasets. The control dataset has 2% more lineaments and 17% more hillocks. The close agreement between lineament totals shows strong consistency between mapping sessions, although the number of hillocks mapped increased in the control dataset. The results for lineament orientation and length are again very similar, although the values for northmost and southmost orientation are

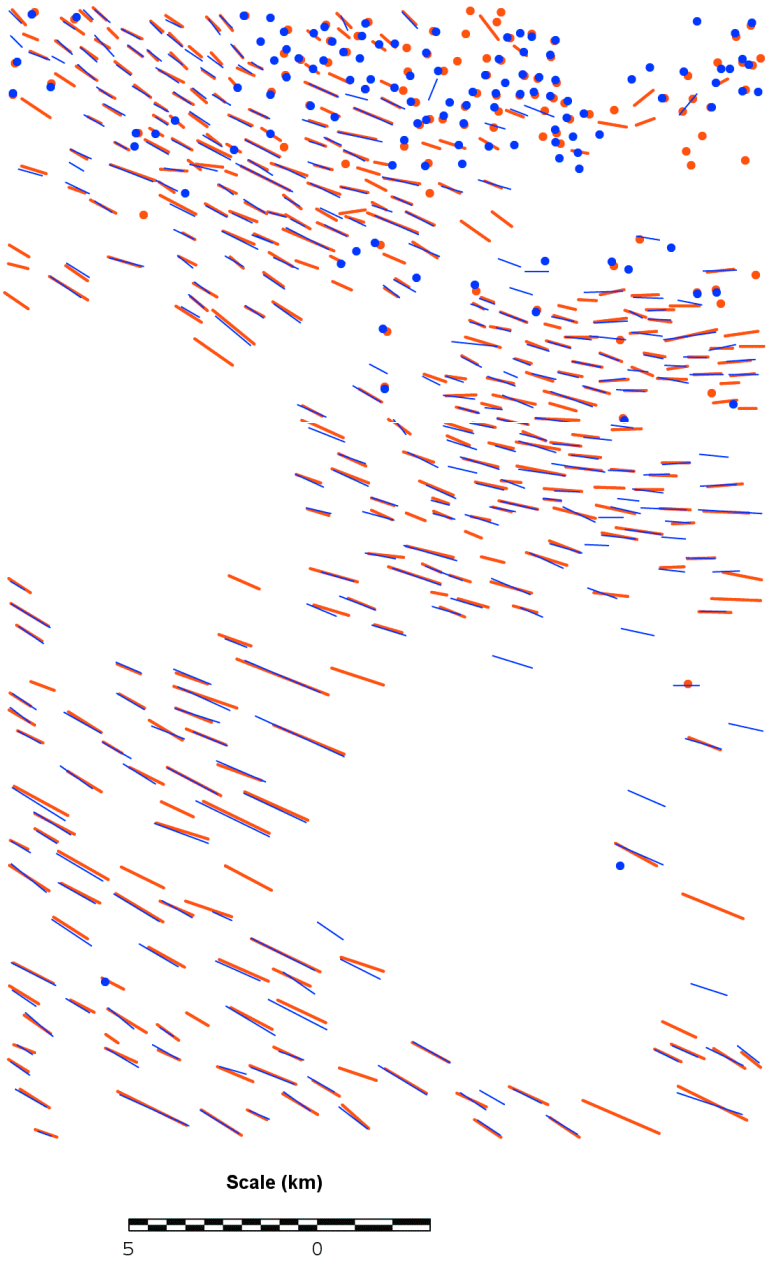


Figure 6.14 Overlay of lineaments and hillocks mapped from Orthogonal and Control imagery.

different due to several lineaments digitised differently between interpretations. The coincidence between mapped lineaments (Table 6.4) also shows good consistency with an average 83% coincidence.

Consistent mapping requires a fixed and rigorous method in identifying and delimiting individual features. This usually requires several different iterations in the mapping process, as well as much concentration. If the mapping process is divided between several operators then it is important that they can identify individual landforms and that they are consistent in this through the use of specific definitions of these landforms and the methods used to identify them.

It is probable that general mapping programmes will have lower rates of coincidence by individual operators. Such inconsistencies are unfortunately inherent to visual mapping and require that a rigorous approach to the mapping process is taken. However it must be born in mind that, for glacial reconstructions, general lineament trends are the most important result and inconsistencies can be accepted as long as they are randomly distributed across the image rather than systematically.

This section has attempted to show that operator variability is minimal, however even when larger variations are evident they should be randomly distributed. In contrast, many of the relief shaded visualisation methods implicitly incorporate selective bias which has a more drastic result on the interpretation of mapped glacial landforms and it is therefore more important to select an appropriate method of mapping.

6.5 Recommendations

The single most important conclusion to draw from the above results is that, although the data used for geomorphological mapping can generally be considered consistent (i.e. DEMs), the methods by which they are used to perform such mapping are not. It is therefore possible to introduce bias' into these maps that make them inconsistent. Strong landform assemblages will be readily apparent regardless of the method used to visualise them. However it is subdued landforms that are of particular importance to the glacial researcher as

they can be informative about the previous state of the landscape in relation to prior glaciations and, as a result, provide information about landscape change through time. *Observation* is the key to environmental understanding, and we are obliged to observe in an impartial, appropriate and consistent manner.

More generally, there are a variety of methods that can be used to visualise landforms from a DEM, each with their own advantages and disadvantages. Relief shading is the most common method by which this is achieved. Most general texts suggest illuminating from the NW as this provides a more "natural" means to view the data. However it is when illuminated from an orientation normal to the dominant lineament direction that the most visually pleasing results are obtained. Several authors have commented on the bias that *may* be introduced by single azimuth illumination (e.g. Graham and Grant, 1991 and Lidmar-Bergström *et al*, 1991) and as such it is suggested that two illumination angles, orthogonal to one another, and parallel and normal to the dominant lineament orientation, are used.

The results indicate differences in the landforms mapped from the different visualisation methods, such that this is an important consideration in any future mapping exercise. All datasets pick out the strong NW-SE lineament trend, however it is the more subtle ENE-SSW transverse ridges that are difficult to detect.

From a methodological viewpoint, Gradient, Slope *Curvature* and *Local Contrast Stretching* are the most preferable methods as they provide an unbiased representation of the surface. *Slope Curvature* performs very well, although it is unable to fully represent the variety of orientations of the transverse ridges. *Gradient* provides a visually appealing image, however it is unable to provide a satisfactory level of mapping. Although the *Local Contrast Stretching* is a good idea the resulting imagery is unsatisfactory.

Given that the *Parallel* and *Orthogonal Illuminations* are used to compile the landforms mapped in *Truth*, a combination of these images (the *PCA* image) should have great utility. Unfortunately the transverse ridges depicted in *PCA*

are sufficiently subtle as to prove difficult to map. Therefore this method has proved unsatisfactory and the individual *Parallel* and *Orthogonal Illuminations* are incomplete. The *Intermediate Illumination* is simply a compromise between these two illumination azimuths and is subsequently unsuitable.

In conclusion, all the single image methodological approaches are unsatisfactory and provide an incomplete visualisation of the actual terrain being mapped. This work has been unable to find a single image type that offers both no azimuth bias and yet portrays the landscape optimally. The advent of cheap, high resolution, readily available global DEM data is rapidly approaching and methods to make best use of this resource are needed. Given the good representation of the dominant lineament direction by *all* methods, the most useful results will be obtained by illuminating the DEM *parallel* to the dominant lineament orientation. This should have the effect of visualising these lineaments, as well as more subtle landform remnants within the environ, so providing a means to a more complete and rapid mapping of the desired region. This can be aided by dramatically increasing the vertical exaggeration of the DEM such that small elevation changes are readily apparent. Clearly if an accurate geomorphological map is required this will not suffice. It is therefore preferable to begin mapping with a bias free visualisation and *Slope Curvature* is best suited to this task. This can then be supplemented with further mapping from *Parallel* and *Orthogonal Illuminations*. The following section goes on to apply the visualisation methods, developed above, to a case study in order to learn the best compromise.

6.6 Case Study – Demonstration of landform mapping from a high resolution DEM of the Lake District

6.6.1 Introduction

The above sections have outlined the different methods used to visualise DEM data. This section aims to provide a demonstration of this methodology applied to the mapping of landforms from a high resolution DEM.

In selecting an area to apply the methods developed in this chapter, it was decided that this should incorporate the most difficult elements that are likely to be encountered during mapping. These include:

- a large area
- lineaments of a wide variety of sizes
- a mixture of different bedform shapes
- intermixing at the surface with geological structure
- high, variable, relief
- multiple ice flow directions incorporating cross-cutting

A large area (8,900km^2) of previously glaciated terrain located around the Lake District, United Kingdom, was selected (Figure 6.15) as it incorporates all of the elements noted above. In addition, there has been some field mapping performed within this area (e.g. Mitchell, 1994, Riley, 1987) and these are discussed later. The DEM used was the Ordnance Survey Panorama© dataset. This is 1:50,000 scale DEM that has a spatial resolution of 50m and was produced from original contour data (height accuracy of ±3.0m; Ordnance Survey, 1995). The Panorama© data is freely available to the British academic community for research and teaching purposes and its resolution is representative of the type of DEM data that will shortly be available globally. It has been discontinued as a commercial product and there is currently no direct replacement. Using the visualisation techniques outlined above, landform mapping was performed. The mapping process follows the same techniques used earlier in this chapter and outlined in §6.3. The landforms mapped during this exercise have been used to produce a subglacial bedform map of the Lake District (located on the inside cover). This represents the most complete glacial landform mapping covering the entire Lake District. Although partially covering areas that have already been field mapped, it identifies a considerable amount of previously unmapped landforms.

6.6.2 Visualisation Methods

Given the demanding nature of the terrain that was being mapped, a variety of visualisations and mapping methods were reviewed in order to achieve the best results. These were based upon the recommendations developed in §6.5. After

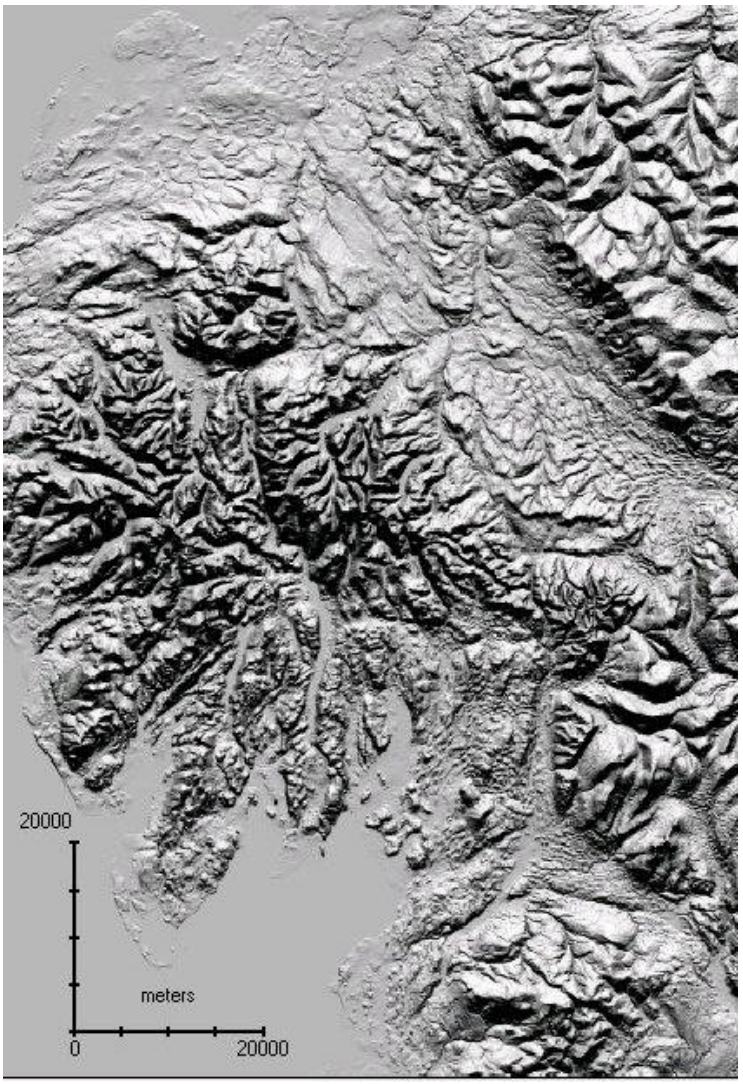
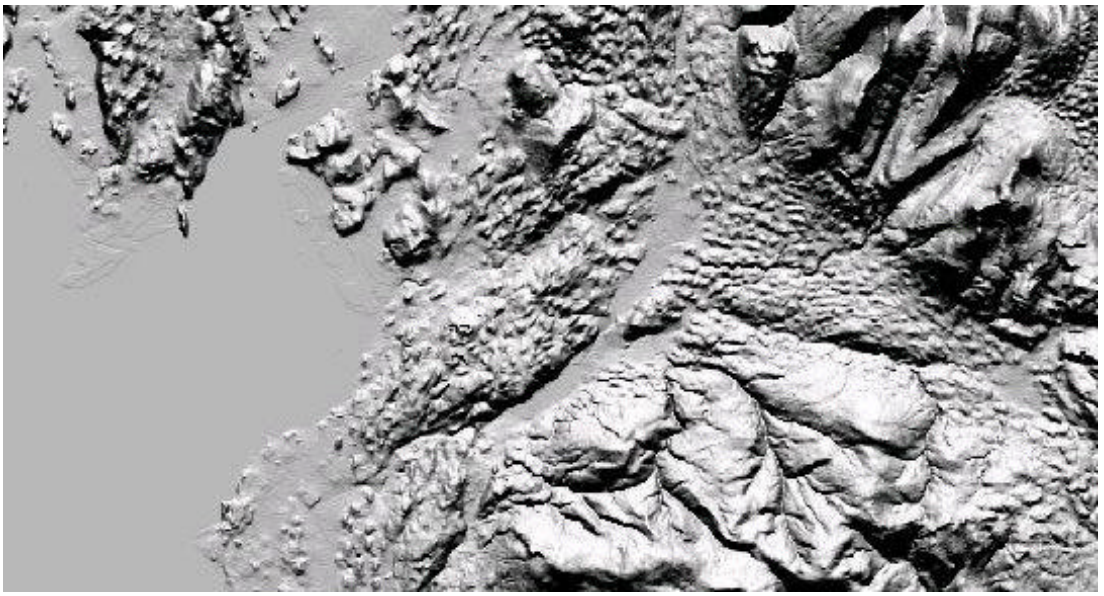


Figure 6.15 a (top) Relief shaded DEM data of the Lake District, United Kingdom. Relief shading is from the north, parallel to southerly dominant lineament direction (©Ordnance Survey).

b (bottom) Zoomed section of figure a. In the north central region are broadly SW trending lineaments, whilst the east central region contains a mixture of irregular bedforms and hummocky terrain.



initial exploration of the terrain, it was ascertained that the dominant lineament direction was southerly, although there were areas where there were easterly and south-easterly elements. Parallel (Figure 6.15) and orthogonal (Figure 6.16) relief shaded images were generated. These were the principal images used for mapping and were excellent at identifying the predominant lineaments in the image, as well as other, less common, bedforms. Depending upon the principal orientation of the bedforms being mapped, either the parallel or orthogonal images were used. After the first-pass of mapping, the latter image was used to check for other bedforms not readily apparent on the first image. Additionally, gradient and profile curvature images (Figure 6.17) were generated to aid the overall mapping process.

Selecting images with appropriate relief shading becomes difficult when there are multiple lineament orientations, however the above approach works well. Of more concern to consistency in the mapping process is the presence of geological structure and high relief. The former can be mitigated against through the aid of geological maps to avoid mapping structure as lineaments. The high relief of the Lake District was more problematic when mapping from relief shaded images due to the shadows cast into valley areas (Figure 6.18a). Although an obvious problem, it is difficult to remove. One solution is to increase the illumination elevation angle (Figure 6.18b) such that it comes closer to overhead illumination, however this reduces the benefit of emphasis of less-well delineated forms within the landscape. A second solution is to change illumination azimuth by 180º to illuminate areas that were previously in shadow (Figure 6.18c). This worked well, however it adds a further two images that then require viewing. In addition, some observers may find it difficult to map as it may have the optical illusion of inverting the landscape, although this can be mitigated against by turning the image upside down.

One of the limitations of relief shading noted in Chapter 5 was the assumption of an homogenous, specular, surface. The relief shaded scene therefore visualises high reflectance from all surfaces. This has the effect of removing shadow from areas of high reflectance and therefore making bedforms difficult to map, an inverse to the problem noted above (Figure 6.18a). Lowering the

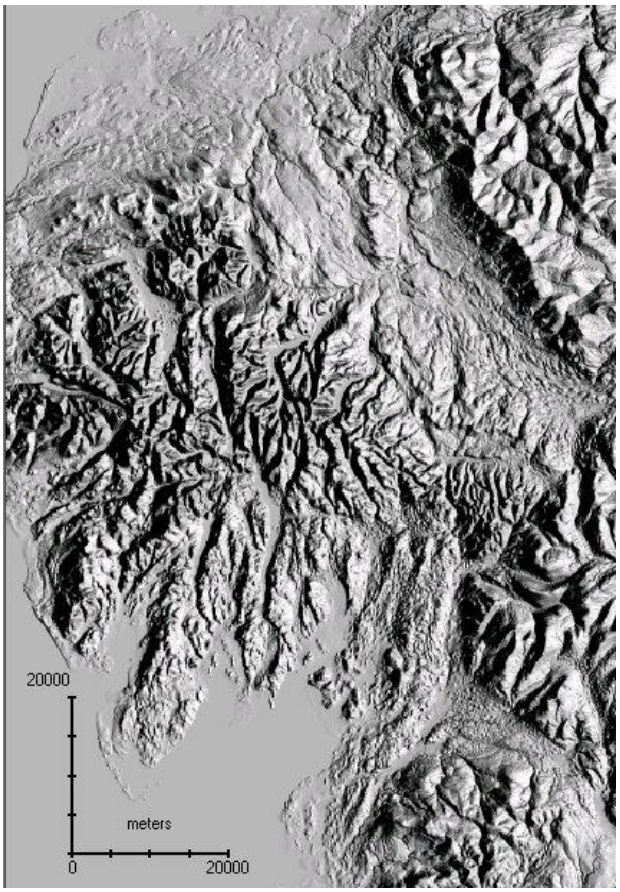
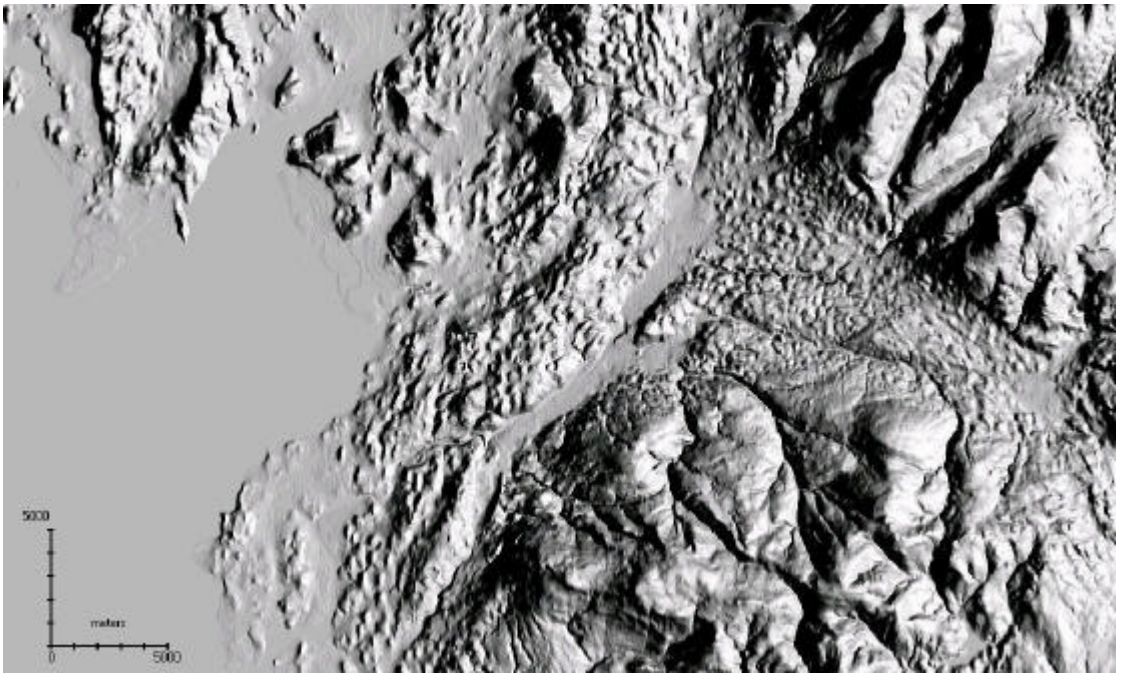


Figure 6.16 a. (top) Relief shaded DEM data of the Lake District, United Kingdom. Relief shading is from the east, orthogonal to dominant lineament direction (©Ordnance Survey).

b (bottom) Zoomed section of figure a. In comparison to 6.15b the lineaments in the north central region are strongly defined, whilst the bedforms in the east central region appear to composed almost entirely of hummocky terrain.



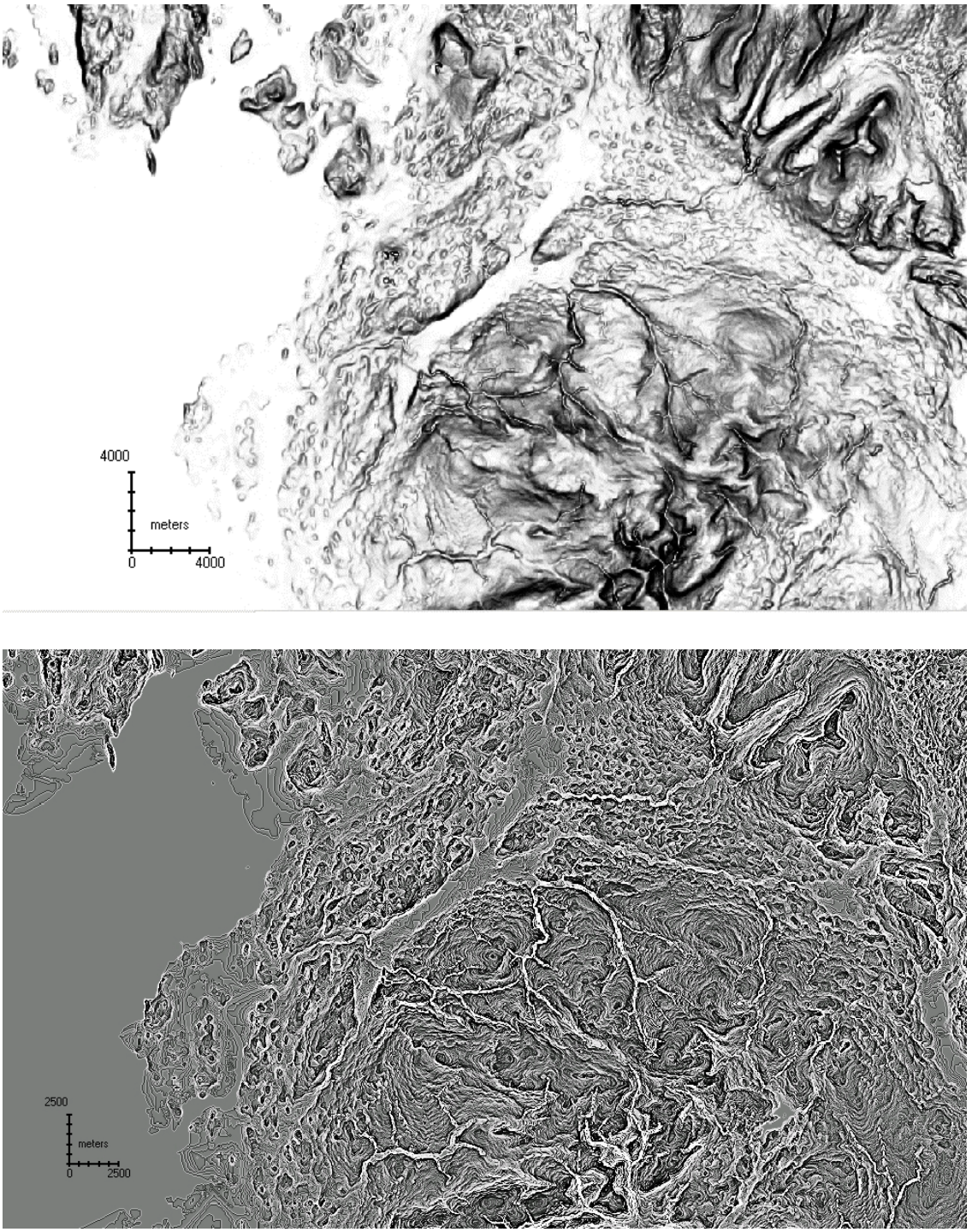
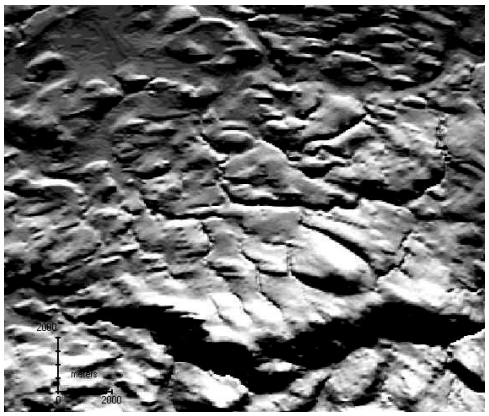
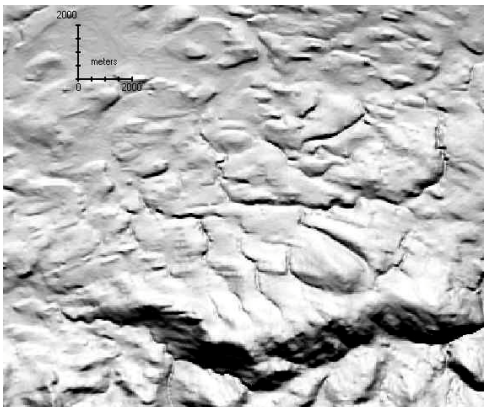


Figure 6.17 a. Gradient calculated from the Lake District DEM data (top). The principal landform elements appear similar to those using orthogonal shading. b. Profile curvature calculated from the Lake District DEM data (bottom). Although more difficult to interpret there is a lot of detail present.





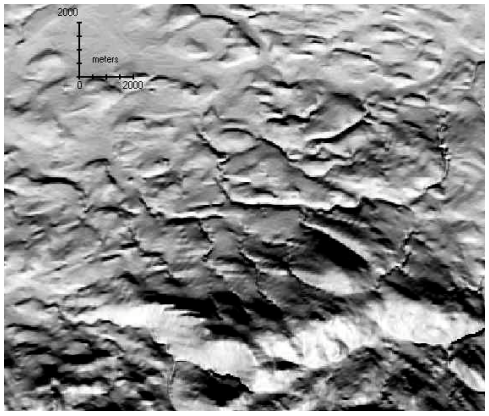
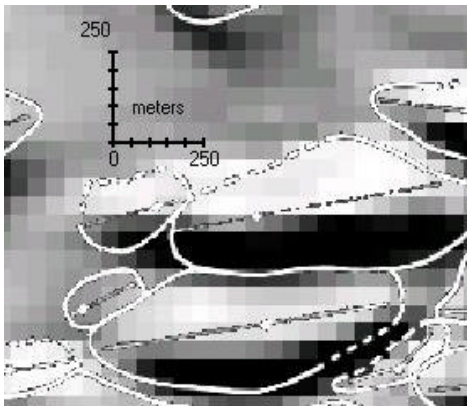


Figure 6.18 a,b,c Relief shaded DEM's of the Lake District, illustrating the problem of shadow. A standard relief shaded image (illumination from the north with mid-illumination elevation; top left) has landforms hidden in the shadow on the south side of the main bedrock ridge. High illumination elevation (top right) solves this problem, but then obscures bedforms on the north side of the ridge through high reflectance. Relief shading from the south (bottom) can also mitigate this problem, however some observers may need to invert the image (©Ordnance Survey).



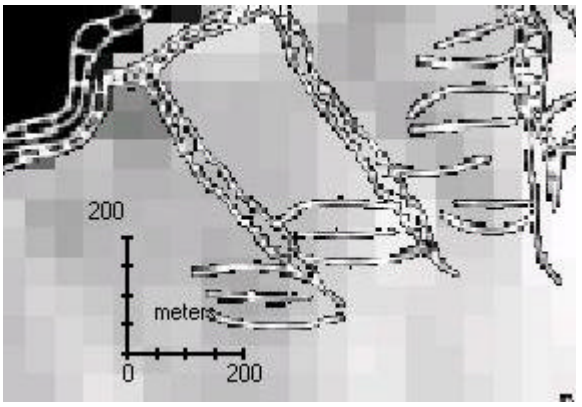


Figure 6.19 Relief shaded DEM (left; shaded from the north) overlaid with field mapped data (Riley, 1987). Large lineaments are clearly visible, whilst smaller ones are not. A second relief shaded DEM (right; shaded from the north) overlaid with field mapped data (Mitchell, 1994) showing that spatially large lineaments may not be visible. In this case the relief of lineaments is too small to be detected by the DEM. (©Ordnance Survey).

illumination elevation angle helps mitigate against this, but then puts other areas of the image in shadow such that they cannot be mapped from (Figure 6.18b).

One final area of difficulty is concerned with the resolution of the DEM. Horizontally, the OS DEM has a pixel size of 50m. In practise, mapping landforms less than ~200m in length is difficult (Figure 6.19a). The vertical resolution of the OS DEM is based upon contours from the original 1:50,000 map series which have an interval of 10m. Clearly this will not be sufficient for lineaments with a low height as they will not be delineated (Figure 6.19b), even if they are spatially extensive.

6.6.3 Mapping Results

This section briefly presents the mapping results of the case study for the Lake District, using the DEM and mapping techniques described above. The pullout map (back cover) displays the lineaments, transverse and circular/ovoid bedforms that were mapped during this process. Immediately noticeable are the lineaments in the north that tightly curve around the northern extent of the Lake District mountains. They display parallel conformity such that they appear to make up one contiguous set of lineaments. This continues south-east towards the eastern edge of the area. The density of lineaments, in comparison with the rest of the area, is relatively low. There are few hillocks, other than on the outer northern fringe. There is also a small set of lineaments oriented towards the north-east.

The eastern fringe of the area is a region of very dense bedforms, including lineaments intermixed with hillocks and irregular shapes. Initially it might appear that the lineaments oriented N-S join with these, however closer inspection shows that some lineaments are oriented at up to 90° to one another. The irregular make up of bedforms in this area suggests that there is a mixing of different bedforms from different flow events and this is supported by the presence of cross-cutting lineaments. Indeed, lineament orientations suggest three main sets broadly oriented south-east, south and east.

The southern portion of the image is composed of a mixture of easterly and northerly oriented lineaments, intermixed with many hillocks and irregular shaped forms. Unlike other parts of the area, lineaments encroach upon and traverse across areas of relatively high relief. This is particularly apparent in the areas previously field mapped by Mitchell (1994; Figure 6.19b). It also shows that in these upland regions, at least, there are many smaller bedforms that are unresolvable by the OS Panorama© DEM data (the following section discusses this in more detail).

Given that lineaments were actively being formed at high elevations, it is surprising that there is a band where no landforms have been mapped separating the north and south. This apparent absence of lineaments is possibly due to them being undetectable by the DEM at the current resolution. Further investigation would be required to confirm this.

Closer inspection of the easterly oriented lineaments suggest that these can further be split into two separate groups. The eastern and central areas of the south, have lineaments oriented in a south-easterly direction that, in at least one location, cross-cut with easterly oriented lineaments. The easterly oriented lineaments continue into the central region and intermix with the southerly oriented lineaments. This latter group appear consistent with those from the northern region. The south central and easterly areas are composed of heavily deformed transverse ridges and hillocks which are indicative of re-orientation of landforms within this area by later ice flow events.

This section has described the basic patterns evident from the landform mapping presented earlier. It also highlights interesting features within the dataset that can indicate different flow stages and later be used to interpret the ice flow evidence. Chapter 7 goes on to provide techniques to aid in the preparation of lineament data for interpretation. This case study is explored further in that chapter.

6.6.4 Comparison with Field Mapping

Due the abundance and quality of lineaments, in comparison to other areas within the UK, the Lake District has been the focus for several mapping exercises. These include Hollingworth (1931), Raistrick (1933), Burgess (1979), Vincent (1985), Riley (1987), Arthurton (1981, 1988), Boardman (1981), Whiteman (1981), Mitchell (1994) and Brandon (1998). Riley, Mitchell, Whiteman and Boardman produced detailed morphological maps, whilst British Geological Survey (BGS) memoirs produced by Burgess, Arthurton and Brandon all contain maps of drumlin location and orientation. In addition, these data have been incorporated into a *generalised* glacial landform map of the UK through the BRITICE project (Clark, 2002). It is therefore appropriate to compare the mapping performed in this thesis, with those of previous exercises. This will focus on a comparison of field mapping with the DEM and the data mapped from it.

Moderately detailed mapping was performed by Hollingworth (1931), who covered the Eden Valley and Solway Basin, and Raistrick (1933), who reviewed the area around Settle. Vincent (1985) provided a general description of the area immediately around Morecambe Bay. In all cases the broad orientation of lineaments is matched by that of the DEM mapping.

Burgess (1979), Arthurton (1981, 1988) and Brandon (1998) all produced summary drumlin location maps in the geological memoirs accompanying BGS 1:50,000 map sheets. Drumlin mapping is not within the direct remit of the BGS and therefore the quality and methods employed is dependent upon the individual members of the survey. The above authors could have used satellite imagery, topographic maps or aerial photography, referenced to a field based overview, to perform their mapping. Detailed morphological mapping is unlikely given the time consuming nature of the process. Only Brandon (1998) provided detailed mapping (covering the Lancaster region), whilst all the remaining authors performed drumlin crest mapping.

Burgess covered the Brough region. The mapping is very general and could well have been performed directly from topographic maps. It covers the same

region as Riley (1987; see below), with the latter providing detailed morphological mapping. Arthurton covered both the Settle and Penrith regions. Penrith occupies the lower Eden valley, close to the Solway Firth. The general location and orientation of drumlins is matched by the mapping performed here, although more forms are included. The Settle region covers broadly the same area as Raistrick (1933); only the western area mapped by Arthurton is covered in this research. Again the broad distribution and orientation of drumlins is similar. Detailed mapping by Brandon (1998) shows very close agreement with the relief shaded DEM (Figure 6.20a), however Figure 6.20b is dominated by small, ovoid, bedforms with no preferred orientation. This borders a region tentatively interpreted as ribbed moraine and are possibly representative of highly dissected transverse bedforms. Overall the similarity between the two datasets is very good.

The detailed morphological maps of Boardman, Whiteman, Riley and Mitchell are now discussed. Boardman (1991) mapped drumlins immediately around Keswick and further west at Troutbeck Station, just bordering the Eden Valley. Both sets of drumlins are moderately small (~300-500m long) and, although just resolvable on the DEM, were not mapped due to their isolated nature and uncertainty over their origin.

Figure 6.21 shows the field mapping of Riley (1987) overlaid on a relief shaded DEM. On reviewing the mapping of Riley it is immediately apparent that there is strong correlation between the two datasets. Although some lineaments are not visible on the DEM, these are the exception and are probably below the resolution capabilities of the DEM data. The fit of the remaining data is excellent, even matching changes in the shape of individual lineaments. It should be noted that this area is generally flat, having well defined lineaments which are up to 950m long and 50m high. The mean lineament length is 325m, with a standard deviation of 175m. They are consequently large, well defined landforms. Riley does go on to discuss cross-cutting drumlins. These have been heavily modified by subsequent ice-flow and are visible on the DEM. Similar mapping was performed by Whiteman (1981) just to the north-west (surrounding Appleby) with a close match to the underlying DEM also good.

Field mapping performed by Mitchell (1994) is depicted in Figure 6.22. This bears almost no relation to the DEM. Although there are some lineaments which align well, there are many lineaments for which there is no direct comparison, whilst others have a vague representation on the DEM. Lineaments are oriented in many directions in this complex area and changing the illumination azimuth helps further mapping. However many of the lineaments mapped by Mitchell are at, or below, the resolvable threshold. This is confirmed by the statistics for the area, which show a mean length of 220m and a standard deviation of 90m. The maximum lineament length is 640m. This highlights the resolution limitations of mapping from this DEM, although there will also be accuracy limitations in both the mapping and plotting of the original fieldwork. One further explanation for the discrepancies is the low relief of the lineaments (Mitchell, pers comm). Inspection of 1:10,000 and 1:25,000 maps shows no lineaments. Both these series have a 10m contour interval and are unable to define these landforms. More detailed mapping is unavailable due to the remote, upland nature, of the terrain. As the OS DEM is created from original 1:50,000 mapping with 10m contours, it is not possible to extract the lineaments from the surrounding terrain. Indeed DEM interpolation from the contours will have smoothed the slope so that they are not visible. Further examination of 1:10,000 aerial photography reveals *some* of the lineaments. The high resolution, in comparison to the DEM data, allows better interpretation of the landscape, however there are many lineaments which are not clearly identifiable. Mitchell (pers comm) states that the relief of the lineaments is small and that field mapping is the best method for their identification.

Finally, Figure 6.23 shows the lineament mapping overlaid onto those of the BRITICE project. The BRITICE project used photocopies or scanned images of the original, published, mapped data from which lineaments were generalised into a single data source. By its nature, this is not an accurate procedure. The original sources for compilation may well have inaccuracies or inconsistencies in both the mapping and coordinate system. Indeed, many “maps” do not use a coordinate system and require “eyeballing” into an approximate location.

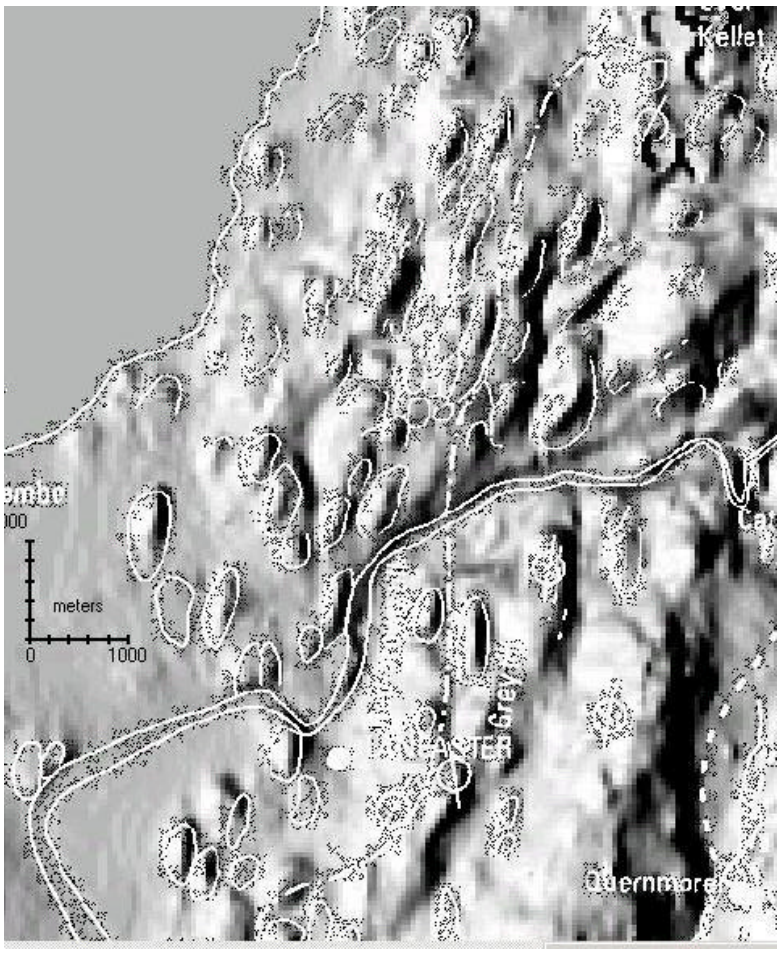


Figure 6.20a Relief shaded DEM (shaded from the west) of the Lake District overlaid with field mapping data from Brandon (1998). Note the close correspondence between the DEM and the field mapping (©Ordnance Survey).

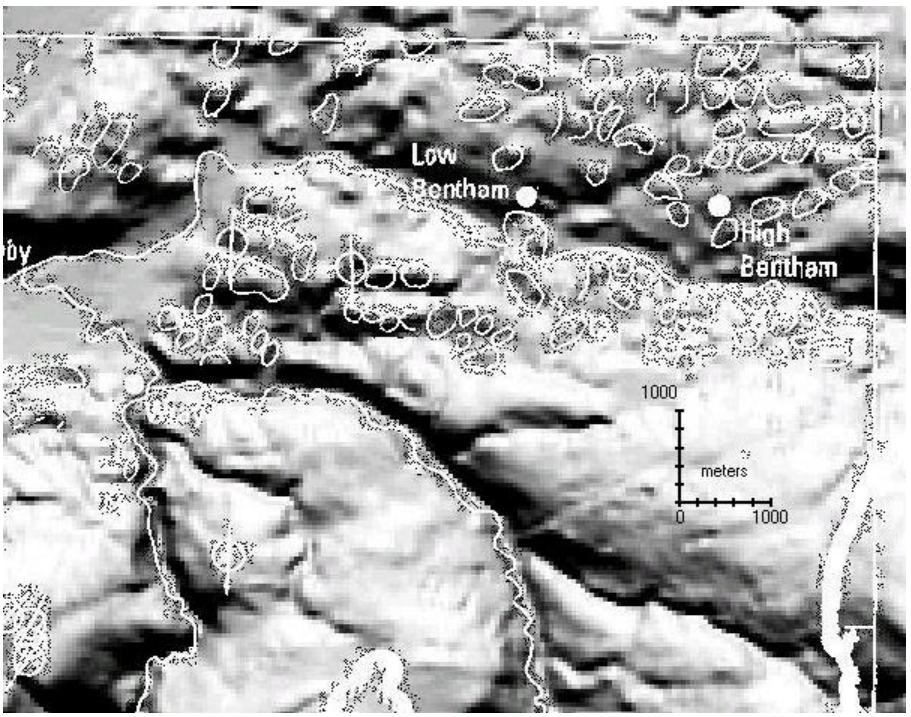


Figure 6.20b Relief shaded DEM (shaded from the north) of the Lake District overlaid with field mapping data from Brandon (1998). Note small, ovoid, bedforms with no preferred orientation in the top right corner (©Ordnance Survey).

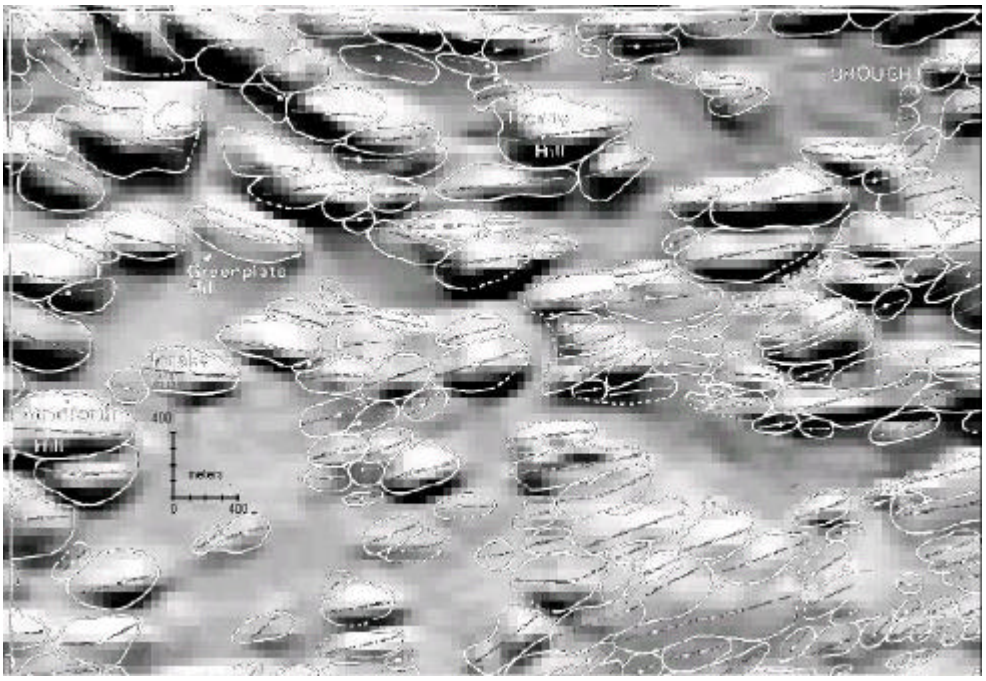


Figure 6.21 Relief shaded DEM (shaded from the north) of the Lake District overlaid with field mapping data from Riley (1987). Note the close correspondence between the DEM and the field mapping, although smaller lineaments are not visible on the DEM (©Ordnance Survey).

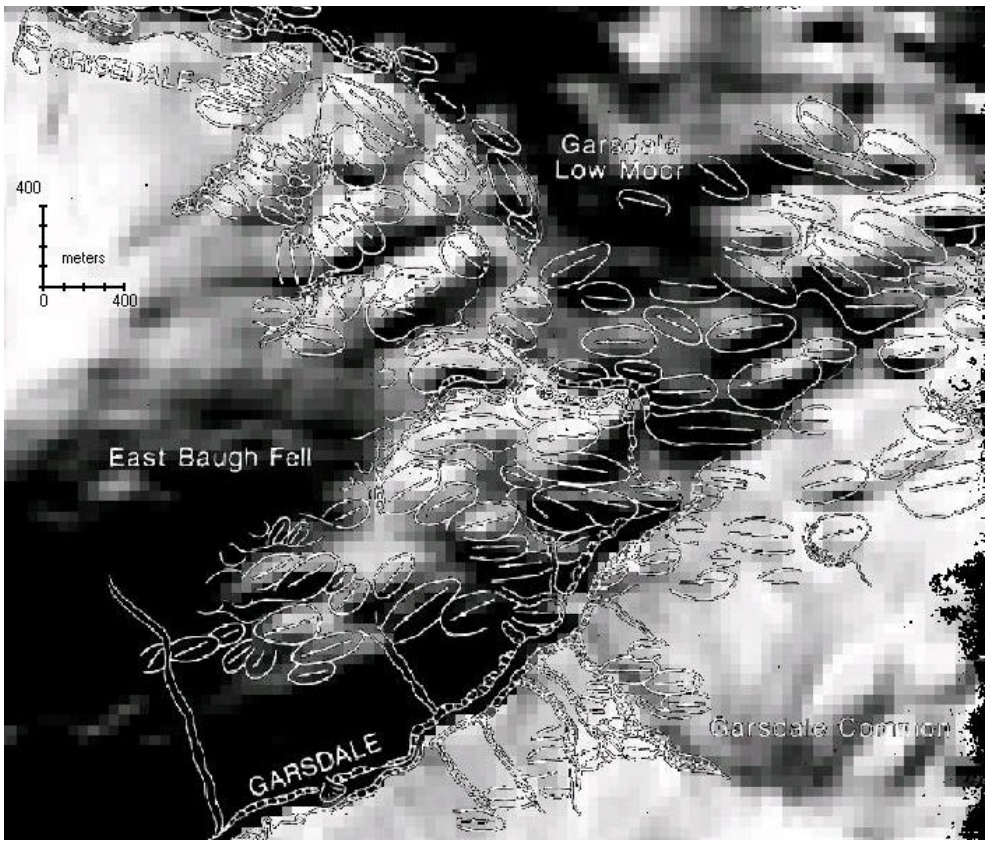


Figure 6.22 Relief shaded DEM (shaded from the north) of the Lake District overlaid with field mapping data from Mitchell (1994). Note the poor correspondence between the DEM and field mapping. Some larger lineaments (middle left) are visible, whilst others are not.

In general there is good correspondence between the two data sets, although the DEM mapped data is generally more numerous. However both sources have small, localised, regions of mapping where there is not coverage by the other. In the north both data sets show the tightly curving lineaments around the north of the Lake District, with the suggestion of a further flow direction towards the north-east. The eastern region again shows two or three main flow components, although the BRITICE data show no cross-cutting landforms. This is unexpected as Riley specifically discusses cross-cutting in this area. In the southern portion of the Lake District, the BRITICE data is sparse. In the mountainous area in the east there are some lineaments which generally confirm the mapping from the DEM, whilst in the central region there are virtually no landforms mapped. This area is perhaps one of the most interesting areas as the bedforms are heavily deformed and record multiple flow directions. Indeed nearly all the mapping here represents new data.

This section has compared the DEM mapped data with those performed by field mapping. These publications have essentially been used as verification through being used as a higher resolution data source. In general the DEM data have performed very well, however issues of completeness as a result of both horizontal and vertical resolution need to be born in mind. Given the coverage of DEM data and the speed of mapping, these limitations are fairly minor. Further investigation could be appropriately directed at higher resolution DEM data to assess the potential benefits and to see if the above issues can be resolved.

6.6.5 DEM Datasets

Although §6.3-6.5 outlined, tested and reviewed a variety of different methods for visualising DEMs, this has been performed using data supplied by the Irish Ordnance Survey (IOS) based upon direct terrain extraction (DTE) from stereo aerial photography. The above case study used Ordnance Survey (OS) data based upon DEMs interpolated from contours created using stereo aerial photography. The products clearly have different derivations and this section addresses some of the issues that arise from this.

Chapter 4 introduced some of the different methods used to create DEMs. These are principally the conversion from contour data, satellite stereo imagery and radar interferometry. Contour based DEMs have traditionally been the most popular, but with the rapid collection of remotely sensed terrain data the other types are becoming more common. The IOS and OS DEMs used in this chapter have been produced using different methods and, although the visualisation techniques apply equally, the two DEMs are not directly comparable. It is worth noting the following points about these DEMs:

- DTE measures the exact surface height and so will incorporate the elevation of vegetation and buildings into the DEM.
- Contours typically attempt to represent the actual, bald earth, surface. The landscape is smoothed during the generation of contours, with further smoothing sometimes taking place during interpolation, although there will also be the introduction of noise.
- There is less contour information available for interpolating DEMs in flat areas and ”stepping” is often noticeable.

These three main points affect the methods used to visualise the DEMs. The “rougher” surface produced by the DTE DEMs should produce a lower level of specular reflection under relief shading, adding a “fuzzy” texture. This feature is not apparent on the Irish DEM, perhaps a result of the low levels of urbanisation and a rugged upland landscape (i.e. little surface cover). The Irish DEM was also initially produced at 10m resolution and then re-interpolated down to 50m (O’Reilly, pers. comm 2003). This will undoubtedly have smoothed the landscape.

Relief shading is therefore not seriously affected by the differences between DTE and contour based DEMs, however the same is not true of the shape related (non-directional) terrain visualisation methods (i.e. curvature, gradient and local contrast stretch). These rely on terrain shape and it is not surprising that they perform less well when based upon contour generated DEMs. Figure 6.17b shows curvature for the Lake District, depicting the strong influence of contours on the image, particularly in the flatter coastal areas (e.g. north-west part of the figure). There is still a lot of very useful information in the image

making it worthwhile to use during the mapping process, however interpretation is much harder in comparison to the one created from the Irish Ordnance Survey DEM. Similar observations can be made concerning the local contrast stretch and gradient images.

Overall, this highlights the differences between DEMs generated using different methods. Further investigation could be usefully applied to describing the broad parameters effecting the different types of DEM and how these affect the uses to which the DEM is put. In this context, the visualisation techniques that have been assessed will all broadly operate in the same manner, however some are better suited to certain types of DEM. The generation of a better quality curvature image is strongly beneficial for the use of DTE data. Further investigation of SAR interferometry (both space and airborne based) and satellite stereo imagery will highlight the benefits and deficiences in using this data.

6.7 DiscussionandConclusions

Satellite imagery is likely to be replaced by DEM data and this has been used as a data source for landform mapping by several researchers. Again comments have been made concerning the best use of relief shaded DEMs, however no one has faced the central issue of how best to visualise 3D data. Stereoscopic mapping is perhaps the most preferable. Even where suitable small scale photography is available (~1:150,000), the process is time consuming and, if geometric accuracy is desired, difficult. Workstation based methods are slowly arriving and will hopefully provide a more integrated visualisation and mapping based approach. However the high cost of proprietary software and hardware mean that this will not become a ubiquitous method for some time.

The advent of near-global DEM data provides an economic and quick alternative. Three dimensional viewing of digital DEM data has been available on commercial grade photogrammetry workstations for some years. This technology is beginning to filter down to mid-range computer mapping solutions, however it is still expensive and often requires proprietary software and

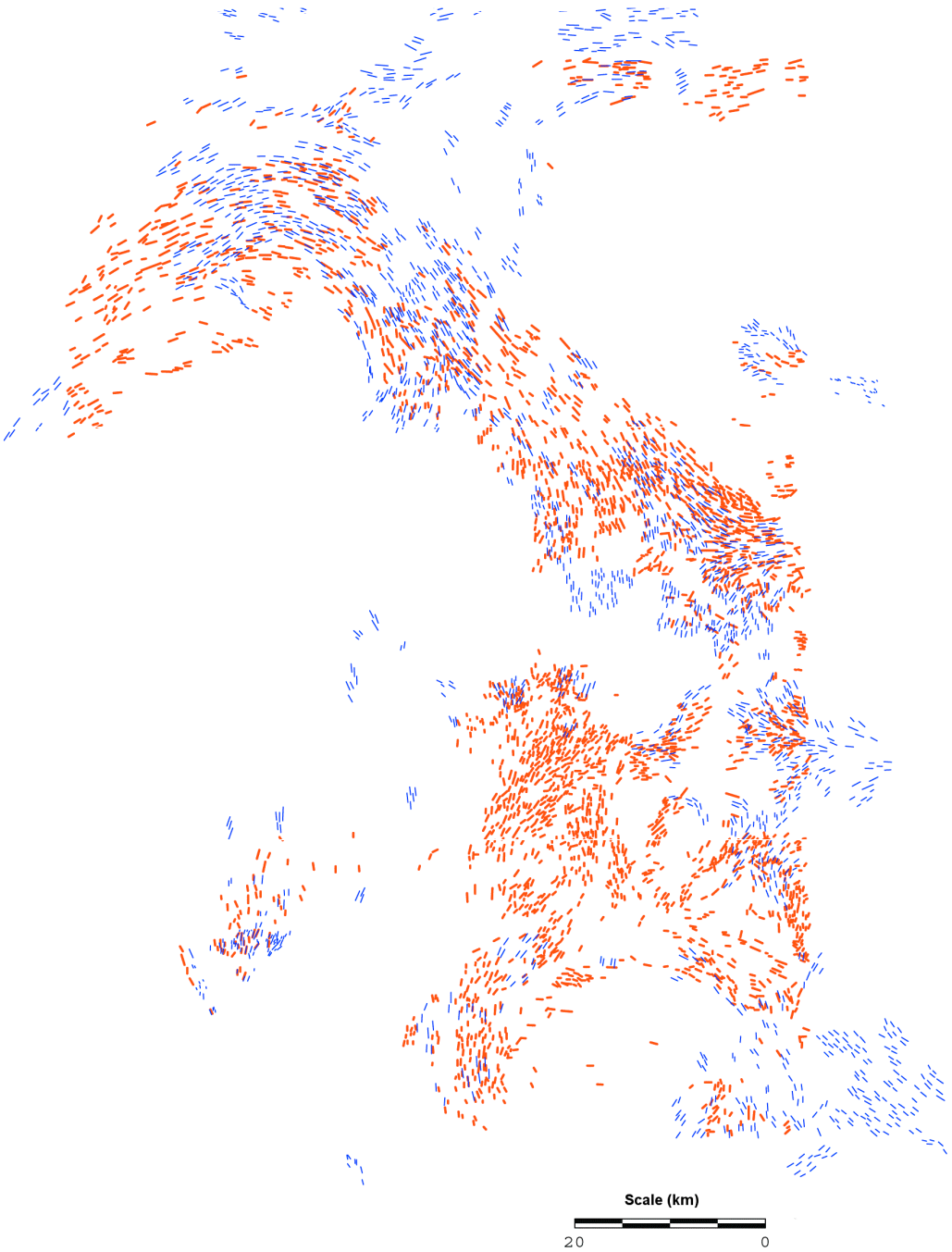


Figure 6.23 Lineaments mapped for the BRITICE project (blue) overlaid on those mapped and from the DEM data (red). In general there are far fewer lineaments in BRITICE, although the general trends match well. BRITICE has far less data for the southern region, although there are small localised clusters throughout the area which are not present on the data mapped from the DEM.

hardware. In addition, to be of use, it must allow the observer to digitise orthographically, even when viewing perspectively. This technology is not accessible, or cost-effective, for many researchers and therefore appropriate methods of viewing 3D terrain in two dimensions are needed. Section 6.2 presented a variety of different visualisation techniques, including relief shading, image processing of textures and analysis of curvature. These techniques all provide different ways of interpreting the terrain; some introduce bias' which may disguise certain landforms or enhance them to make interpretation easier. They are all designed to help the observer explore their data further so that appropriate mapping can then take place. Five of these techniques were tested in their ability to represent glacial landforms. Section 6.4 presented the results of these inter-comparisons, with §6.5 making recommendations for the use of DEM data in a systematic mapping exercise. Finally, §6.6 used these recommendations in providing a case study for glacial landform mapping from DEM data. The Lake District was selected for the case study as it provides a complex array of landforms and relief that make mapping difficult. It is clear that no single visualisation method is able to provide a source for consistent, complete, mapping. Rather, one or two methods are required to map the majority of landforms and these need to be supplemented with a variety of other visualisations in order to cross-check and complete the mapping exercise. It is preferable to begin mapping with a bias free visualisation (i.e. gradient or slope curvature) and, once first pass mapping has been completed, move on to supplementing this data with mapping from parallel and orthogonal relief shaded imagery. This sequence is important as it places more emphasis upon the use of bias free visualisations during the initial mapping phase.

This chapter has been concerned with the methods used to visualise DEMs for landform mapping, so that consistent data can be acquired. However DEMs are created from a variety of different sources and it is important for the observer to be aware of the implications of using different datasets. DEMs were originally developed from contour maps produced using field and aerial survey data. The resultant digital DEM data products have therefore been interpolated, with the exact methods used determining the quality of the final data set. For example, the Panorama© data were originally produced for military applications and so

individual grid cells contained maximum height values to make sure that aerial guidance systems could guarantee they were “above surface”. However, alternative acquisition methods are now driving the production of modern DEMs and with them come different data quality issues.

Digital aerial photography, digital photogrammetry and SAR interferometry are the most popular methods currently in use. The type of sensor, and whether they are spaceborne or airborne, will determine the specific type of dataset that is eventually acquired. Chapter 5 briefly introduced some of the DEM alternatives to using satellite imagery for landform mapping, including ASTER and SRTM. The availability of data for the UK is particularly illustrative of the recent interest and explosion in DEM data sets.

The original Ordnance Survey Panorama™ 50m and, higher resolution Profile™10m, data are currently available. CHEST has recently released the Landmap dataset (25m resolution) which was created using spaceborne SAR interferometry (ERS Tandem strip data). The SRTM C-band (30m and 90m resolutions) and X-band (25m resolution) data will shortly be available. Finally, Intermap has recently completed airborne SAR interferometry with the intention of producing a high resolution product (3m resolution) of the whole country and an ultra-high resolution product (0.3m resolution) of urban areas.

Before any mapping begins, it is important to appreciate the characteristics of the source data set, including any limitations in its use. For example, the Landmap DEM is a *surface* model, in that it provides height values for the visible surface. It does not provide height values for the bare earth or basic terrain. Therefore it may be unsuitable for landform mapping in a heavily forested landscape.

With appropriate visualisation methods and an understanding of the constraints imposed by different DEM datasets, an observer can be confident that, within these constraints, an accurate and complete mapping exercise has been performed. Chapter 7 now goes on to review the methods by which this mapped

data is incorporated into a glacial reconstruction and implements techniques by which this can be performed in an objective and quantitative manner.