7 Lineament Spatial Variability and Classification into Flow-Patterns

7.1 Introduction

Aerial photo and satellite image mapping has revealed complexity within glacial landform assemblages that had previously been unrecognised (Clark, 1993). An increase in the amount of data has forced a re-evaluation of interpretive methods that has resulted in a shift away from a tendency to “clump” lineaments together into single generalised flow patterns, to “splitting” them into components of distinctive patterns that record flow configurations at different times (e.g. Figure 7.1). This process allows the development of alternative interpretations from which realistic flow configurations can be devised. Lineament generalisation and interpretation is concerned with how complex patterns of individually mapped lineaments can be coherently organised into feasible glaciological scenarios.

This chapter reviews the manual approaches used in generalisation and how these are applied to glacial reconstructions. Technical and methodological advances in mapping and understanding glacial assemblages mean that new demands are being placed on the interpretation of mapped data. With the complexity of the processes that create landforms being unravelled, it is vital that both mapping and generalisation are performed as objectively as possible, such that they are reproducible by other researchers. This chapter explores and presents a set of techniques to allow researchers to do this, concluding with a discussion of best practice.

7.2 Generalisation:AVisualMethodology

7.2.1 Introduction

Although chapters 2 and 4 introduced the concepts behind the generalisation of raw lineament data into recognisable flow patterns so that they could then be interpreted, it is hard to appreciate the difficulty that this task presents. Figure 7.2a shows nearly 12,000 lineaments mapped from a part of Canada (after Stokes, 2001). The patterns displayed by this data are both complex and

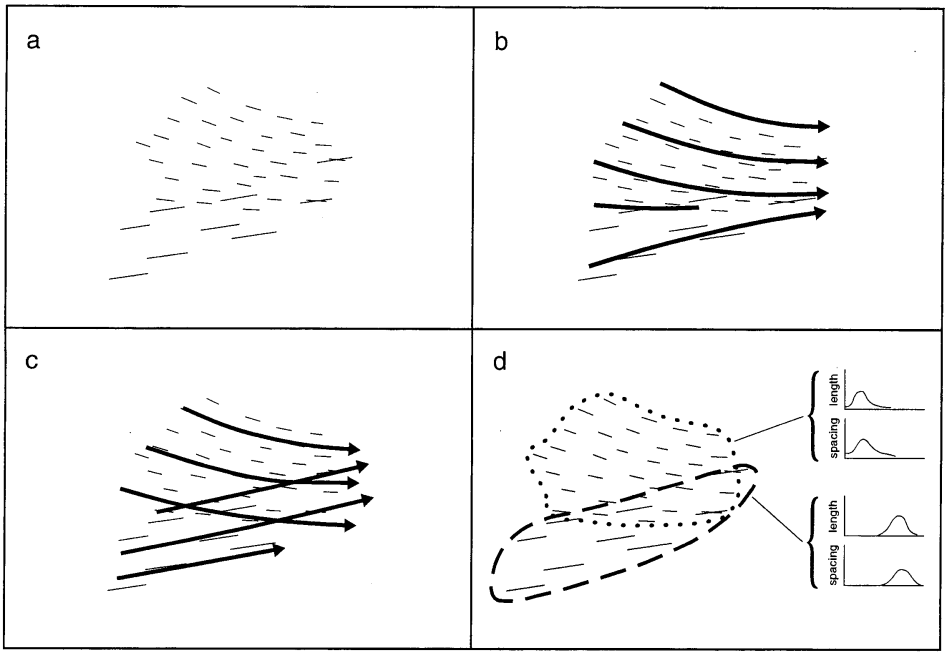


Figure 7.1 (a) shows individual mapped lineaments. These would traditionally have been interpreted as representative of a single ice flow event (b), however cross-cutting evidence means that they must have formed from two events (c). In the absence of cross-cutting indicators, interpreters visually discriminate between flow patterns, however flow pattern characteristics can potentially provide quantitative methods to validate such groupings (Clark, 1993).

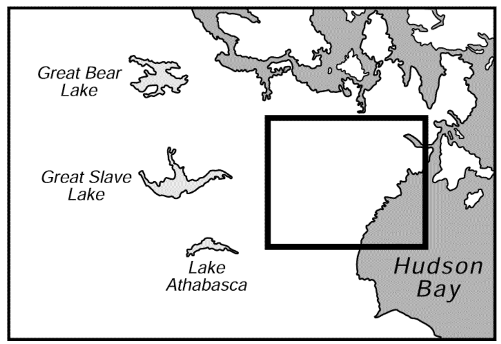
confusing. Trying to order the data so that a concise set of flow patterns can be produced allowing interpretation and explanation is a time consuming task. This has traditionally been performed using manually based, visual, techniques. They are strongly dependent upon the ability and experience of the interpreter and it would be easy for this qualitative assessment to include an element of interpretation. Figure 7.1 illustrates a scenario which could be generalised into one converging flow pattern or two cross-cutting patterns. Clearly the presence of cross-cutting is important here, however the characteristics of each flow pattern can equally be used to verify that such a division exists. Ideally generalisation should form a semi-quantitative stage that can then go on to produce flow sets which can be interpreted. Figure 7.2b shows the flow sets that were generated from the raw lineament data presented in Figure 7.2a. Generalisation is therefore a stage which goes from "more" data to "less" information. It is this process that identifies broad trends within the data set and allows them to be highlighted for later interpretation. The following section introduces the visual heuristics used by researchers to perform such a task, before going on to suggest how better techniques may be used to implement this.

7.2.2 Identification

Within the context of glacial lineaments, generalisation involves the simplification of detailed landform patterns (recognition of the main trends) by removing potential noise and random effects. This initial stage provides a reduction in the complexity of lineament patterns. The reduced data set is then classified into component flow sets (see §2.3).

A visual approach to generalisation begins with the premise that *a similarity of form indicates a similarity of formation* (see below for a full discussion of the different variables this includes). Given that flow sets can vary in time and space depending on whether they are identified as synchronous or time-transgressive, it holds that flow patterns can also vary in time and space. This extra layer of complexity in interpretation, produces a similar increase in complexity of the original mapped lineaments. However simply because

Figure 7.2 (a) Example of 'raw' lineaments mapped from satellite imagery for the Dubawnt region, Canada (Stokes, 2001). There are nearly 12,000 lineaments that need to be generalised into a simpler dataset ready for interpretation.



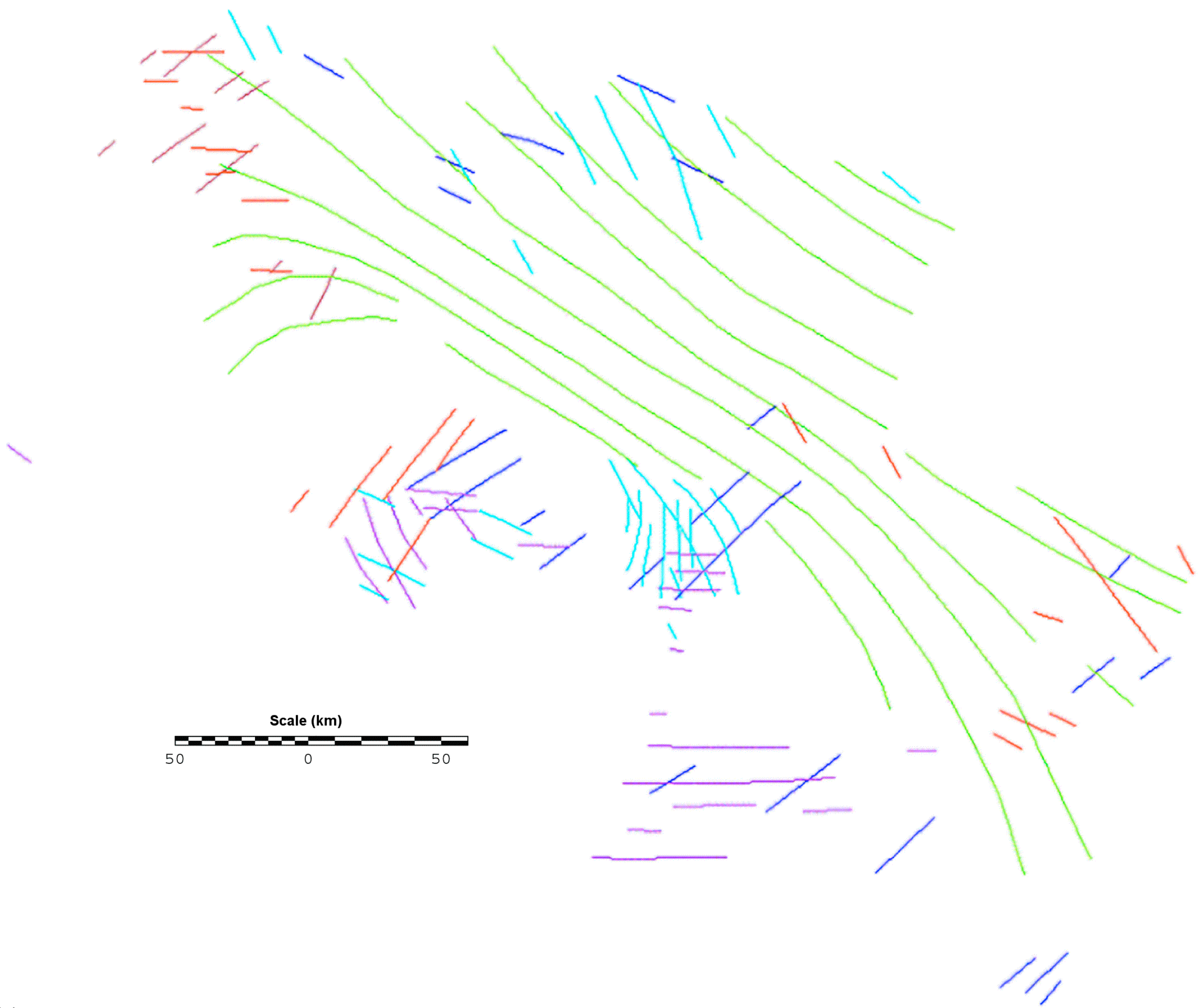


Figure 7.2 (b) Flow sets produced from Figure 7.2a have reduced the amount and complexity of the raw data allowing an interpretation of the main flow patterns (Stokes, 2001).

lineaments do not display consistent spatial trend in morphometry and orientation does not mean they do not have a similarity of formation. The identification of lineament similarity needs to address these complexities and as a result needs to be performed at the local scale, identifying gradual changes in form, in order to reveal patterns at the regional scale. This distinction is important as visual identification requires devolving a complex pattern at large scales (to produce flow patterns) and then combining these results to reveal a global arrangement (flow sets). Methodologically, this involves the non-interpretative generalisation at the local scale (e.g. flow patterns), before interpretative generalisation occurs at the regional scale (e.g. flow sets).

As similarity of form controls whether a lineament is included within flow pattern or flow set membership, it is important to understand which morphological variables are visually useful and the manner in which they are used. These include:

- Orientation
- Orientation conformity (or parallel conformity)
- Length
- Length conformity
- Spacing (density)
- Spatial Continuity

- *Elongation ratio (and other shape factors)*
- *Height*
- *Material composition*

The availability of data depends upon the method in which lineaments have been surveyed; if this has involved digitising from satellite imagery, height and composition data will not be available. Historically, satellite imagery has not been detailed enough to map beyond crestlines (i.e. outlines or break-of-slope), although the availability of economic, and high resolution, Landsat ETM+ data is changing this. Crestline mapping also allows large areas to be covered rapidly. The advent of high resolution, widely available, DEM data means that, for many areas height *and* shape information will be available. Although height varies within groups of lineaments, this is usually related to length, width and volume. In terms of understanding lineament flow patterns, it is less useful.

Lineament morphometry has been studied in detail to help decipher the glaciological context of sediment emplacement, with the elongation ratio a popular shape factor (Menzies, 1987). The value of this information is debatable as lineament length can be considered a good proxy. Indeed, variation in lineament shape can be due to cross-cutting through superimposition and re-orientation. Within these contexts, the elongation ratio is meaningless. For these reasons, and because lineaments are most commonly mapped, the remaining discussion will focus solely on mapping lineament crest lines.

A crestline is composed of a single line and its attributes are therefore length and orientation. As generalisation is concerned with similarity *between* forms, conformity of orientation and length can also be considered, in addition to the density and spatial continuity of lineaments. These six variables (highlighted above) form the basis of any generalisation procedures.

Orientation conformity, or *similarity in orientation*, is probably the most influential variable as an observer will be visually drawn to this feature. If a lineament is surrounded by like oriented lineaments, the strength of similarity is high. As this check is performed at the local sale, gradual changes in orientation, whilst maintaining parallel conformity, are allowed (e.g. Figure 4.11).

Equally, similarity in length is expected, with gradual changes in length (within an individual event) allowed. This is related to the speed of ice flow, sediment supply and residence time. However, there may be groups of lineaments whose length are very similar or (as in Figure 4.11) groups of long lineaments surrounded and intermixed with lineaments of a variety of sizes. This is not a random mix but a structured intermixing.

Finally, density and spatial continuity need to be considered. Lineament density should be consistent throughout a group of lineaments. Again this can be expected to change gradually, however it is common for “gaps” to appear within groups of lineaments. This is due to topographic (i.e. relief) or glaciological factors. Groups of lineaments should still appear continuous, as large gaps could well signify a separate ice flow event.

This section has outlined the importance of grouping lineaments locally and has identified the main variables that are used to do this. However nature is far more complex, and makes generalisation difficult. For example, Figure 7.3 shows two hypothesised splaying lineation patterns. Although initially similar in appearance, the first shows high orientation conformity (Figure 7.3a) and no cross-cutting, whilst the latter has low orientation conformity (Figure 7.3b) and cross-cutting. The latter pattern can easily be mis-interpreted which leads the interpreter to a different set of contextual assumptions concerning the process of formation. This would then be interpreted into flow sets incorrectly. To complicate this record of a single event, it would be possible for the pattern to be further intermixed with a later, superimposed, set of cross-cutting lineations. Deciphering this record of landform assemblages requires an understanding of how they were formed with as an objective generalisation of the original mapped data as possible.

7.2.3 Quantitatively Based Solutions

The above sections have outlined the scope of the problems involved when generalising and how current manual methods attempt to solve them. The methodologies developed to interpret complex ice flow patterns place new demands upon the data (and consequently the techniques and processes by which they are collected and collated) which they are based. Although a whole variety of landform data are collected, lineaments are the most common, widespread and prolific. For these reasons, generalisation is necessary. At its most basic, the data is simply composed of lineament crestlines which allow the use of length and orientation, and their associated variables, to be use for generalising. Above all else, generalisation needs to be locally based and adaptive. Therefore any solution to providing objective-based generalisation needs to consider the above factors. Two broad approaches can be devised:

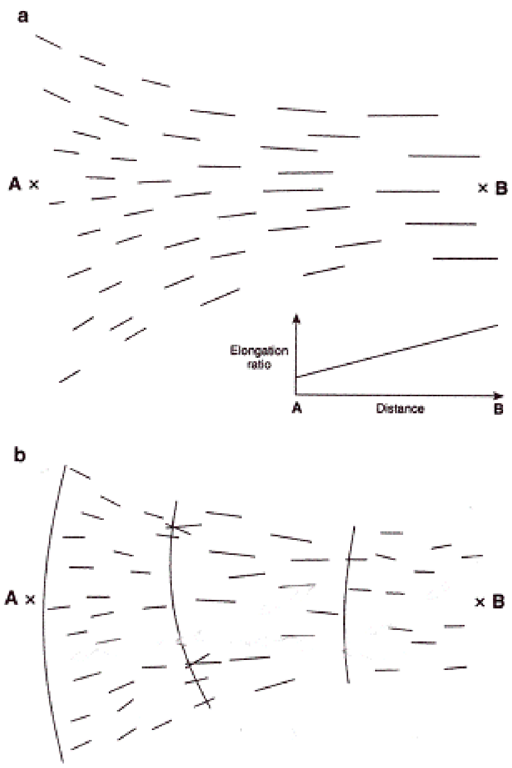


Figure 7.3 Lineament generalisation needs to correctly identify flow patterns. In this scenario, (a) depicts clearly defined lineaments that are generated isochronously. Cross-cutting and low orientation conformity occur in (b). A single, time-transgressive, flow pattern is depicted, rather than two cross-cutting flow patterns (modified from Clark, 1999).

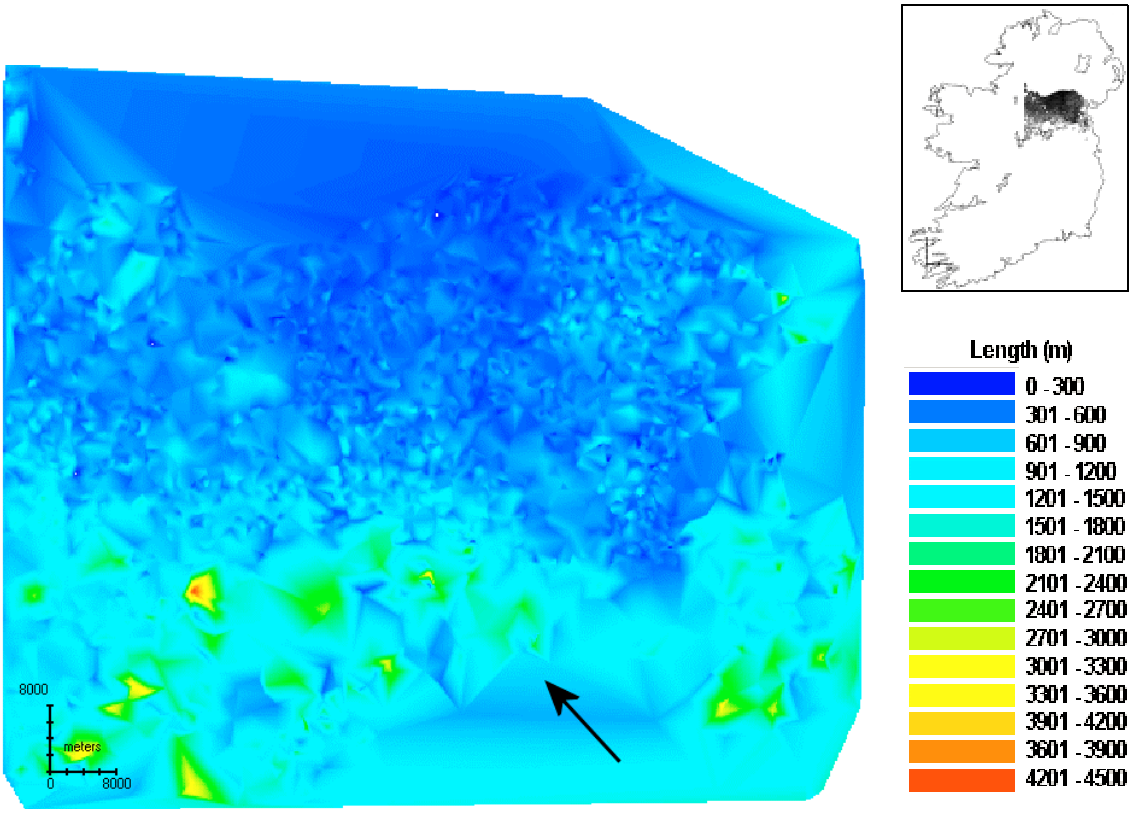


Figure 7.4 Interpolated surface of lineament length generated using a Triangular Irregular Network (TIN) for the Irish Midlands. Note the "gap" effects (arrow) that occur as a result of interpolating across large areas with no data values (data from Clark and Meehan, 2001).

1. **Manual Flow Set Classification** - a fully iterative, interactive, approach that provides quantitative checks on the generalisation procedure. This approach uses visualisation techniques to aid the identification of flow patterns. Mapped lineaments can be difficult to interpret, therefore "surface" maps of orientation and length are suggested to help guide the observer into separating lineaments into flow patterns. Once complete, statistics and graphics on each flow pattern (e.g. orientation, density) are provided to allow an assessment of the component flow patterns. This iterative approach provides the observer with a set of tools to converge upon a solution or set of solutions, and so give a quantitative check on a qualitative procedure. It is essentially a manual procedure that is validated by the use of exploratory statistics.
2. **Automated Flow Set Classification** - an algorithmic based approach (that could potentially be automated) to group lineaments together. This would be locally adaptive and developed from the visual heuristics used by interpreters.

Methodologically the second approach is the most desirable and should provide an objective approach to generalisation. However it is not easily possible to automate within current GIS and requires thorough testing in a variety of glaciological scenarios. The first approach is therefore appropriate as it is can be performed without proprietary software and allows the interpreters own expert knowledge to be used in the generalisation process. In addition, the use of exploratory statistics allows interactive back-checking.

The remaining sections develop and appraise these two approaches and then apply them to an actual case study. The chapter is then concluded with recommendations for best practice.

7.3 Development of Manual Flow Set Classification and Verification Techniques

7.3.1 Introduction

This approach outlined above aims to provide the interpreter with graphical data to help identify areas where there may be multiple flow patterns. Following the manual assignment of lineaments to flow patterns, iterative exploratory statistics are then used to provide quantitative checks. This section develops these two components to provide a method that can be used by the researcher.

7.3.2 Spatial Data Visualisation

Although the human eye uses complex visual heuristics to assign lineaments to flow patterns, it is difficult and prone to variation. Providing clear graphical representations of lineament data, within a methodological framework, should allow a more quantitative approach to developing flow patterns.

Lineaments have two main characteristics; length and orientation. If a lineament is reduced to point data, then these attributes can be interpolated (separately) as a surface and so provide clear and concise detail concerning the variation of attribute values within an area. Given the circular scale used for orientation data, it is not appropriate to directly interpolate orientation (i.e. the average of 358° and 2° is **not** 180°). Rather, it is required that the sine and cosine of orientation is interpolated and then, using the tangent, these values are recombined to give an interpolated orientation.

The type of interpolation used also requires consideration. It is not necessary to use an exact interpolator (i.e. the fitted surface is not required to honour the exact values of the attributes as the plot is purely illustrative), however it is important that interpolation is restricted to areas where data is available (i.e. only interpolate across small "gaps"). The use of Triangular Irregular Network (TIN) is not appropriate as it interpolates an entire area (i.e. it is space exhausting; Figure 7.4). Grid based methods however allow the restriction of interpolation of individual grid cells to areas where there is data nearby. It is important to realise that all interpolators suffer from problems at "edges". If there is no data beyond a certain point, the algorithm is extrapolating rather than

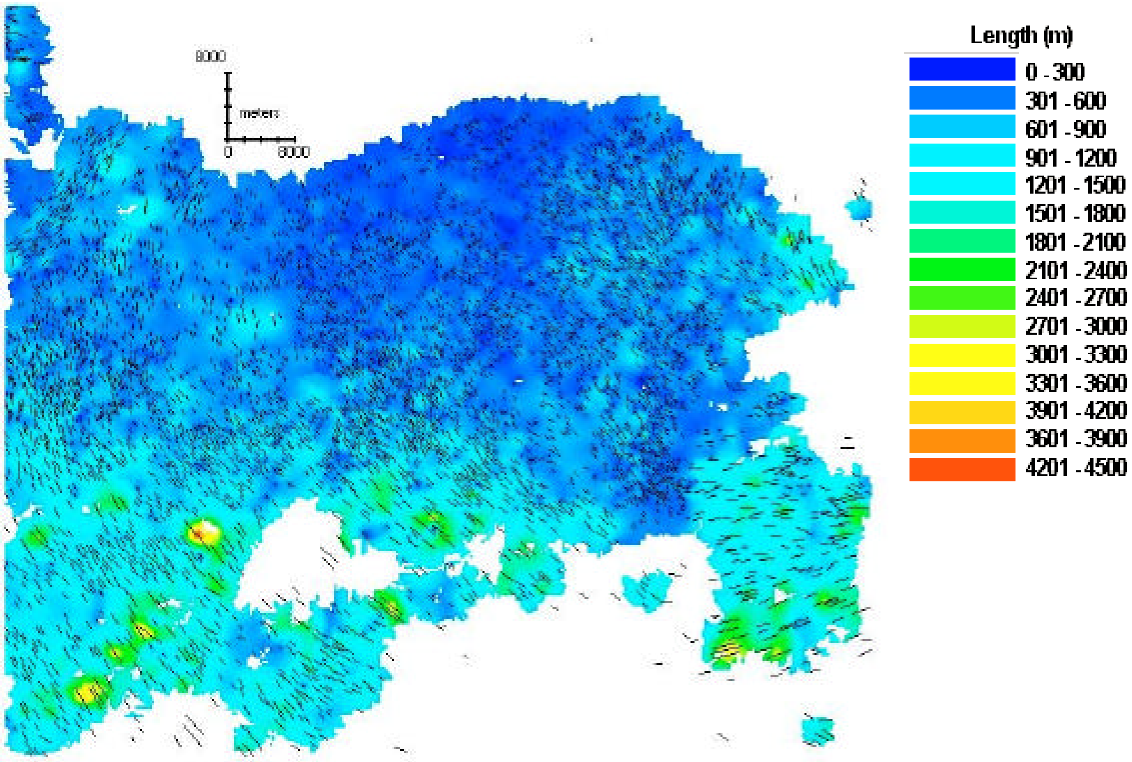


Figure 7.5 Interpolated surface of lineament length generated using the lineament midpoint. A grid based Kriging interpolator, restricted to interpolation within 3km of at least three data points for the Irish Midlands. This grid based interpolator demonstrates how they can be configured to remove edge effects and only interpolate where there is sufficient data available. Mapped lineaments are overlaid to show correspondence to the original data (data from Clark and Meehan, 2001).

interpolating. If there really is no data, then strange “edge effects” will become apparent (displayed in Figure 7.4). For this application, a “patchy” surface is desired so that “holes” are left with no data interpolated across them (Figure 7.5). However it should be noted that there will be small edge effects around all of these holes. The software used for this purpose was Golden Software’s Surfer™ which has a diverse selection of interpolators that allow detailed control over which lineaments are used for interpolation.

The main interpolation methods include *nearest neighbour*, *inverse distance*, *kriging* and *radial basis functions* (which includes the popular splines method). Kriging and splines are generally considered the best interpolators, although they can be slower than methods such as inverse distance and nearest neighbour. Radial based functions use data within a local radius to fit a user selected quadratic applying optimal weights. Kriging uses weighted values from data in the surrounding region to estimate the current point, however its weightings are derived from an understanding of the spatial structure (autocorrelation) of the data. Several different methods were tested, however for the visualisation purposes required, they were all fairly similar and took the same amount of time to produce. Kriging was selected for all interpolation.

For my purposes, two main options are available which control the final interpolated surface. The first is the density, or resolution, of grid cells. The greater the number of cells the smoother the surface, but the longer the interpolator takes. In addition, the coarser the surface, by definition, a greater amount of generalising will take place thereby highlighting trends within the dataset. The grid density value selected will depend on the distribution of lineament lengths that have been mapped.

The second option relates to the number of points used to interpolate each grid cell and the radii from which points can contribute. If input points are sparse then reducing the number of points that are required to contribute to a pixel value will increase the number of interpolated pixels. Reducing the radii will ensure that only *local* points are used in interpolation. This value may vary by up to an order of magnitude depending on the resolution of the original source data and the size and density of lineaments being mapped. In general a value between 1 km and 5 km sufficed.

With the selection of a grid based surfacing technique and interpolation method complete, it was necessary to reduce the lineaments to data points in order to perform the actual surfacing. There are three options available:

1. Lineament midpoint
2. Lineament endpoints
3. Lineament segmentation (into points)

All three options were explored to see which best represented the data. The first solution provides a very good representation of the data, however the lineament attribute is now simply a single point. The original mapped lineament may well have been long and so appeared important to the interpreter, however its spatial extent is not spatially represented on the surface plot (e.g. Figure 7.5). Grid based algorithms use points closest to a grid cell in order to calculate its value. Therefore a long lineament exerts proportionately greater influence over pixel values close by and clearly identifies an “island” of long length. The longer the lineament the taller the island appears, rather than appearing as a spatially larger entity.

The second solution initially looks appealing, however by selecting endpoints artificial islands are incorporated into the plot (Figure 7.6). These are unsatisfactory and not appropriate. The final solution appears to solve these problems by segmenting the lineament into several points, all with the same attribute. However the pixel value of the surface is simply a combination of the surrounding points and with many points in a segmented line, a series of line like shapes appears on the plot. This can be avoided by increasing the area of inclusion for points making up the pixel value, but this simply reintroduces the edge effects noted earlier (Figure 7.7).

The original solution of using lineament midpoints provides the most graphically pleasing plot, each lineament simply has one value. Locally, longer lineaments

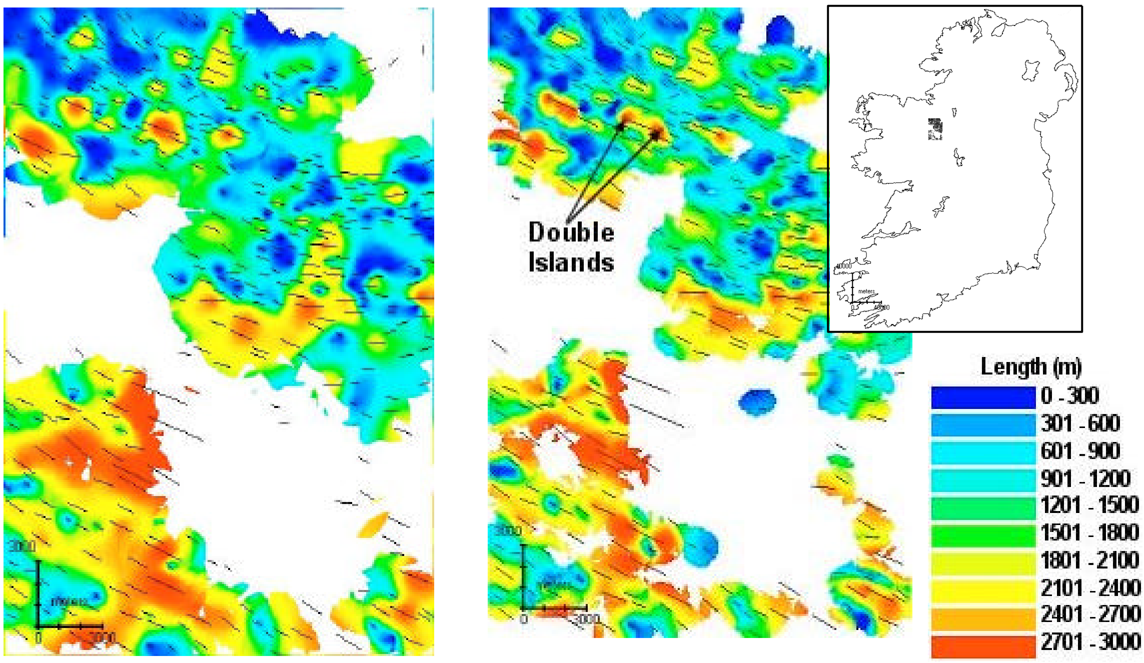


Figure 7.6 a and b Interpolated surface of lineament length generated using the lineament midpoint (a) and end points (b) for Lough Gara, Ireland. Note the appearance of double islands as of result of using end points. A grid based Kriging interpolator, restricted to interpolation within 3km of at least three data points is used.

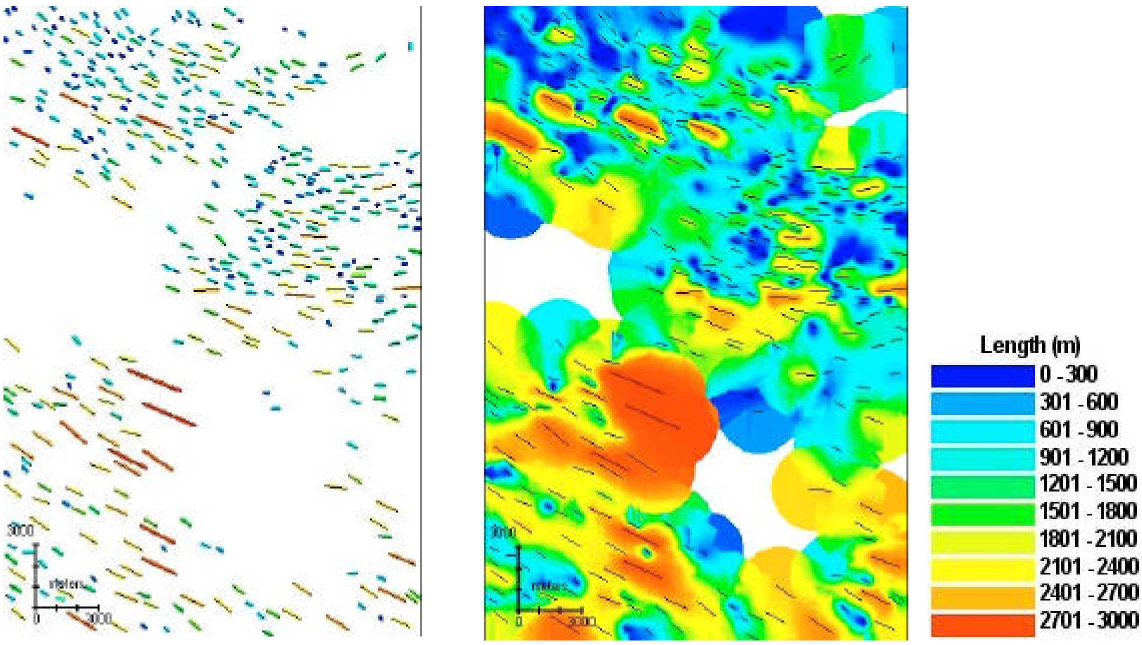


Figure 7.7 a and b Interpolated surface of relative lineament length generated using the lineament segmentation for Lough Gara, Ireland. Note the use of a restricted radii of interpolation (a) results in very little interpolation, whilst increasing the radii (b) produces very poor, overlapping, edge effects.

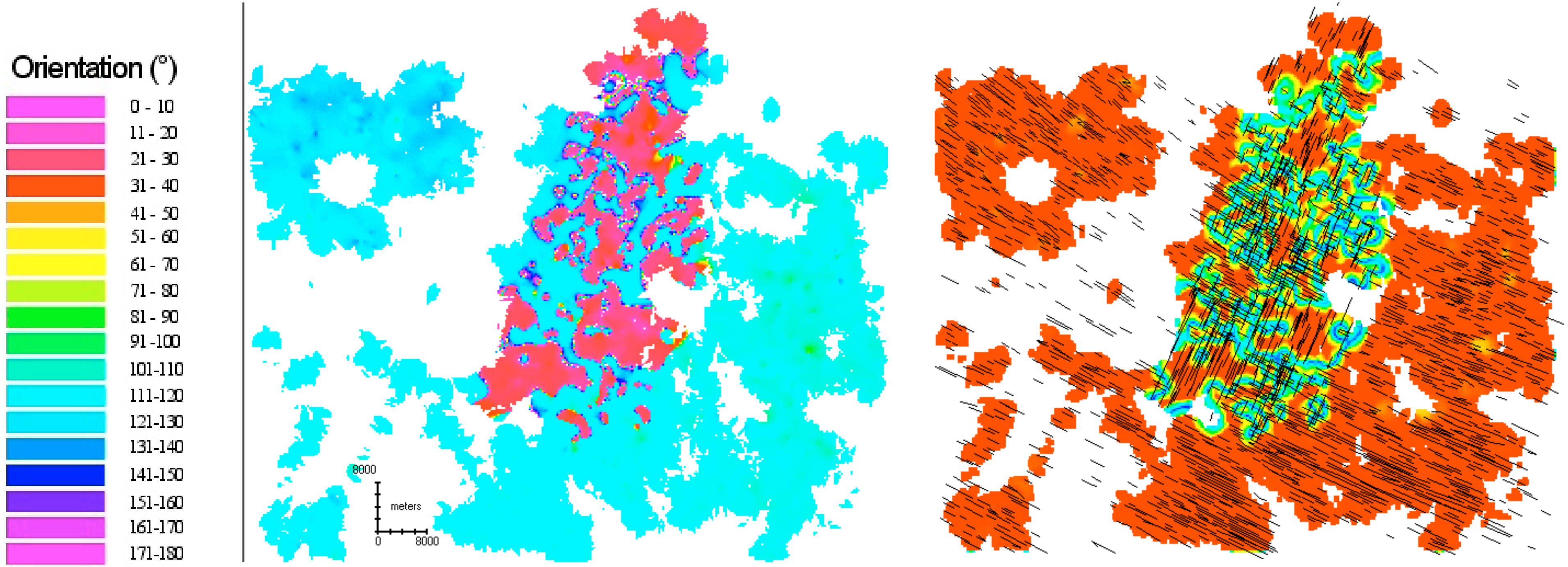
can influence the region immediately surrounding them and this shows up well on the plot. Over large areas, the small number of long lineaments is unimportant. Rather the overall trend of changes in length and orientation is vital in order to decipher the validity of an individual flow pattern and its glaciological context.

7.3.3 Visualisation Examples

As a demonstration, some real and simulated datasets are used to produce surface plots for each of the different variables. The previous section presented surface plots of lineament length, with the surface presented by a colour gradient from blue (short lineaments) to red (long lineaments). This is perfectly satisfactory for continuous variables, however the display of (aspatial) orientation is typically performed using rose diagrams or corona plots. With respect to spatial data, it would be feasible to use these plots on grid sampled data, however this is not appropriate as each grid cell contains orientation data. An option that was explored, was the use of vector plots (i.e. each grid cell containing an oriented arrow), however the presence of “halos” (see below) and the number of grid cells (well over 100,000 for a 100 km by 100 km area) made them difficult to interpret. The exploration of colour gradients was again pursued through the use of the colour circle used in computer graphics for the display of colours by hue, saturation and luminescence. This is an accepted colour gradient based upon circular visualisation and is appropriate for the display of orientation data.

Visual generalisation is strongly determined by lineament orientation and orientation conformity and this is an appropriate place to begin. Figure 7.8a shows a surface plot of orientation, overlaid with the original lineament data. The lineaments are simulated, being idealised into a highly conformant, cross-cutting, pattern. The different sets of lineaments are clearly picked out by the strong variegated pattern in the centre. In addition, a slight curvature from NW-SE can also be noted.

What is immediately apparent is that *three* directions are implied by the surface plot when only two are present. Because kriging essentially performs averaging



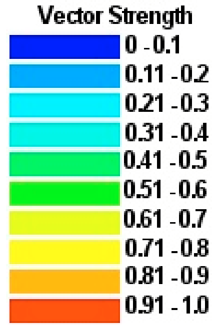


Figure 7.8 a. Idealised lineament dataset (cross-cutting), with each flow pattern showing high orientation conformity. The generated surface (100km across) shows a very slight curvature in lineament orientation from NW-SE that is dissected by lineaments oriented NE-SW (300m resolution, 3 min data points, 3000m radii). b. Using the surface generated for (a), the second image shows vector strength applied to a 3x3 window. The red depicts areas of high vector strength (i.e. good parallel conformity). The variegated areas are where there are deviations in orientation (modified from original data by Stokes, 2001).

over pixels, they can contain the orientation of *either* flow pattern or an average of *both* flow patterns. This is the reason for the “halos” surrounding the variegated region in the centre. Although not strictly “correct” it is a diagnostic feature that can be used to locate and verify cross-cutting. The previous sections have outlined the importance of *localised* lineament conformity. Therefore, an appropriate solution to visualising orientation conformity is to use a filter to calculate vector strength over an area (or window). This provides a measure of how parallel local landforms are. The best window size is partly dependent on the size of lineaments being studied, as well as the resolution of the surface plot. Different window sizes were applied and a 3x3 window was found to work effectively (Figure 7.8b). It is important to remember that this shows local *variation* in orientation (orientation conformity) and not orientation. Therefore high variability (variegated areas) denote areas where there are sudden changes in orientation. High vector strength (red) denote areas with low variability. In this example, high variability occurs where the two flow patterns intersect.

This above scenario is fairly simply and designed to highlight the interpretation of surface plots. Real lineament patterns are often more complex, such as those shown in Figure 7.5 for Ireland. This dataset is now used to compile the same orientation and orientation conformity plots (Figure 7.9a and b). There are two main glaciological scenarios where multiple flow patterns can occur: *separate* and *cross-cutting*. Figure 7.9b highlights the second of these. As seen in the previous scenario, cross-cutting results in a variegated pattern. Spatially delimited flow patterns will usually lead to a band of high variability where the two groups meet. If they are separated by a large distance, then orientation conformity will not delimit them and the original orientation plot should be reviewed.

Lineament orientation and orientation conformity are very valuable tools in distinguishing flow patterns, however other strands of evidence can help in identification as well as providing further glaciological information to help with interpretation. A further measure of orientation conformity is vector strength (based upon the original lineament data) , as described in §5.2.3. This is a

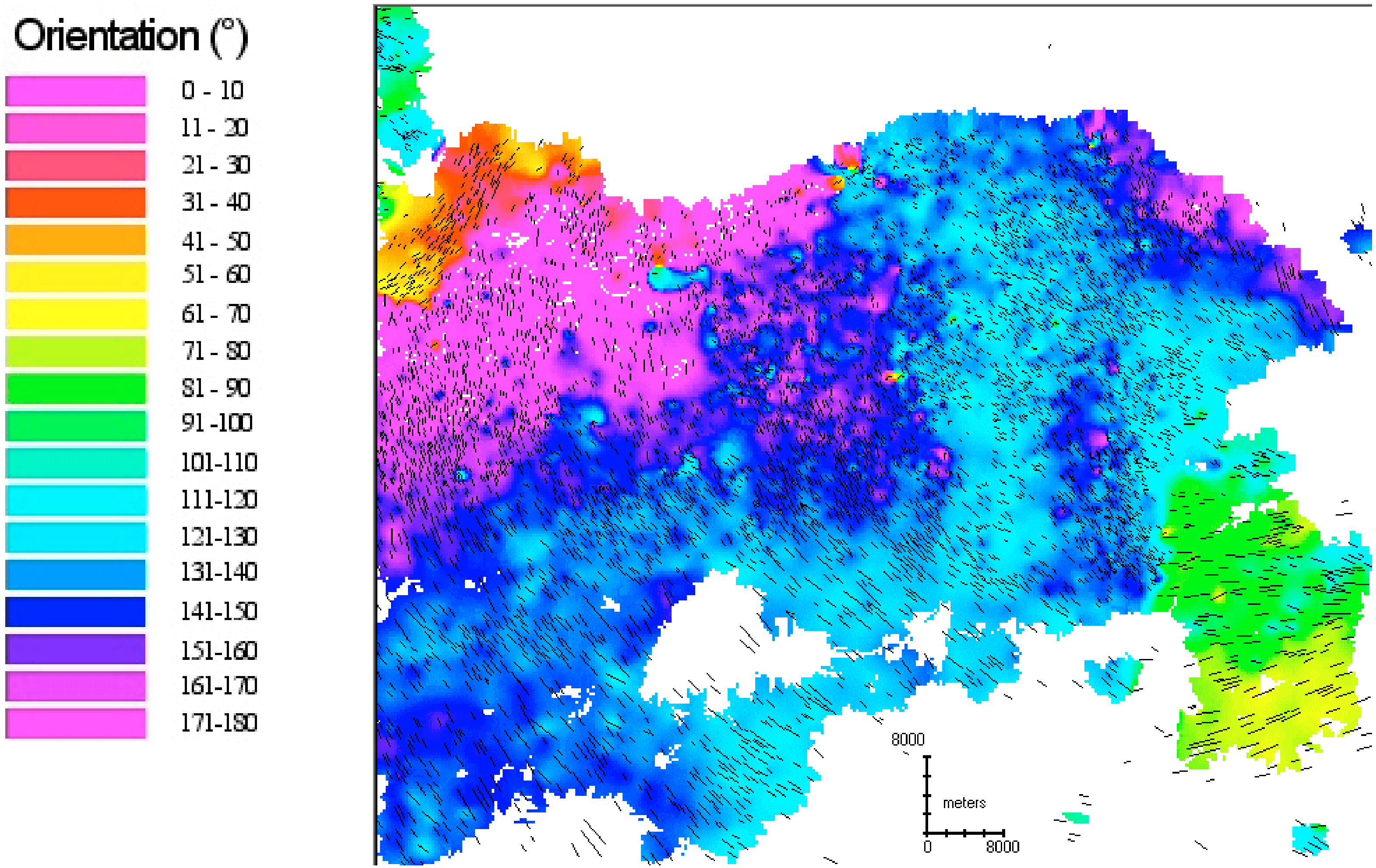


Figure 7.9 a. Vector Mean of lineament orientation for the Irish Midlands (300m resolution, 3 min data points, 3000m radii) (data from Clark and Meehan, 2001).

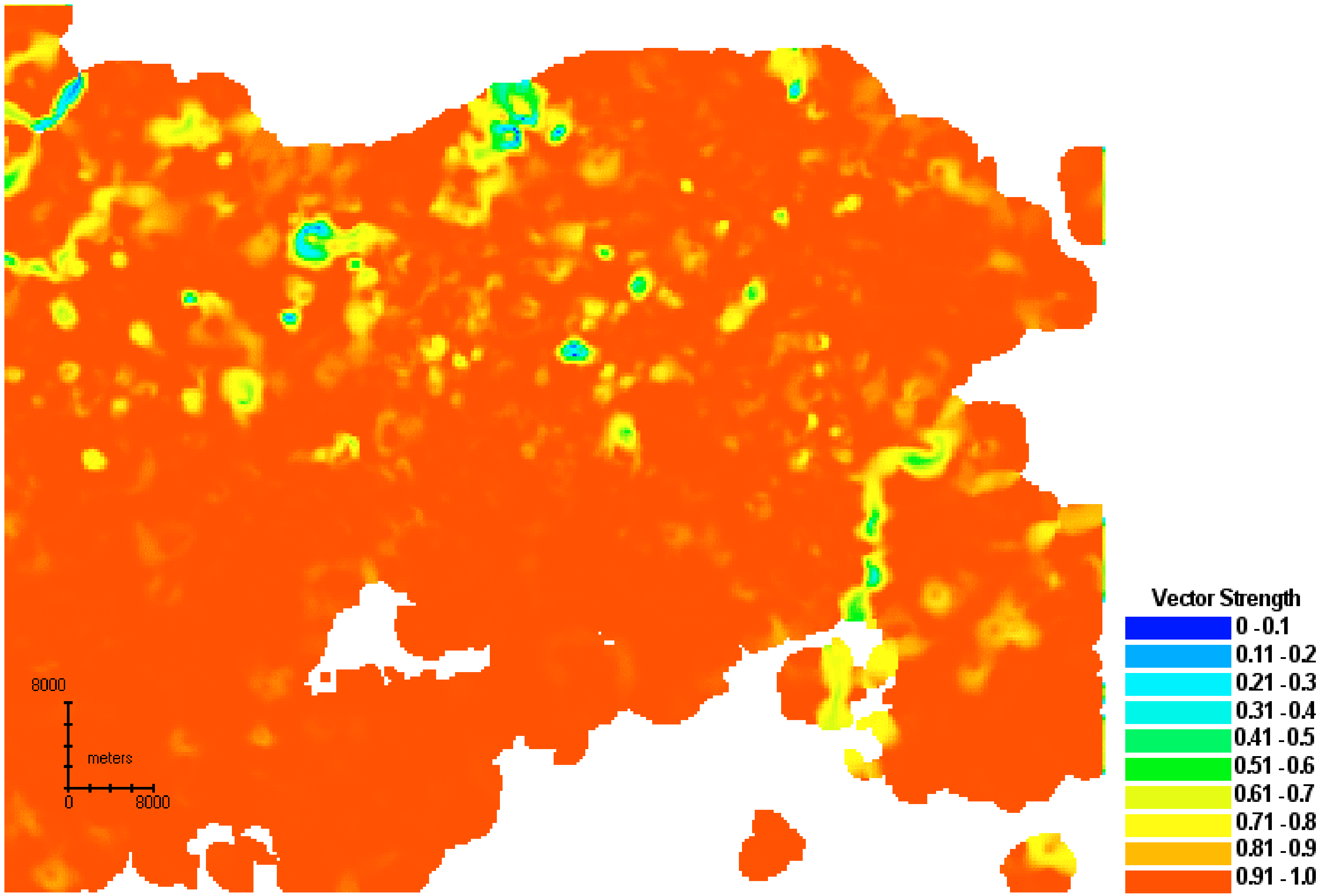


Figure 7.9 b. Vector strength for the Irish Midlands applied to a 3x3 window. The yellow depicts areas of high vector strength (i.e. good parallel conformity). The variegated areas are where there are deviations in orientation (data from Clark and Meehan, 2001).

region based measure and therefore it is necessary to apply sampling in order to apply it to spatial data. After lineament orientations and mid-points had been calculated, a grid was generated. Again, it is necessary to choose an appropriate grid size such that there will be enough data within each grid to make the results meaningful. Grid cells between 5 km and 20 km were appropriate. Lineaments falling within each grid cell were noted and the vector strength calculated on a cell by cell basis (Figure 7.10a). Cells that included less than three lineaments were excluded as they tended to occur around the edges of mapped areas and gave artificially high vector strength values. The figure clearly shows a dominance of high vector strength values, supporting the other evidence for high orientation conformity in the main NW-SE flow pattern. This is a useful indicator that shows if lineaments correctly belong to a single flow set and that they therefore likely represent a single event formed isochronously. In this particular scenario there is one dominant pattern, inter-mixed with several weaker ones. The figure particularly highlights orientation variation in the NW corner, as well as areas of mixed orientations across the N of the area. The NE and SE corners also show small amounts of variation in orientation. Vector strength clearly shows areas with good parallel conformity and provides good information on areas with potential multiple ice-flow directions.

Lineament length and length conformity can also be useful. As noted earlier, lineament attenuation is controlled by ice sheet *velocity*, *residence time* and *sediment supply*. Information on the variability of length can provide further information on glacial dynamics, as depicted in Figure 7.5. This shows a large region of short lineaments in the central north, which is bordered on the east and west by lineaments of varying sizes (variegated). Further out they are ringed by much longer lineaments. In this instance length variation could also be due to different flow patterns.

The final variables used in generalisation are *spacing* and *spatial continuity*. One measure of spacing is the density of lineaments, which is closely related to

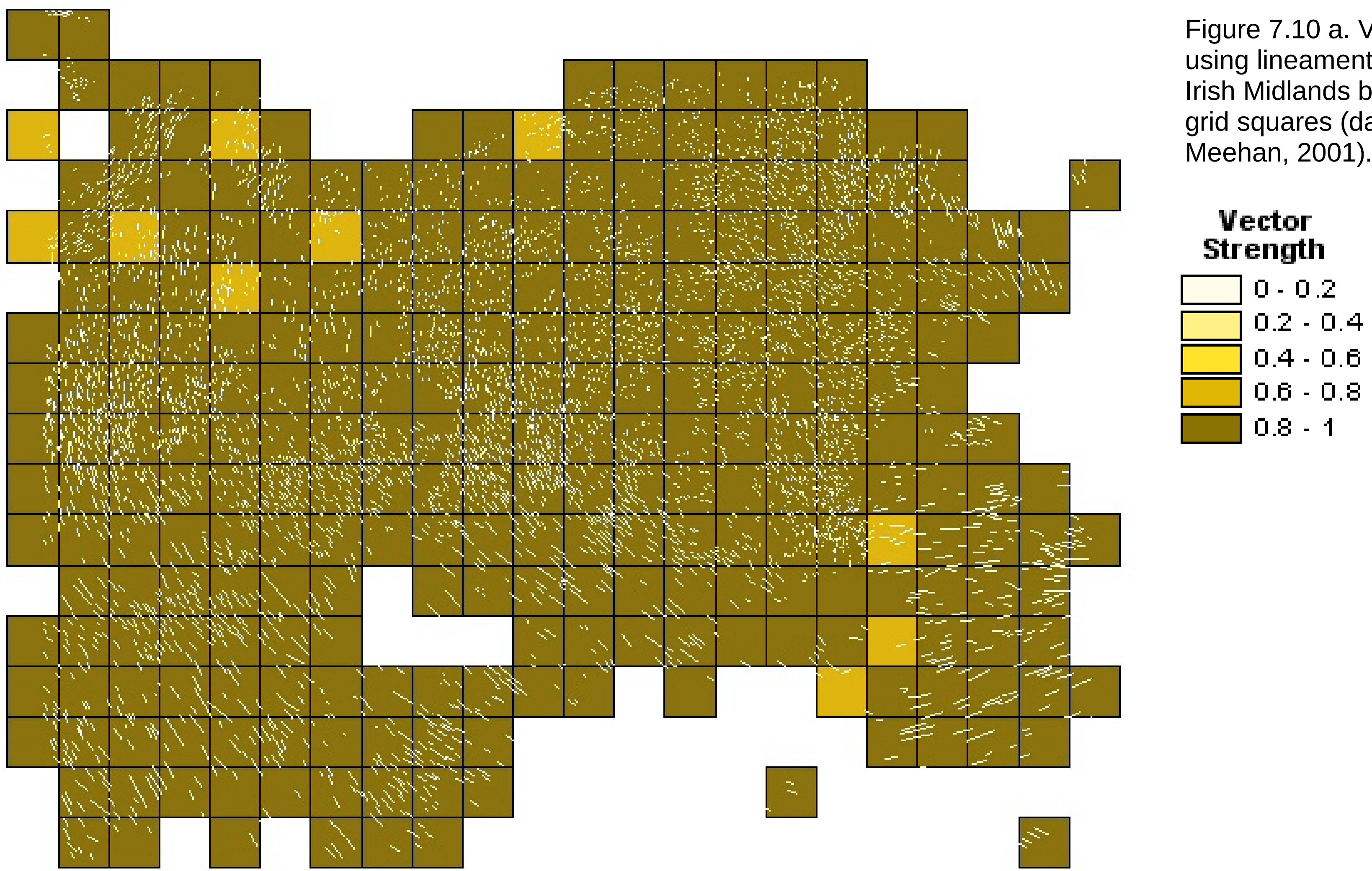


Figure 7.10 a. Vector strength using lineament orientation for the Irish Midlands based upon 5km grid squares (data from Clark and Meehan, 2001).

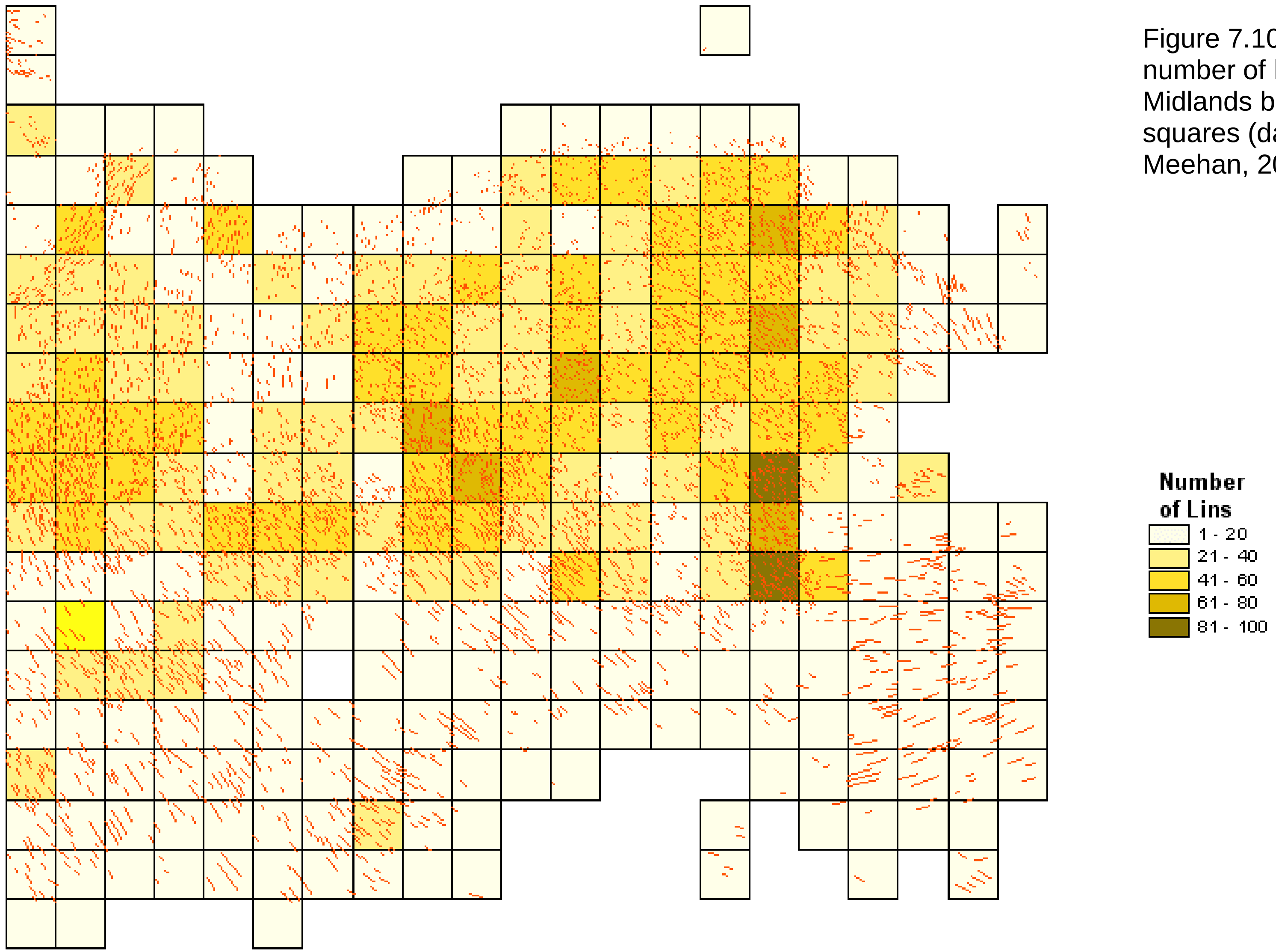


Figure 7.10 b. Density using the number of lineaments for the Irish Midlands based upon 5km grid squares (data from Clark and Meehan, 2001).

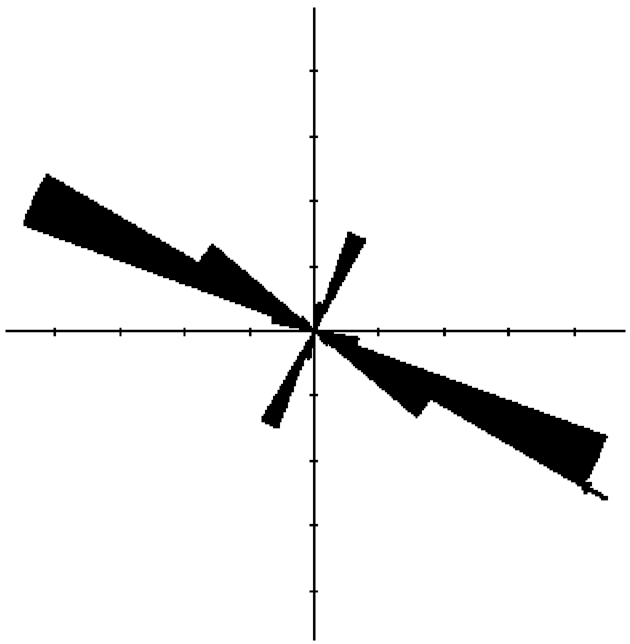
spatial continuity. Density can be measured on a region basis by counting the number of lineaments within a grid square. The number of lineaments within 5km grid squares were counted and these values directly plotted (Figure 7.10b). The plot clearly identifies areas of dense lineaments, as well as how continuous the patterns are.

7.3.4 Statistical Back Checking

Generalisation and the classification of lineaments into flow patterns has been a purely qualitative procedure relying on the ability and experience of the observer performing it. Although there are general ideas about the basic visual heuristics used, these are not firmly defined. As a result there are no objective checks that allow the procedure to be verified. This means that, using the same data, a different observer could yield different results. Ideally, flow set definitions should be openly verified such that others can validate them. In addition, comparisons of results using different source data will be more appropriate. This section provides simple statistical procedures to allow flow set definitions to be objectively verified.

As with the previous section, it is appropriate to use a simple, idealised, scenario to explore the basic techniques (as used in §7.3.3). Figure 7.8 clearly identified two main flow patterns based upon their orientation, which was then verified by looking at orientation conformity (i.e. vector strength). The lineaments were split into component flow patterns and, for each set, the orientation and length of lineaments extracted. Orientation data was then plotted on a rose diagram (Figure 7.11a) clearly depicting two distinct flow patterns. This is visualised in Figure 7.12 by creating surface plots for *each* flow pattern separately. These clearly demonstrate that each flow pattern appears as a distinct and valid unit, as they both show *internal* consistency and smooth gradients with high parallel conformity.

Frequency polygons depicting lineament length for each flow set were also plotted (Figure 7.11b). These show a strong similarity. In this example, length alone does not discriminate between the two flow patterns.



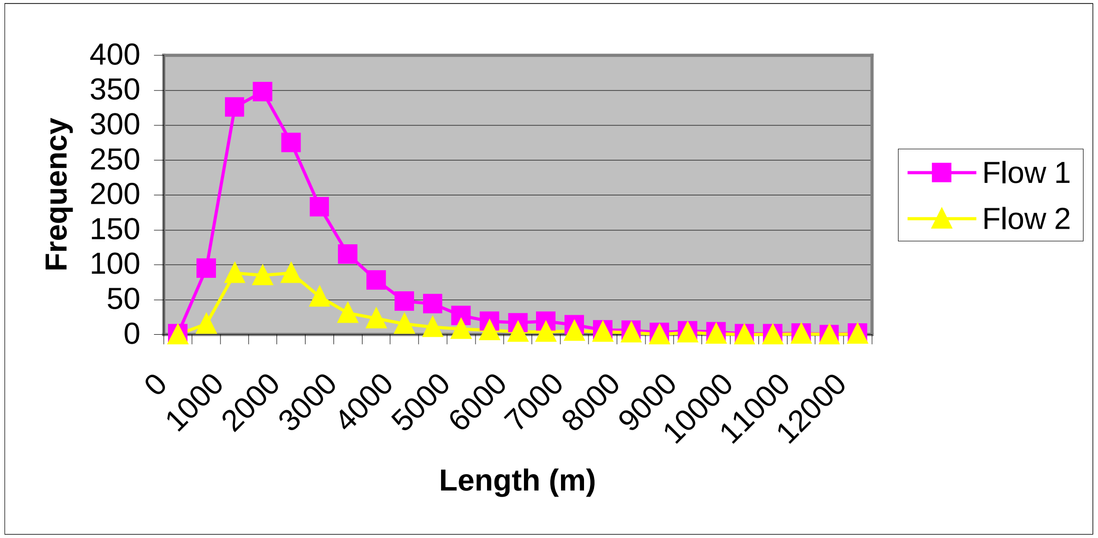


Figure 7.11 a. Rose diagram (frequency) showing the easily identifiable lineament orientations for two flow sets from the idealised data set. b. Frequency polygon of lineament length for the two flow sets. This shows a close similarity in the distribution of lineament length.

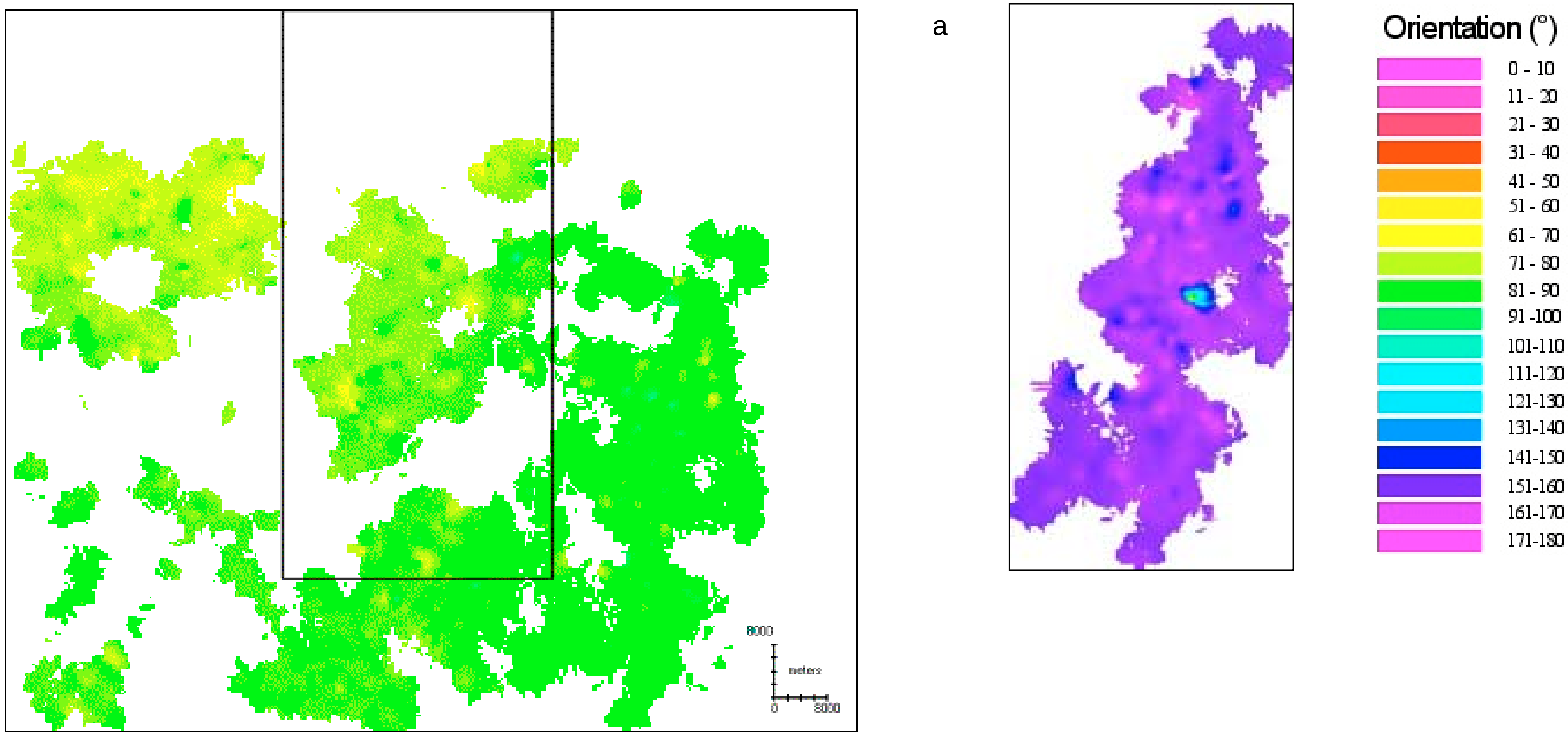


Figure 7.12 Variability of lineament orientation for the idealised data set (300m resolution, 3 min data points, 3000m radii). Dataset is 100km across. The two flow patterns have been separated and are visualised separately (see also box outline of a on b). This shows very strong parallel conformity, with a slight curvature for the first flow pattern (a). The second flow pattern (b) has a single lineament forming a small “island” oriented differently.

The above example is purposefully simple to highlight the basic ideas behind the verification of manually assigned flow pattern classifications. If a flow pattern is considered an individual *unit* then it should display consistency. Consistency is dependent upon whether a flow pattern is deemed to be time-transgressive or isochronous (as discussed in §7.2) and the glaciological context in which these patterns were generated (Clark, 1999 and Figure 3.20). Isochronous patterns are expected to display gradual changes in either (or both) lineament orientation or length (i.e. a smooth gradient of change). Time-transgressive patterns should be identified through cross-cutting, poor orientation conformity and abrupt changes in morphometry. Isochronous patterns are clearly easier to recognise, but careful study of both the surface plots and original lineament data should provide diagnostic features that allow the identification of either; and this can then be visualised and quantitatively verified through the use of the surface plots.

This approach is now applied to the lineaments mapped from the Irish Midlands, as used in the previous section. The lineaments mapped, and visualised in Figure 7.9, were separated into individual flow patterns. This required careful study of the surface plots, particularly orientation and orientation conformity, as well as the original lineament data. In addition, the regional topography must be considered as this can lead to the channelling of ice flow and so a convergence or divergence of localised lineament orientations. In general the Irish Midlands are relatively flat, however there are localised areas of moderate relief which could modify ice flow at a thinned ice sheet margin (i.e. during recession).

Figure 7.13 shows the four flow patterns (FP) that were developed. FP1 is both separate, and orientated transverse to, those in FP2. It is possible that FP1 also forms part of FP3, however this cannot be verified given their spatial separation. FP3 is composed of broadly S and SE oriented lineaments, which, in the south, lengthen the further south travelled (Figure 7.5). FP3 intersects with, but doesn't cross-cut, FP4. These two patterns are distinguished by differences in lineament orientation and length (Figure 7.5). Figure 7.14 shows rose diagrams for each flow pattern, highlighting their distinctive orientations. This also shows a greater spread in orientation for FP1. FP1 could be composed of two different

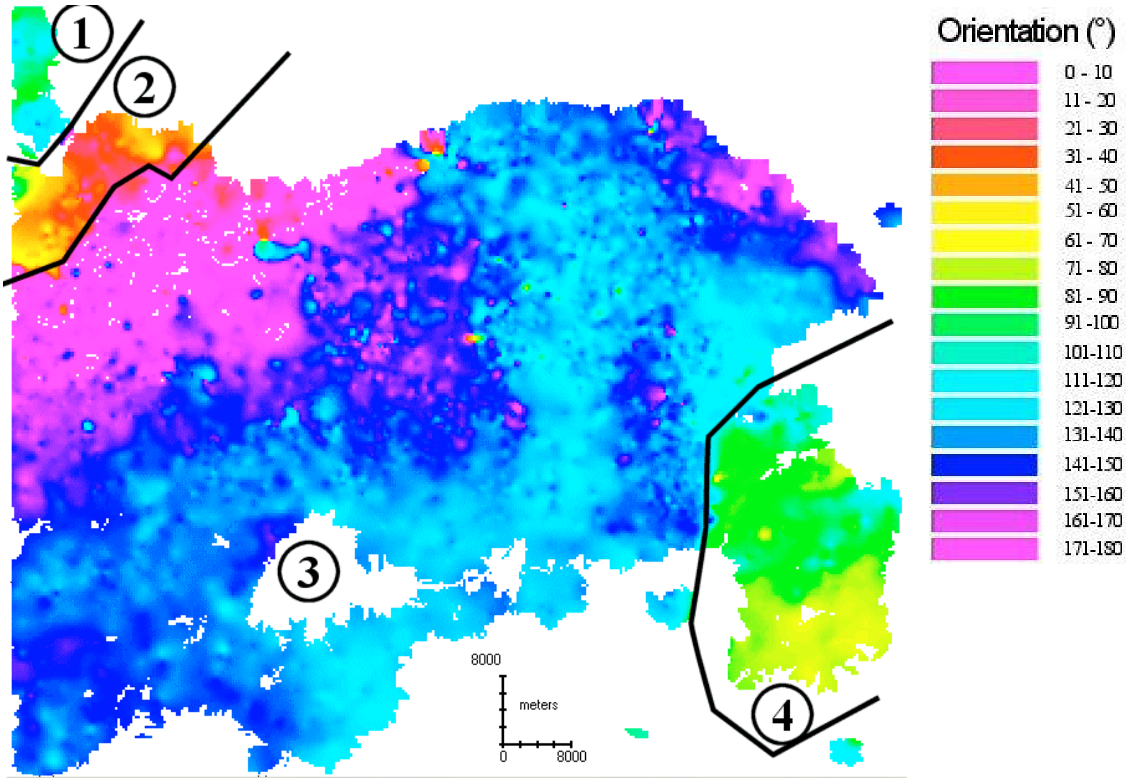


Figure 7.13 Surface plot of lineament orientation for the Irish Midlands (300m resolution, 3 min data points, 3000m radii). The region has four broad flow patterns which are marked. These are all spatially separate, except for a small overlap between 3 and 4. Although presented in a single diagram, they were all analysed separately.

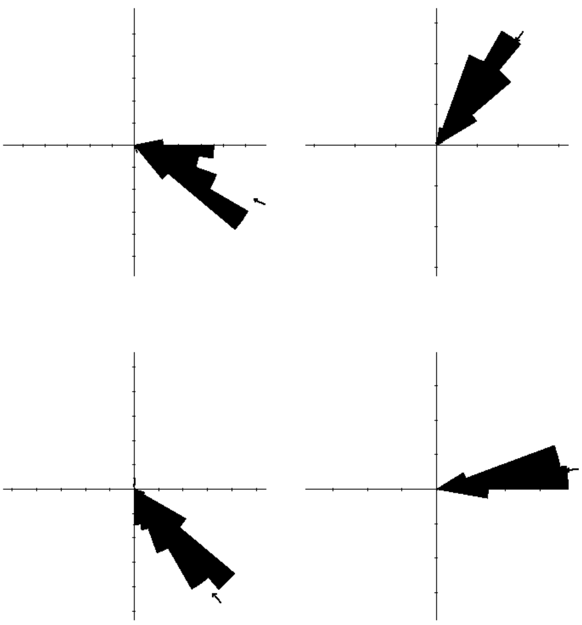


Figure 7.14 Rose diagram (frequency) of lineament orientation for flow patterns 1 (top left; 61), 2 (top right; 183), 3 (bottom left; 5156) and 4 (bottom right; 174) for the Irish Midlands. The four flow patterns are distinct. FP1 shows the widest variation and could be interpreted as two flow patterns, although there are not many data points.

patterns, however reference to elevation data shows moderate relief, which could have caused local divergence. FP3 is the largest flow pattern and covers the majority of the region. This shows a gradual change in orientation (Figure 7.9), although vector strength (Figure 7.15) suggests there is greater variability here. This could be, in part, due to the effects of topography, the presence of a second flow pattern or possibly a time-transgressive flow pattern. The first possibility requires the close scrutiny of topography to account for the effects of relief, whilst the second, although possible, should be more apparent throughout the whole area (rather than restricted to the NE) and additional features such as cross-cutting would be expected. The final suggestion is also possible, although again cross-cutting would be expected. Given the above options and the amount of information available, FP3 is retained as a single, isochronous, flow pattern due to the high orientation conformity.

7.4 Lake District Case Study

7.4.1 Introduction

This section is designed to use the techniques developed above and apply them to a real-world situation. Just as Chapter 6 used the Lake District as a study area for landform mapping, so this section will use those landforms mapped previously and separate them into flow patterns using these methods. In addition to the figures presented in this chapter, the map on the inside cover should also be consulted. It is important to note that this section provides no interpretation beyond that required to form flow patterns. It is a non-interpretative stage that is quantitatively verifiable and so re-usable by other researchers.

7.4.2 Flow Pattern Formation

The Lake District presents many difficulties both for landform mapping and the creation of flow patterns. For the latter, these difficulties include:

- Multiple flow sets
- Cross-cutting
- Different bedform shapes
- Interruption of bedform suites by relief.

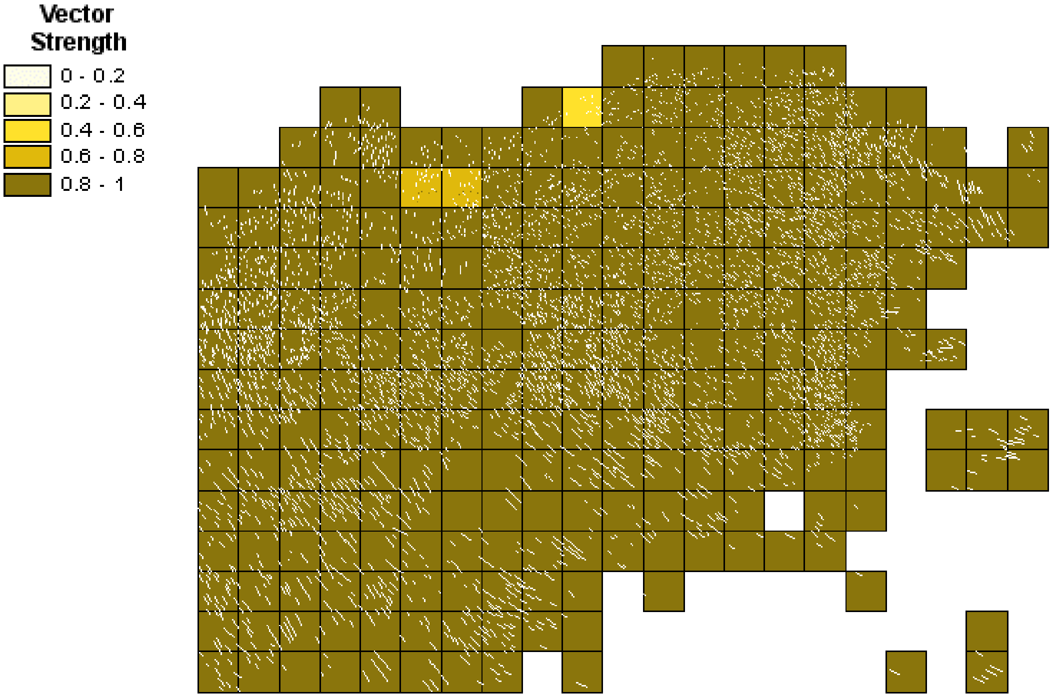


Figure 7.15 Vector strength using 5km grid squares for flow pattern 3 in the Irish Midlands. Note the lower vector strength values in the NW corner.

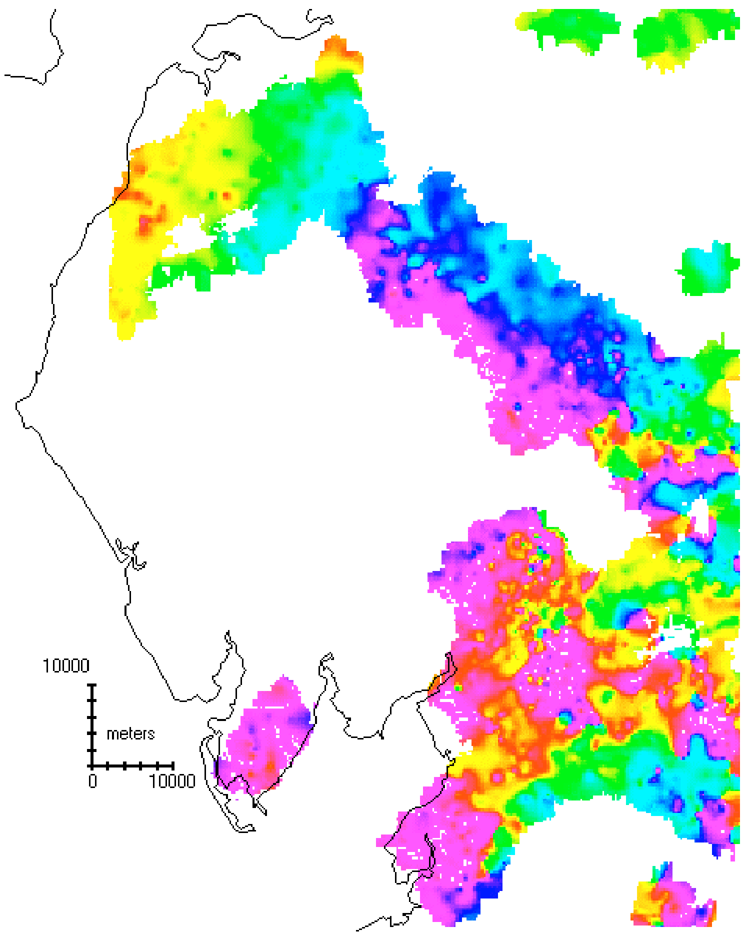
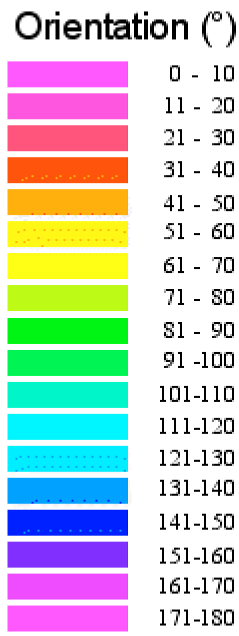


Figure 7.16 Surface plot of lineament orientation for the Lake District (300m resolution, 3 min data points, 3000m radii).



Initial exploration was performed by creating a surface plot of orientation for the Lake District (Figure 7.16). This highlights the complexity of lineament patterns within the study area. The northern region initially appears broadly straightforward. A curving pattern of lineaments is readily apparent (purple [0-20º], to red [21-50º] through yellow [51-70º], to green [71-100º] and blue [101-160º] then back to purple), however this is partially dissected by a variegated area on its southern edge (in the vicinity of Shap) indicating the possible presence of another flow pattern. On the eastern side (around Brough and Stainmore) there is a sudden change from lineaments trending to NW-SE (blue) with those trending W-E (green). This again has a variegated pattern suggesting cross-cutting. In the southern region the pattern becomes more complex. The western edge (from Kendal down to Lancaster) is strongly variegated showing one broadly dominant pattern trending N-S (purple) which is heavily dissected. The eastern region (incorporating the head of the Wensleydale valley and southwards into Ribbledale) has an intricate mix of lineaments of various orientations. This is partly due to the extensive relief in this region and requires careful investigation.

Further evidence for discriminating flow patterns is provided by vector strength applied to the original lineament data (Figures 7.17) and to the interpolated raster data (Figure 7.18). These plots both highlight high variability in orientation in the northern area, around Shap, of the dominant NW-SE flow and around Brough. In the southern region, the western and eastern edges are again highlighted. Figure 7.19 is a surface plot of lineament length and this further emphasises these zones of variability.

The manual development of flow patterns involved the use of the above figures, in conjunction with the original lineament mapping. Careful consideration was given to conformity in orientation and length and the patterns were iteratively developed to help converge upon consistent flow patterns. The broad outline of flow patterns is shown in Figure 7.20 and descriptive statistics shown in Table 7.1. It is important to note that these are developed as flow patterns and *not* flow sets. They are assessed in terms of orientation, length and spatial continuity and therefore it would be normal for some to link together to form flow

Flow Pattern	Number of lineaments	Mean		Min		Max		Data Spread	
		Length (m)	Orientation (º)	Length (m)	Orientation (º)	Length (m)	Orientation (º)	Standard Deviation Length (m)	Vector Strength Orientation (º)
L1	166	522	89	163		1626		225	0.839
L2	101	489	80	261		863		141	0.946
L3	643	689	90	180		2256		265	0.807
L4	152	460	81	162		1723		207	0.705
L5	576	448	5	103		1229		169	0.827
L6	181	472	89	134		1360		184	0.885
L7	237	469	42	130		1204		169	0.522
L8	27	582	37	269		1025		157	0.878
L9	71	690	85	269		1691		288	0.930
L10	147	493	113	115		1170		181	0.920
L11	126	431	17	145		1308		163	0.886
L12	80	452	102	134		1360		226	0.935

Table 7.1 Descriptive statistics for flow patterns L1-L12. For the mean, min, max data spread, the first column shows lineament length (In metres) and the second orientation (in degrees). For orientation, the vector mean and vector strength have been calculated, whilst the minimum and maximum have been omitted as they are meaningless for undirected circular data.

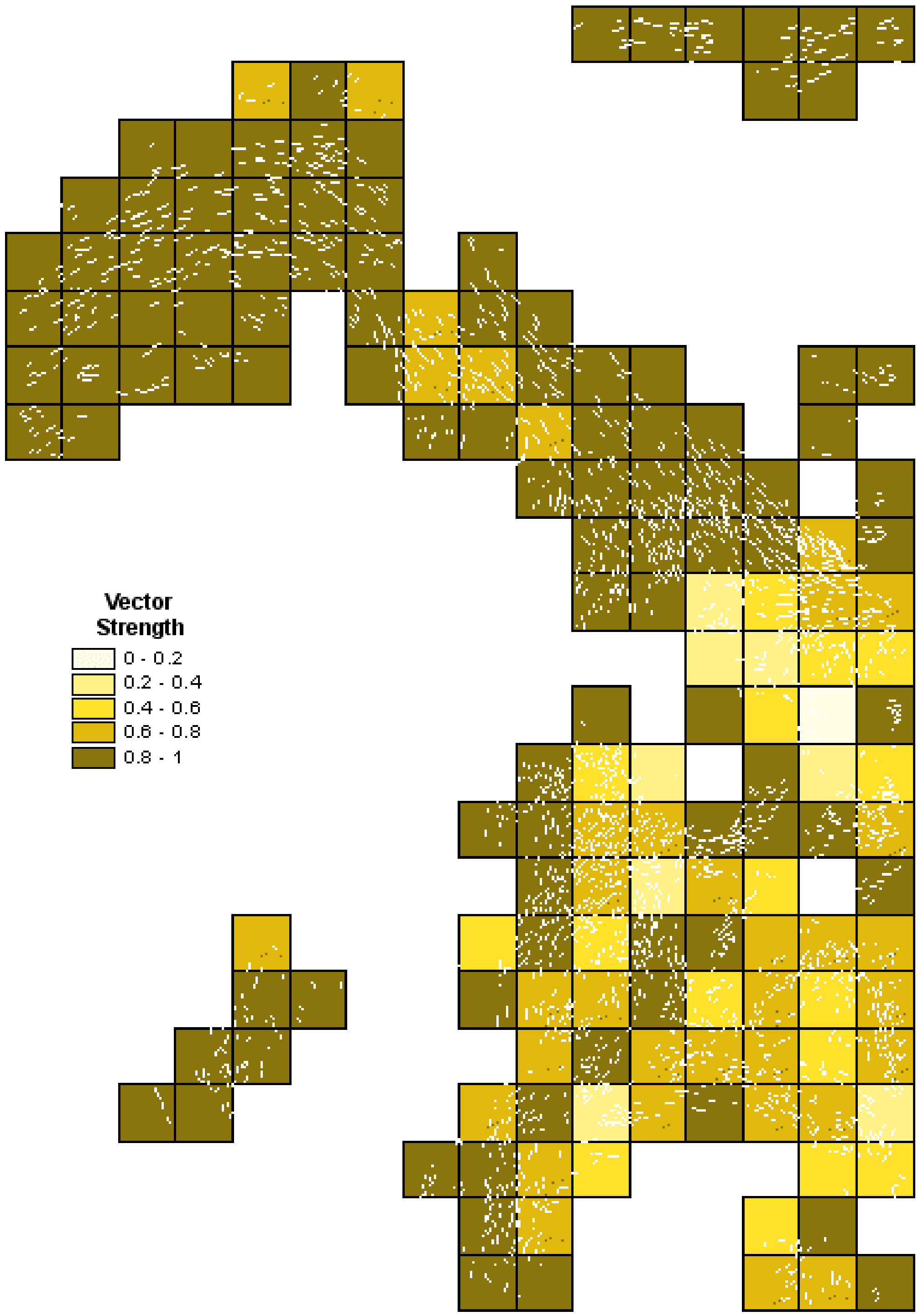


Figure 7.17 Vector strength using 5km grid squares for all lineaments mapped in the Lake District. Note that only parts of the north and central regions in the south have high vector strength values indicating a complex mix of multi-oriented lineaments elsewhere.

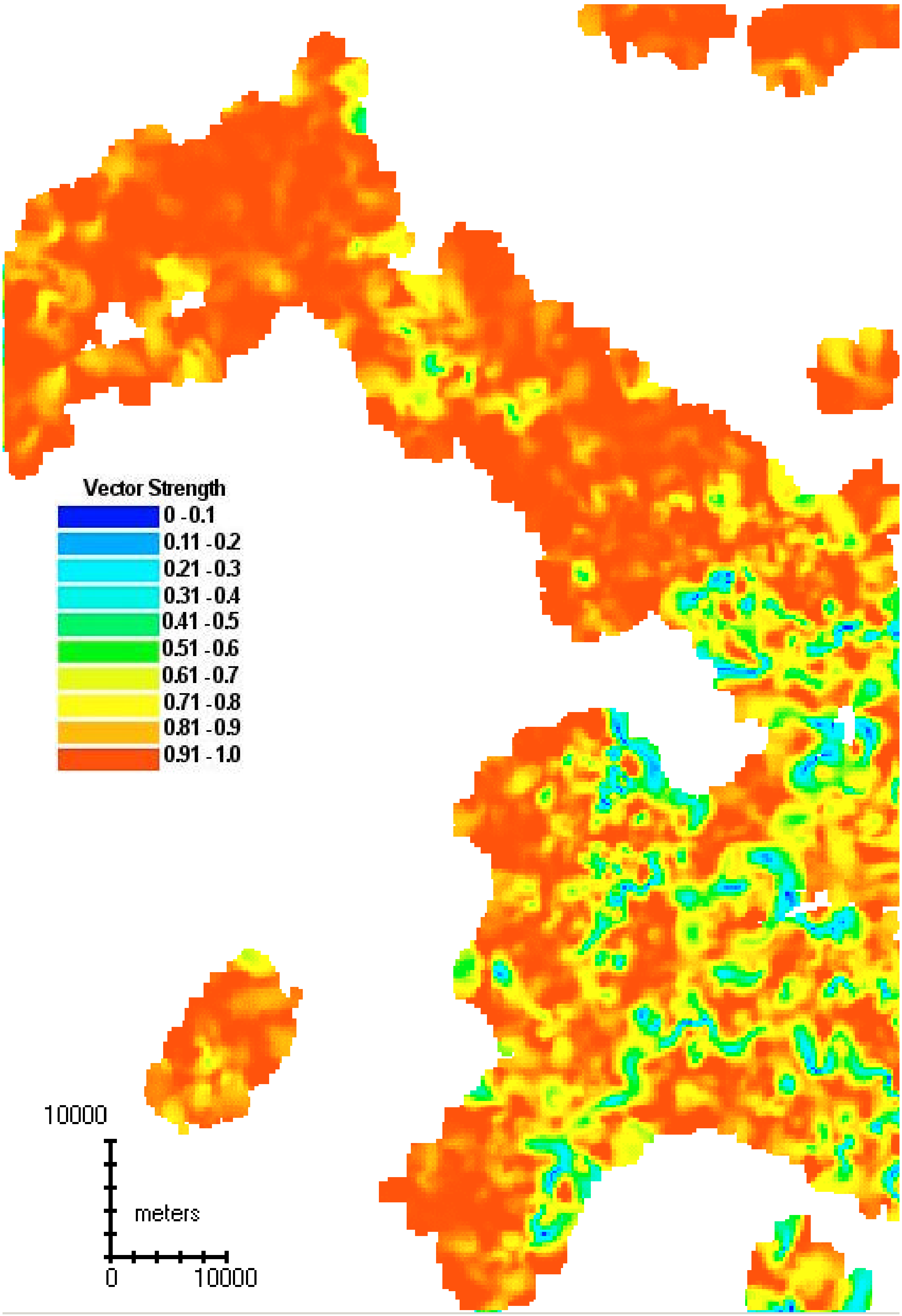


Figure 7.18 Using the surface generated for Figure 7.16 this image shows vector strength applied to a 3x3 window. Orientation conformity is generally good, although there are distinct areas of high variability in orientation. Red represents high vector strength (and so good orientation conformity), whilst variegated areas show lower vector strength values.

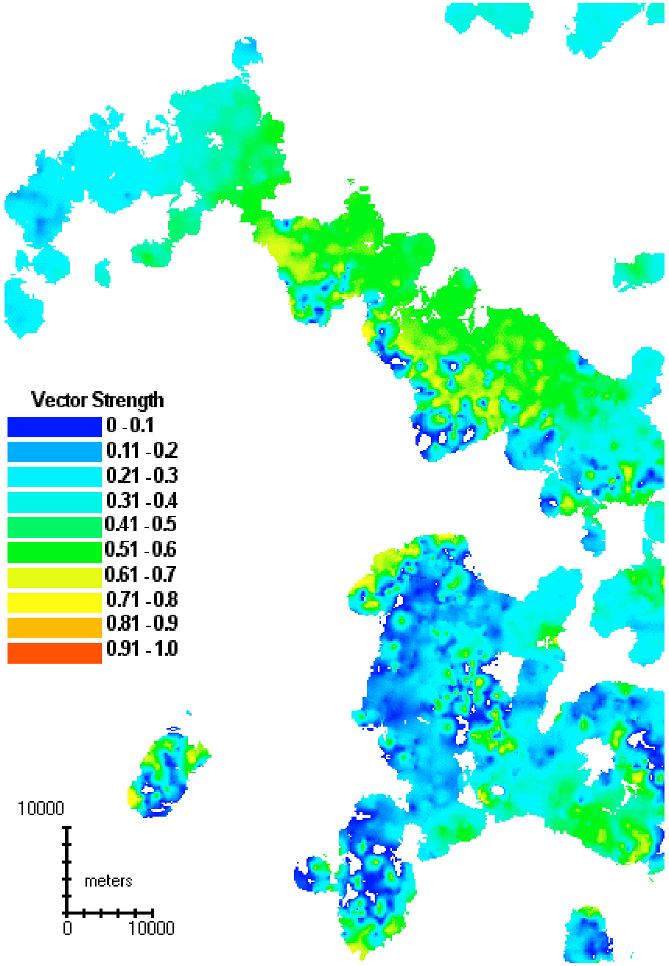


Figure 7.19 Interpolated surface of lineament length for the Lake District (300m resolution, 3 min data points, 3000m radii). Blue represent short lineaments and red, long.

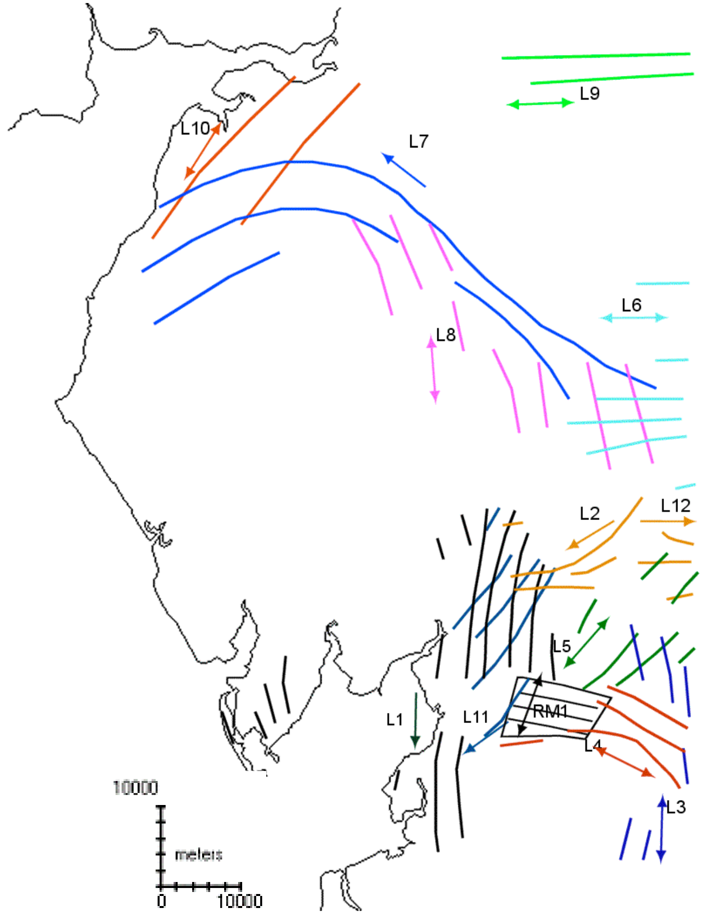


Figure 7.20 Generalised flow patterns developed from the individual landform data. Each flow pattern is numbered, with an arrow indicating the direction of flow. Colours are purely illustrative.

sets. However the Lake District is a fairly small region made up of many isolated flow patterns.

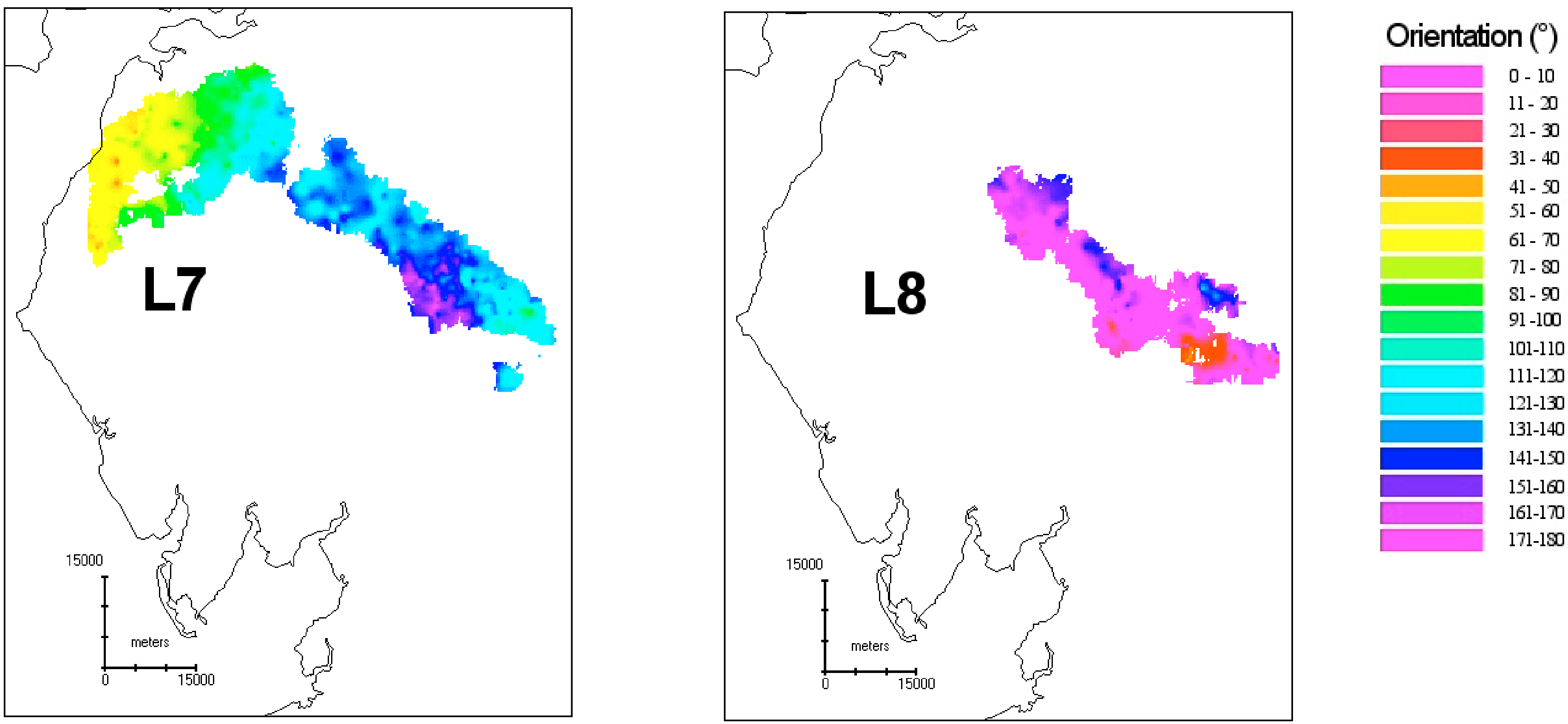
Although not strictly part of the generalisation process, it is also important, prior to the creation of flow sets, to collate pertinent glaciological information. These include ice thickness, ice flow direction and cross-cutting relationships (to infer relative age); this information can then be applied to individual flow patterns. *Ice thickness* can be determined by noting the maximum elevation that drumlinisation occurs at for a particular flow pattern. Field measurement of trim lines can also be used. *Ice flow direction* is determined by noting individual drumlin stoss-lee relationships (i.e. the steeper, fatter, stoss end typically points upstream). *Cross-cutting* relationships require evidence of the superimposition or re-modification of a drumlinised landscape (e.g. Figure 2.5a). Both cross-cutting and ice flow direction evidence requires detailed morphological information. As the discussion regarding satellite imagery recommends in §5.6, 30m or 10m resolution data are ideally needed. This advice is not directly transferable to DEM data; close scrutiny of the OS DEM data for the Lake District shows that it is not able to reliably provide this level of detailed information. In selected situations (e.g. Figure 7.25b) it is able to resolve necessary detail, however this is the exception rather than the rule. For ice flow direction, the traditional stoss-lee relationship may not be visible, particularly in areas that have been remoulded from different ice flow events. Whiteman (1981) specifically notes that, for his small study area in part of the Eden Valley (around Appleby), no preferred ice flow direction could be discerned. Therefore some regions may have no direction indicators available. In general, without clarification from the DEM, and in the absence of further corroboration from primary data sources (e.g. satellite imagery, aerial photography, field mapping), it is necessary to utilise published evidence. This is essential for comparative purposes and can provide additional directional information from erratic evidence. This supporting evidence is now collated using the DEM data and are discussed further in §7.4.4.

The entire area was split into northerly and southerly regions; each flow pattern is now discussed within this context. The northerly region is dominated by the lineaments curving around the north of the Lake District (L7). This main ice flow was separated out from the surrounding lineaments and a surface plot of orientation created (Figure 7.21a). This shows a gradual change in orientation from SW-NE in the west, through to NW-SE in the east, with the overtopping of local relief up to 350m. Small variations in colour highlight localised changes in orientation with a pronounced region in the east trending N-S. Direction indicators from the DEM suggest ice flow was from SE to NW (Figure 7.25a).

L7 is intersected by two other main ice flow patterns, L8 and L6. L8 is predominantly trending NNW-SSE (Figure 7.21b), with ice flow tentatively ascribed as from SSE to NNW (a glaciologically plausible scenario) overtopping elevation of 300m. The NW part of this flow pattern shows good orientation conformity, whilst the SE section less so. L8 is cross-cut by L7 (i.e. L8 is older; Figure 7.25b). L6 is a predominantly W-E trending flow pattern (Figure 7.24a) that has good orientation conformity. There are no direction indicators in this area (see also the following section). Although cross-cutting is clearly evident with L7, it is not clear which flow pattern is older. The northern part of L6 occupies an upland region (around Stainmore) at ~500m and is associated with transverse forms located here.

The final two flow patterns in the northern region (L9 and L10) possibly form part of the same flow set. L9 forms a predominantly E-W flow which climbs elevation of 300m at the DEM edge (Figure 7.24b), whilst L10 is trending NE-SW. The latter has too few points (27) to be able to reliably create a surface plot for. No direction indicators are readily apparent.

In the southern region the dominant flow pattern is L1, which is trending N-S (Figure 7.22a) with direction indicators recording a flow direction towards the south (Figure 7.25c), overtopping 200m elevation. Although broadly exhibiting a single ice flow direction, the pattern is relatively discordant with variability in lineament orientation. This flow pattern is tentatively described as time



a　　　b

Figure 7.21 Surface plots of lineament orientation (300m resolution, 3 min data points, 3000m radii) for flow patterns L 7 (a) and L8 (b). L7 depicts a gradual change in orientation, curving around the northern Lake District. L8 is less conformable than L7 and is possibly time-transgressive.

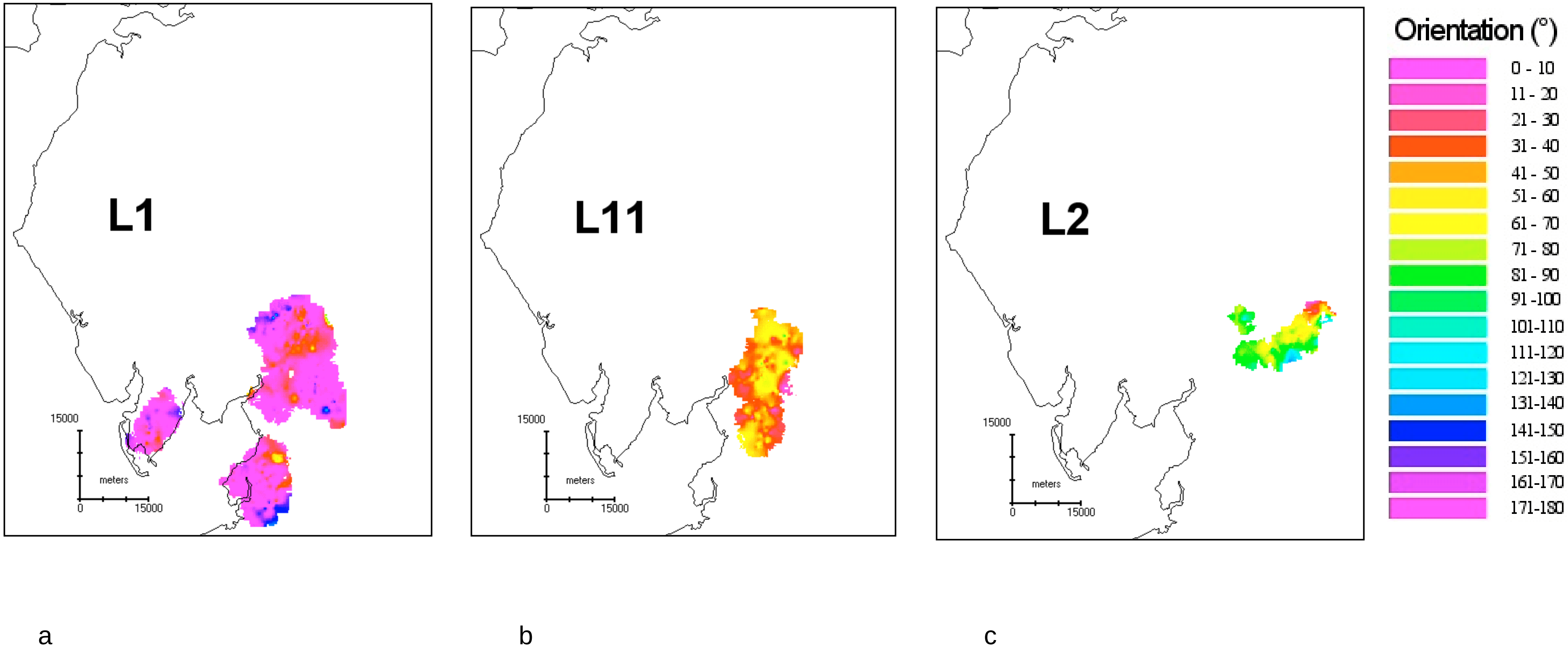


Figure 7.22 Surface plots of lineament orientation (300m resolution, 3 min data points, 3000m radii) for flow patterns L 1 (a), L11 (b) and L2 (c). L1 is dominated by a predominantly S oriented flow direction, although there are localised areas of inconsistency, possibly denoting a time-transgressive flow pattern. L11 and L2 both shown good orientation conformity, although the latter is effect by the constraints of topography.

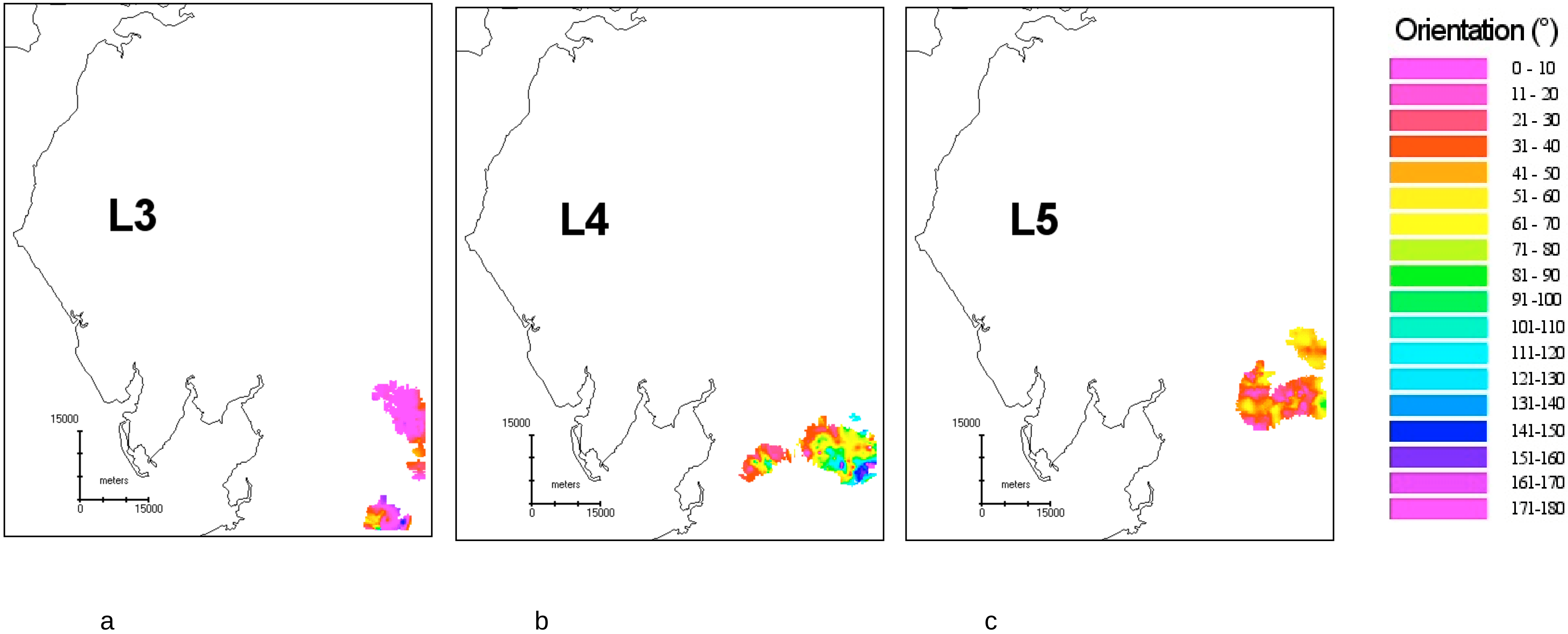


Figure 7.23 Surface plots of lineament orientation (300m resolution, 3 min data points, 3000m radii) for flow patterns L 3 (a), L4 (b) and L5 (c). L3 shows localised inconsistencies in orientation, although it is constrained by topography. L4 and L5 both show good orientation conformity, again they are both partly controlled by topography.

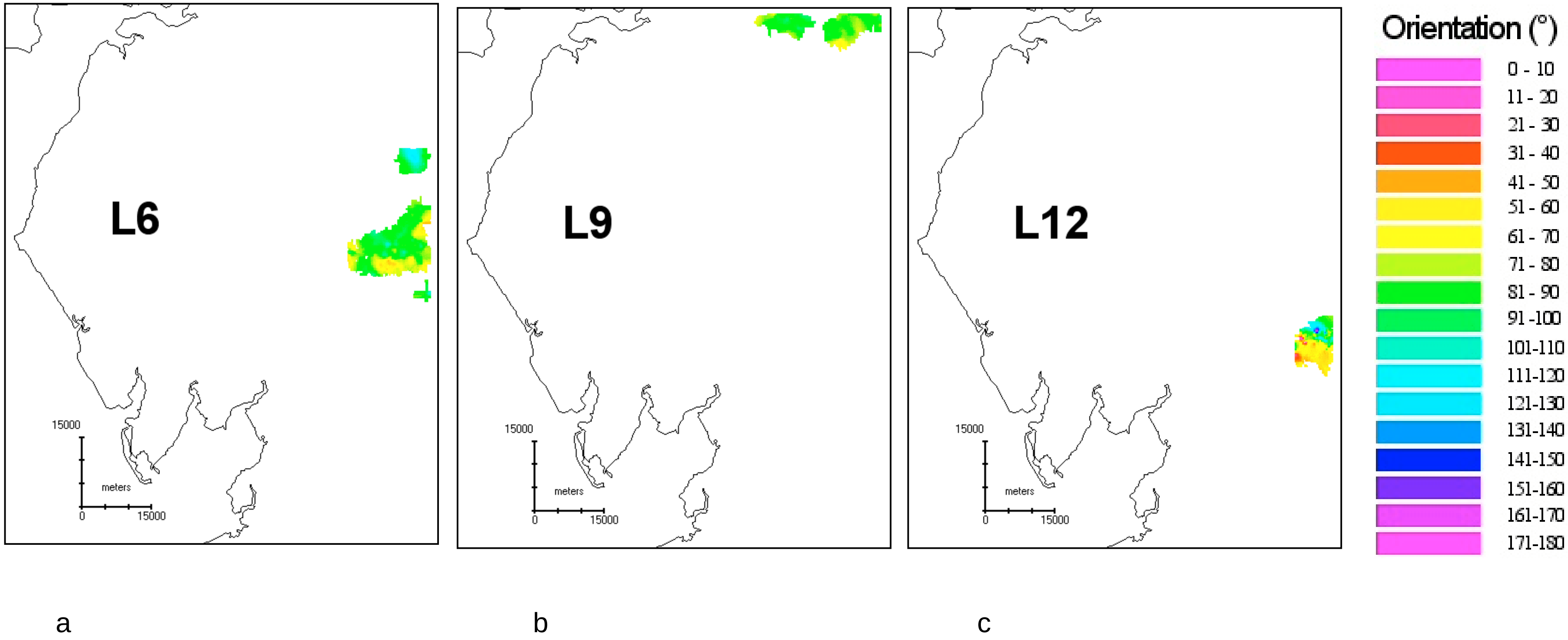
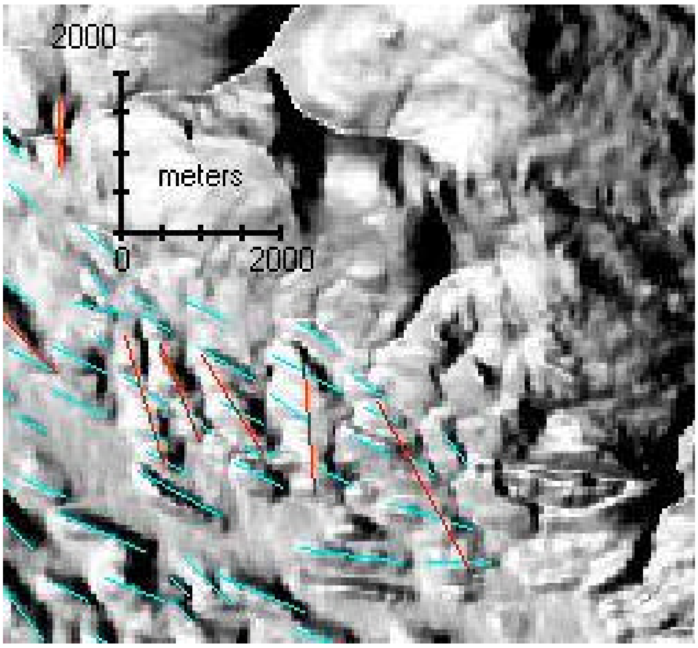
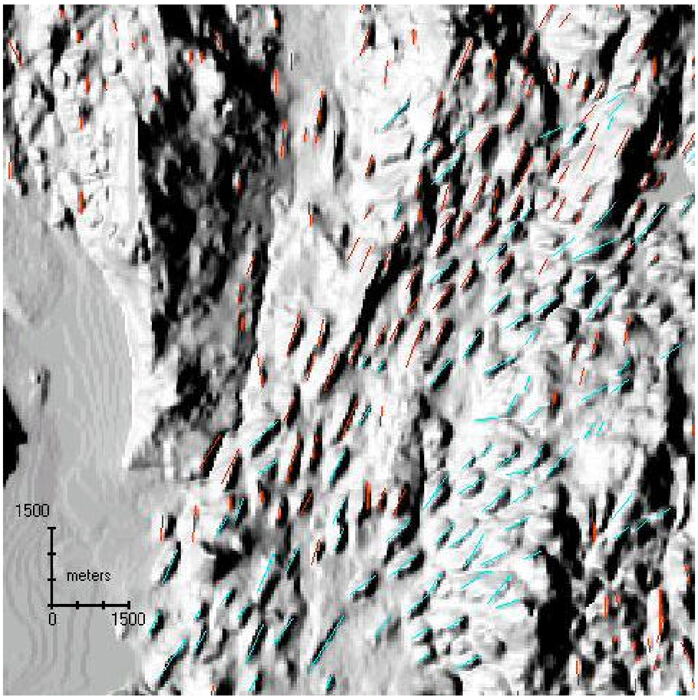


Figure 7.24 Surface plots of lineament orientation (300m resolution, 3 min data points, 3000m radii) for flow patterns L6 (a), L9 (b) and L12 (c). L6, L9 and L12 show good orientation conformity.



a



b

Figure 7.25 a. Example of cross-cutting showing smaller drumlins (L7) superimposed on larger, N-S trending, drumlins (L8).

b. Area of L1 showing traditional stoss-lee relationship with steeper, fatter, stoss end pointing upstream.

(©Ordnance Survey).

transgressive. The transverse bedforms located around Ingleton (RM1) are associated with, and are cross-cut by, L1.

L1 is intersected by L11 and L2. L11 exhibits strong orientation conformity (Figure 7.22b), with direction indicators confirming flow direction of NE to SW (and, as for L1, overtops 200m elevation). There are no clear signs of cross-cutting so a relative age relationship cannot be inferred. L2 (Figure 7.22c) exhibits good orientation conformity, although there are small changes in lineament orientation. This appears to be due the effects of topographic constraint (around 500m), with direction indicators tentatively suggesting ice flow broadly from E to W (supported by the convergence of topographically constrained drumlin patterns). L2 is cross-cut (i.e. older) by L11. L12 (Figure 7.24c) is also topographically constrained and, although there are no direction indicators, ice flow would be expected to flow to the lowlands in the east.

The remaining flow patterns (L3, L4 and L5) occupy the areas around Ribblesdale, Ingleton and Whernside, respectively, in the central and eastern parts of the southern region. L3 is located in an upland basin (~300m) and is trending N-S (Figure 7.23a), running incontinuously to the southern border of the DEM. These forms are relatively short, heavily modified and closely associated with the transverse bedforms located in the upper reaches of Ribblesdale. L4 forms part of a heavily modified lowland region that was partially mapped by Raistrick (1933). Although there are no direction indicators, lineaments are broadly trending E-W (Figure 7.23b). Finally, L5 is a NE-SW trending flow pattern (Figure 7.23c) which predominantly follows valleys but at its western extent climbs relief to 400m. It is also possible that RM1 has removed any previous bedforms beyond its current western extent. Again there are no direction indicators.

7.4.3 Geomorphological Ice Flow Direction Indicators from the Literature

It is appropriate to consult the literature to confirm the assessments of ice flow direction (using lineament stoss-lee relationships), as well as filling in areas where my assessments are not available. In the northern area the most prolific fieldwork was performed by Hollingworth (1931) and summarised by Mitchell and Clark (1994). This work confirms the existence and direction of flow pattern L7 (SE to NW) and provides new direction information for flow patterns L6 (W to E), L8 (SSE to NNW) and L9 (W to E). It is probable that L10 links with drumlin flow direction NE to SW identified by Hollingworth (1931) just north of the border. Mitchell and Clark (1994) also summarise regional patterns identified by the distribution of Shap granite erratics which broadly support these flow directions. Riley (1987) reports on cross-cutting drumlins in the east, suggesting that flow pattern L7 is succeeded by L6. Whiteman (1981) is unable confirm ice flow direction, although concurs with Riley (1987) that it was probably broadly south to north. His morphological mapping confirms the cross-cutting of L7 on L8 (i.e. L8 is older). Boardman (1981) also confirms the northerly flow of L8 from the Lake District. The drumlin mapping of Burgess (1979) covered from Appleby to Brough. Unlike Riley (1987), he did not identify superimposition within the drumlin assemblage. However he suggests ice flow directions of west to east (as for flow pattern L6) linking with ice flow from NW to SE. This is opposite to the ice flow assigned to L7. He confirms this interpretation with erratic evidence east of Stainmore which shows evidence of Lake District and Scottish ice (Shap and Galloway erratics). Arthurton (1981) confirms the northward ice flow direction around Penrith (consistent with flow patterns L7 and L8) although his he was not able to confirm the existence of two different flow patterns. Erratic evidence shows the presence of both Lake District and Scottish ice. In the northern part of his region he specifically notes the existence of rough ground made up of irregularly shaped bedforms as possibly indicating where Lake District and Scottish ice sheets may have converged.

Far less landform data is available for the southern Lake District. Vincent (1985) reports broad ice flow patterns which simply depict southward flowing ice. For the Ribblesdale Valley and the area around Settle Raistrict (1933) reported striae orientations of NW to SE (my flow pattern L4), whilst Arthurton (1988) suggests ice flow from N to S, however he provides no corroborative evidence. For the area around Lancaster, Brandon (1998) identifies two tills in the region and suggests that they demarcate two ice flow events, supported by erratic evidence. One ice flow from an ice divide centred over the Howgill Fells (representative of my L5) and the other from the Lake District (representative of my L1). He also notes the presence of a section of hummocky terrain which forms part of my flow set tentatively identified as ribbed moraine. Mitchell (1994) mapped drumlins in the Baugh Fell region (Wensleydale/Garsdale) where the cross-cutting and ice flow direction indicators are more complex. In general, he identifies a convergence of drumlins in Wensleydale and Garsdale indicating ice flow *down* these valleys (equivalent to L2 and L12). However these drumlins are superimposed upon larger drumlins which indicate ice flow from SW to NE. This ice flow direction is also supported by erratic evidence and drumlin mapping by Hollingworth (1931) in the Mallerstang area. It may link with my L5, although this flow pattern is more indicative of flow from NE to SW. §6.6.3 highlighted the reasons for poor correlation between the mapping of Mitchell and this work. It is possible that the DEM is unable to resolve the flow patterns Mitchell has mapped or that the bedforms identified as transverse forms in this region were mapped by Mitchell as drumlins. Mitchell confirms the easterly and westerly ice flow directions of L12 and L2 respectively, as well as southerly flow direction for L3 (the latter also confirmed by Hollingworth).

7.4.4 Summary of Flow Patterns

This section applies the techniques developed earlier in this chapter to the landform data mapped in Chapter 6. The use of orientation data was the primary tool in separating lineaments into individual flow patterns and was highlighted through the use of spatial variability plots of orientation and orientation conformity (i.e. vector strength of the interpolated dataset). Using this information, lineaments were separated into twelve flow patterns, according to their orientation and spatial continuity. This information needs to viewed within the context of ice thickness (where indicators are available) and the effect of topography for channelling ice flow. Further information that can be gained includes ice flow direction and relative age (through cross-cutting relationships).

The work concludes the grouping of lineaments into flow patterns and precedes the full glacial reconstruction. The latter would involve the grouping of flow patterns into flow sets and a subjective assessment of the timing of their formation (i.e. isochronous or time-transgressive). A thorough review of the available literature is required before a final reconstruction is performed.

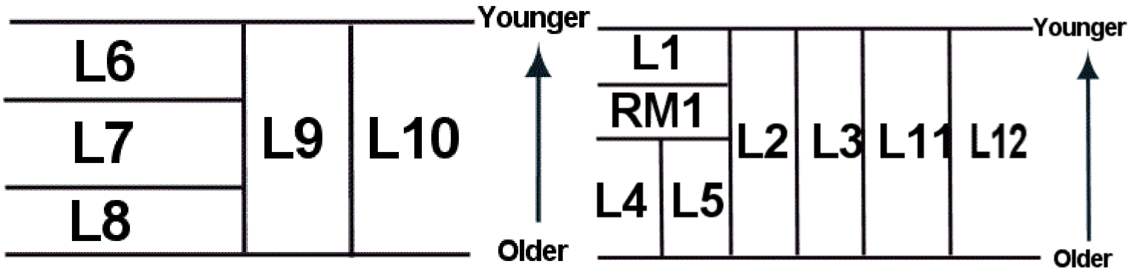


Table 7.2 Relative ages for the northern (left) and southern (right) Lake District. Horizontal lines denote a known or inferred (see text for further details) relative chronology. Vertical lines separate flow patterns where no relative chronology is known; for example L3 could "slide" up and down in time.

It is appropriate, at this stage, to comment on the data as it now stands. Initial evidence needs to be viewed within the constraints imposed by relative age relationships (Table 7.2) which, for example, broadly state that L8 precedes L7 in the north, whilst L4 precedes L1 in the south. L6 appears to have removed any past bedform traces of L8 and so is inferred to be younger; Riley (1987) has confirmed that L6 is younger than L7. In the south, RM1 is cross-cut by L1 and so precedes it. Their formation is thought to be closely linked (e.g. Clark and Meehan, 2001) and so they would probably have been formed during the same period. RM1 appears to have removed possible previous bedforms from L5 and L4, so these are inferred to be older.

Phase 1: Early expansion of Eastern lakes/Pennine/Howgill Fell ice.

For Phase one, L8 is proposed as the first recorded ice movement demonstrating the dominance of ice expanding out from the Pennines with a divide centred on the Eastern Lakes/Howgill Fells. The strong imprint of L8 on the landscape (with northward ice flow indicated by Hollingworth) does not extend beyond the Vale of Eden. Either such a trace has been removed or this early expansion was not extensive. This ice flow would have been followed by, or contemporaneous to, L11 and L3. These are again strongly imprinted upon the landscape and extend southwards. During this period there is no evidence for activity related to the central Lake District, however this must have had an ice dome and it is likely that any early traces of ice movement have been removed.

Phase 2: Major expansion of Pennine ice, confluent with Scottish ice, and a restricted Lake District ice dome.

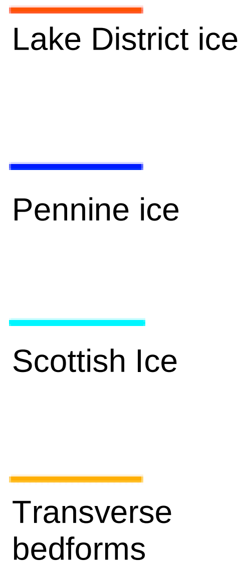
Phase two would have seen the dramatic development of Pennine ice, forming the strongly curving flow pattern of L7. This is important as major westward flowing ice from the Pennines is not currently considered likely; this is, in part, because there is no evidence of Pennine erratic dispersal west of Stainmore. This flow pattern also suggests the presence of Scottish ice blocking the Solway Firth, as well as ice over the Lake District blocking a direct western passage. Hollingworth (1931) commented on the odd bedform shapes in the Carlisle region which show no preferred orientation. These *could* be indicative of the confluence of Scottish and Pennine ice. L10 and L9 indicate SW and E flowing Scottish ice respectively. Huddart (1994) presents erratic evidence to support the direction of L10, whilst Catt (1991) presents similar evidence for L9. Although these are tentatively grouped together, there are no constraints on their relative chronology and it is quite possible that L10 is representative of a re-advancing Scottish ice sheet in Phase 3 (this is also supported by Huddart, 1994). L5 is possibly contemporaneous. Finally L2 is possibly a late phase movement, as the flow pattern is contained within the valleys, before finally exiting west.

Phase 3: Expansion and subsequent retreat of Lake District ice.

Phase three is dominated by the strong imprint of L6 showing a possible expansion of Lake District ice, along with L12. L1 (including RM1) is possibly deglacial, demonstrating late phase retreat of ice towards the Lake District (i.e. it is *not* synchronous with L6 and L11). It should be noted that L4 (as shown in Figure 7.20) is somewhat of an anomaly. It is possible that L4 fits into the flow set formed by L6 and simply demonstrates the expansion of Lake District ice. The preservation of these landforms is poor and has been almost entirely erased by the transverse bedforms mapped further west.

Phase 1

Phase 2



Location

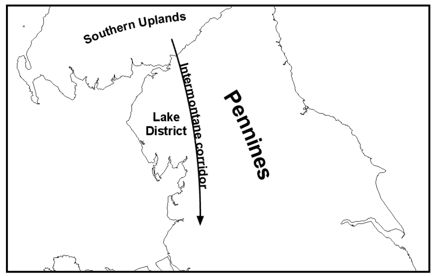


Figure 7.26a Preliminary ice sheet reconstruction reducing the 12 flow patterns to three main phases of ice flow. Phase 1 depicts the dominance Howgill Fell Ice (L8, L11 and L3) This expansion becomes a dominant pattern around the Lake District in Phase 2 with the formation of the curving ice flow around the north (L7). This is confluent with Scottish ice (L9 and L10) which is deflected eastwards and westwards. An ice dome over the Lake District probably blocked the direct westerly passage of L7.

Lake District ice

Pennine ice

Scottish Ice

Transverse
bedforms

Phase 3

Figure 7.26b Phase 3 demonstrates the expansion of Lake District ice forming L6 and L12. Although in the same phase, L1 is representative of a waning ice dome over the Lake District and (in conjunction with the transverse bedforms of RM1) possibly shows of a deglacial pattern.

Discussion

The above phases are based upon ice flow directions and relative chronologies derived from the geomorphological record portrayed on the DEM and supported by similar evidence from the literature. It is important to understand the context of this work in relation to current ideas about the glacial history of the Lake District and surrounding region, as well as within the stratigraphic framework.

Two main hypotheses have been extended to interpret the evidence that have been reported. Huddart (1994) (see also Lezter, 1978) reviews and presents evidence for an early advance of Scottish ice penetrating the Eden Valley and crossing both the Tyne and Stainmore gaps to the east coast (see also Catt, 1991 and Douglas, 1991). This initial phase was followed by a build up of Lake District ice with northerly ice flow down the Eden Valley. Lake District and Scottish ice would have been confluent in the Carlisle region with both ice masses forced to flow east and westwards. The final phase saw a re-advance of Scottish ice; there is debate as to how extensive this was (e.g. did it penetrate the Vale of Eden?) and this is discussed further by Huddart (1994).

In comparison to this *ground based ice* model, Eyles and McCabe (1989) espouse a *glaciomarine* model which re-interprets sediments believed to represent re-advancing Scottish ice as marine in origin. This depicts the advance of a rising sea level (and so retreat of the Irish Sea glacier) into an isostatically depressed basin. High relative sea levels led to the rapid downdraw of ice, allowing fast ice flow and streaming. The sudden evacuation of ice would have led to a major collapse of ice domes with the probable stranding of dead ice in peripheral regions.

Stratigraphically, St Bees and Sellafield are important sites as detailed data is available for them, revealing a complex series of events. Their location is also significant as they are straddled between the Irish Sea and Lake District uplands and so have recorded major expansion and retreat of both Scottish and Lake District ice.

Huddart (1994) describes four main units at St Bees which are a succession of till (St Bees Till), silts and clays (St Bees Silts and Clays), sands and gravels (St Bees Sands and Gravels) and a final till (Lowca Till). The Lowca till is interpreted to be representative of the main Lake District glaciation which can be traced up the Eden Valley. The St Bees Silts and Clays and St Bees Sands and Gravels are interpreted as different facies of proglacial deposition from eastward advancing ice in the Irish Sea. The St Bees Till is interpreted as deposition from a re-advancing Irish Sea ice sheet, probably synchronous with (and part of) the Scottish Re-advance. This tripartite division of Cumbrian stratigraphy dates back to Hollingworth (1931) and other workers of the period.

Merritt *et al* (2000) interpret the sequences at Sellafield during the last glacial maximum as representative of a major incursion of Irish Sea ice (coalescing with Lake District valley glaciers), followed by a significant retreat, possibly deglaciating the northern Irish Sea basin (synchronous retreat of Lake District ice also occurred). A major re-expansion ('Gosforth Oscillation') of Irish Sea ice then occurred, and coalesced, with ice from the Lake District. They believe that most of the drumlinisation occurred during this period. This was followed by a series of re-advances, the most significant being the 'Scottish Re-advance', although there was probably no re-advance of ice from the Lake District.

Huddart (1994) and Merritt *et al* (2000) do not support the glaciomarine model. They found no evidence to support high marine still stands and refer to isostasy modelling by Lambeck (1996) as further confirmation. Additionally, sequences that Eyles and McCabe (1989) identify as glaciomarine, they interpret as glaciotectonic (and so ground based). McCarroll (2001) critically reviews, and rejects, the evidence for the glaciomarine model, however this is countered by critical support from Knight (2001).

With reference to this work, the simplest explanation for the evidence is an interplay between the Lake District ice dome and the competing ice divides located over the northern Pennines and Southern Uplands of Scotland. As such, the generation of subglacial bedforms would have been strongly influenced by the dominance of these different ice masses at different times.

It is natural to expect early ice flow to emanate from Scotland given the generally high elevations and northerly latitude, however the only evidence of Scottish ice flow in the bedform record is found in the very north of the region (L9 and L10; although these are tentatively placed in Phase 2). Given the erratic and stratigraphic evidence recording Scottish ice flow through Stainmore, the Eden Valley might be expected to retain geomorphic evidence. However a lack of evidence is not unusual as subsequent ice flow from both the Pennines and Lake District may well have erased the previous bedform record.

The first geomorphic evidence is recorded in Phase 1 which places an ice divide over the eastern Lake District, Howgill Fells and Pennines. The Lake District ice dome must have expanded to a significant size in order to support such ice flow (and indeed L8 may have been confluent with Scottish ice), however it suggests a shift in the centre of ice mass *towards* the Pennines. Phase 2 shows the classic curving ice flow around the north of the Lake District (L7); this suggests a centre of mass over the Pennines and, unusually, westwards ice flow *across* Stainmore. There is no supporting erratic evidence for such an ice flow, however the geomorphic signature strongly suggests this. The curving ice flow also suggests the presence of both a Lake District ice dome and confluent Scottish ice in the Carlisle region. L9 and L10 are tentatively placed here as representative of such a configuration, however L10 could easily fit into Phase 3 as part of the Scottish re-advance.

Phase 3 again shows the dominance of a Lake District ice dome with easterly flow over Stainmore and southerly flow towards Lancaster. It is possible that L6 may represent early Scottish ice flow across Stainmore, however it has a strong E-W orientation which suggests a Lake District origin, also supported by the distribution of Shap erratics (Mitchell and Clark, 1994). As noted above, L10 may well fit in this phase as most researchers agree Scottish ice did penetrate down the western Lake District, with limited invasion into the Eden Valley.

The three phases developed in this chapter depict a major ice mass over the Lake District that gradually expands eastwards forming a major ice divide that causes the diversion of incursive Scottish ice both eastwards and westwards, before contracting into a final deglacial pattern. It is also conceivable that the extent of this ice mass remained fairly static until final deglaciation and that the Howgill Fells region operated as an important switch in initiating active ice flow and drumlinisation. Scottish ice is recorded in Phase 2 and, possibly, in Phase 3. In correlation to the simple, tripartite, classification, Phase 3 could be correlated with the Scottish Re-advance (and a deglaciating Lake District ice sheet). This places Phase 2 as the glacial maximum, with phase 1 representative of early build of Lake District ice. The early Scottish glacial advance is not recorded. Unfortunately the detailed stratigraphies from St Bees and Sellafield do not record the complex interaction that occurred in the upper Eden Valley. Further evidence will be needed to help resolve the complex series of ice flows that occurred here. The geomorphological evidence appears not to support the glaciomarine model. The final phase suggests deglaciation through a retreating ice margin in the south, with possible Scottish ice incursive into the Irish Sea. There is no support for ice streaming and subsequent drumlinisation as a result of rapid downdraw during this period.

It should be stressed that the above suppositions are based upon available landform data and the literature. In particular, only relative age assessments have been made so there is no knowledge of how this history fits within an absolute timescale. However, this procedure demonstrates that a complex pattern of landforms can be generalised into a fairly simple set of flow patterns which can then be interpreted into a glacial history.

7.5 Development of an Automated Flow Set Classification Technique

7.5.1 Introduction

The formation of flow patterns requires the generalisation and/or grouping of individual lineaments. These groups show strong similarity in orientation, with other diagnostic features including length, density and spatial continuity. This chapter has reviewed the visual methodology by which researchers have traditionally performed this stage and gone on to develop techniques to help identify flow patterns and to quantitatively validate their grouping. Earlier discussion stressed the need to use objective and quantitative measures to help perform this stage in order to make it verifiable and comparable with other research. It was suggested that a fully automated technique would help alleviate this problem, however it is not a simple process to automate within current GIS and would require extensive testing to accommodate the complex glaciological scenarios it would be required to operate in. It is, however, appropriate to outline and review the broad aspects of such an approach. This section now performs this.

7.5.2 Development of a Fully Automated Flow Pattern Algorithm

This chapter has emphasised the requirement for locally based assessment of lineament grouping and it is therefore appropriate that an automated technique incorporates similar ideas. Indeed such “region growing” techniques are used in remote sensing for classifying imagery. However lineament data are vector, rather than raster based, and require a modified approach in order to work. The initial development of an algorithm centred upon the requirement to manually “seed” a region, from which flow patterns could be “grown” (a technique somewhat analogous to supervised classification by seeding within remote sensing). This would add adjacent lineaments into a flow pattern if they met certain criteria (e.g. deviation of orientation) until no more could be added. The remaining lineaments would remain unidentified and could be explored further if necessary. More specifically such an algorithm would involve the following steps (Figure 7.27):

1. Set threshold values:

a. Number of nearest lineaments to compare (n)

b. Length deviation (L)

c. Orientation deviation (α)

d. Maximum distance to nearest lineaments (M)

2. Choose a seed lineament that visually falls within the middle of a suspected flow pattern.

3. Look at *n* nearest lineaments:

Check M is not exceeded

Check L and α are not exceeded

If found within these thresholds *include* within the flow pattern

If outside threshold, *ignore*

4. Of this set of N lineaments (original seed and n nearest lineaments) take the two that are furthest apart and use these as *new* seeds within the current flow pattern and perform the routine in (3)
- If one of the two new seeds is the original then this is discounted, but no new seed is selected.

4. The procedure in (3) and (4) is continued until no new lineaments can be added.

The use of farthest apart secondary seeds is designed to reduce the number of nearest neighbour calculations whilst allowing expansion of the algorithm into all parts of the study area. If a primary seed is selected as a secondary seed then this would repeat calculations and therefore this seed is removed. Otherwise the algorithm simply operates by testing all lineaments for spacing (i.e. distance to nearest neighbour), orientation conformity and length conformity. The following section provides an initial assessment of the algorithm and then suggests areas for further development.

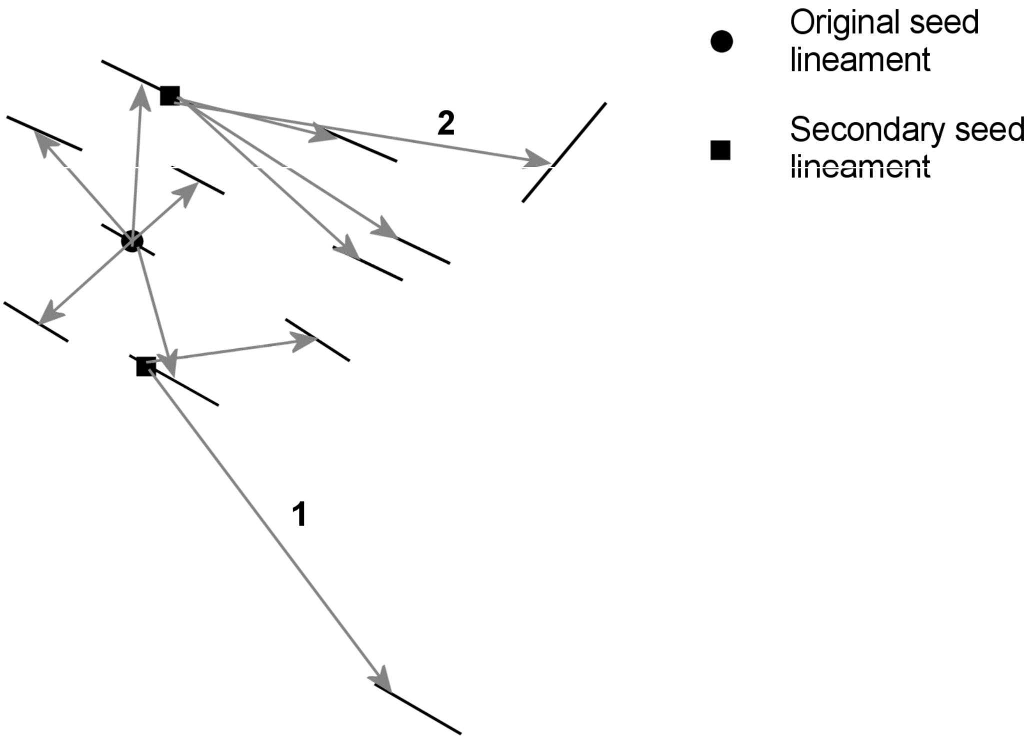


Figure 7.27 Idealised example of the automated flow pattern technique. The original seed lineament is selected and the five nearest lineaments located. Of these lineaments, the two furthest apart become secondary seed lineaments and the five closest unallocated lineaments are then selected. However at (1) the maximum distance to a lineament is exceeded and so cannot be selected. At (2), the maximum deviation in orientation is exceeded and so cannot be selected.

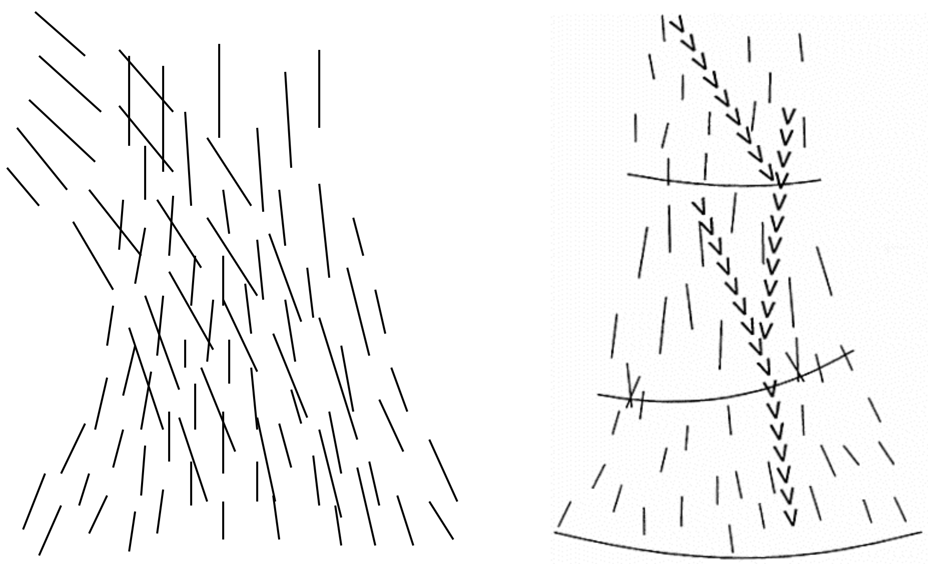


Figure 7.28 Low-angular cross-cutting (left) makes distinguishing flow sets difficult, particularly when lineament orientations coincide, as in the southern part of this example. Time-transgressive (right) flow sets display cross-cutting, low orientation conformity and abrupt morphometric changes yet are a single flow set (modified from Clark, 1999).

7.5.3 Initial Algorithm Testing

The above procedure was manually applied to the idealised dataset (Figure 7.8) used in previous sections. It performed satisfactorily, splitting lineaments into the two principal flow patterns. However it is probably self-evident that the algorithm will perform well in such a simplistic scenario. The full complexity of genuine mapped data needs to be fully explored in order to test how effective it is and develop a routine that will perform satisfactorily in a variety of situations. The algorithm was developed on the assumption that similarity of form suggests similarity of formation. More specifically, it is important to understand the different glaciological scenarios thought to be able to generate flow patterns and the traces they leave (Clark, 1999). In general, isochronous flow sets are easily identified, even when they are cross-cutting as they have high orientation conformity and gradual changes in morphometry. However, there are two scenarios which are more complex and so difficult to identify (Figure 7.28):

1. Low Angular Cross-cutting – lineaments which cross-cut at low angles are very difficult to identify, even by manual techniques. If cross-cutting involved re-moulding, then there may be little morphological trace of pre-existing lineament patterns. Superimposition may have left more morphological traces, but these can still be difficult to determine. In the example illustrated, an isochronous flow set has low-angular cross-cutting with another isochronous flow set. They may be distinguishable through differences in orientation, but at the lobe itself lineaments may be oriented in the same direction. In this instance spacing and length variations may provide further diagnostic information.

2. Time-Transgressive – the diagnostic criteria for time-transgressive flow sets (§3.7) are contrary to all the techniques used to identify isochronous flow sets. There can be cross-cutting (low to medium angular differences) within flow patterns, abrupt changes in morphometry and low orientation conformity. This can be complicated by lineaments being constrained by topography, particularly if the lineament record is not complete. However other associated evidence which can be useful, include the alignment of

eskers and end moraines. Such a situation would clearly become more complicated if there were, *in addition*, low-angular cross-cutting.

As well as the above glaciological scenarios, there may be morphological situations in which the automated procedure may not work. For example, threshold values for lineament length are not always appropriate as there can be scenarios when long lineaments are surrounded by many smaller lineaments.

7.5.4 Review

This section has attempted to develop an algorithm which could eventually be improved to perform fully automated flow set development. Initial development suggests that it is able to satisfactorily separate high-angular cross-cutting isochronous flow sets. However lineament data can be more complex, particularly where low-angular cross-cutting and time-transgressive flow sets are concerned. It would be necessary to perform additional testing and development to ensure such scenarios could be successfully handled. It is not appropriate at this stage to move on and develop this algorithm, however this section has provided a “proof-of-concept” which would allow later integration within a GIS workflow.

7.6 Conclusions

Generalisation is a complex procedure that is difficult to automate and consequently visually based, manual, techniques are preferred. The process of generalisation, as applied to glacial landform data, is poorly documented, relying upon a mixture of an assessment of “parallelness” and interpretation. This is inappropriate as it combines interpretative and non-interpretative stages together such that reproducibility becomes difficult. Two main approaches can be used in defining flow patterns:

- **Manual** - use of spatial variability plots to guide the observer into the classification of flow patterns and then to provide quantitative checks on manual flow pattern classification.
- **Automated** - a fully automated, locally adaptive, algorithm for classifying flow patterns.

The former procedure has been illustrated in this chapter and provides a common set of tools that can be applied by researchers to help generalise their data and then provide a quantitative assessment as to its applicability. This approach worked satisfactorily for both idealised data sets and real data for the Irish Midlands. Orientation and orientation conformity are the most important variables in generalising data into flow patterns, however it is important to supplement them with information on length and density where necessary. This approach was then applied to the landforms that were mapped from the DEM in Chapter 6. This is probably one of the most difficult landscapes not only to map landforms in, but also to create flow patterns. However the complex bedform traces were generalised into 11 flow patterns. Initial assessment of these data suggests that as few as 3 ice flow phases can be formed to explain the bedform pattern that is currently visible today (Figure 7.26).

The chapter was completed with the initial exploration of an automated flow set procedure. It was recognised that, like visually based techniques, any procedure needed to be based upon localised similarity of form. The algorithm therefore operates on a nearest neighbour procedure that assesses similarity in length and orientation. The procedure provides a "proof-of-concept", however the section went on to explore scenarios where further development would be necessary. Ideally the technique would be implemented within a GIS workflow.

In conclusion, generalisation is an important part of ice sheet reconstructions as it helps devolve complex landforms into simpler flow patterns that can then be interpreted. This stage should ideally be as objective as possible, such that it is reproducible by others. The techniques outlined provide tools by which the researcher can assess landforms before they are generalised into flow patterns, as well as substantiate their division.