4 Key Research Topics

4.1 Introduction

During my research into the reconstruction of the Irish ice sheet, it became clear that the results obtained by mapping from remotely sensed imagery may vary according to the nature of the imagery used, and the skill and experience of the observer. If this method is to yield reliable results which are comparable between different regions, mapped by different observers, then there needs to be a greater understanding of the sensitivity of the results to the exact methodology employed.

Ice sheet reconstructions require the mapping of individual glacial landforms from imagery. The results from this stage will depend on the *detectability* of the landforms, a term which incorporates the following two elements:

1. **Image:** the degree to which the physical and spectral characteristics of the sensor allow the landforms to be distinguished from other features on the image
2. **Observer:** the success with which an observer can record these differences and thus map the landforms.

The second stage involves summarising the landform information into meaningful patterns by grouping the individual landforms into sets of features which can be assumed to have been derived by a single glacial event. This is a subjective technique, which resembles the process by which cartographers generalise information from large scale maps to produce small scale ones.

Although remotely sensed images were the main source of data for my original mapping of the Irish ice sheet, they are rapidly being supplemented and, in many instances, replaced, by digital map data, principally digital elevation models (DEMs). Within the restrictions set by data collection and DEM creation, these are accurate representations of a surface and are ideal data sources for morphological mapping.

This chapter discusses methodological problems arising from both the mapping (using satellite imagery and DEM data) and generalisation stages. These topics then become the main foci of this research and the thesis is structured around them. The following three chapters describe the methodology used to investigate these topic areas and present results from these investigations. The thesis concludes with a review of the results.

4.2 Detectability

Scientific investigation can be based around experimentation involving the collection of measurements and their analysis. This can then lead to the creation of a framework through which a phenomenon can be understood. For ice sheet reconstruction, the location of landforms created during the last glaciation is required. Their location (or measurement of their position) is recorded through field mapping or remote sensing. As Chapter 2 has illustrated, this can effectively be achieved through the use of satellite imagery. However the recording of surface reflectance is not a surrogate for the location of glacial landforms. For this to occur, meaning must be assigned to features depicted in the image. This process is termed *landform detection* and is dependent upon the representation of a landform on an image and the ability of an observer to assign meaning to it. That is to say, for a landform to be successfully detected it must be fully represented upon the image and the observer must be able to locate it. This section will discuss the factors that affect these two variables.

4.2.1 Landform Representation

The representation of a landform upon an image depends upon the characteristics of the sensor, the characteristics of the landform, the illumination conditions and sometimes the meteorological conditions prior to and during acquisition. The interaction of these categories combine to produce the following variables:

1) **Relative size:** the relationship of lineament length to sensor spatial resolution. The higher the spatial resolution the greater the ability to resolve shorter lineaments (Figure 4.1).

2) **Azimuth Biasing:** a bias in landform detectability arising from the difference between the lineament orientation and the illumination orientation (azimuth angle). Landforms are known to appear differently when they have different solar illumination directions (Figure 4.2). For example, a drumlin viewed side-on will look like a drumlin, but when viewed head-on can look like a circular hill (Aber *et al* (1993) and Lidmar-Bergström *et al* (1991)).

3) **Landform Signal Strength:** the degree to which the landform can be distinguished from other features by tonal and textural information in the image. These variations are caused by differences between the surface cover of a lineament and its surroundings (Figure 4.1b shows drumlins highlighted by inter-drumlin waterbodies), and the relief effect arising from slopes appearing lighter or darker depending upon the height of the sun in the sky (solar elevation; Figure 4.3). High illumination angles cause lee slopes to be illuminated (so reducing textural information), whilst low illumination obscures lee slope with shadow (also reducing textural information, but highlighting the presence of the lineament). Several authors have investigated the conditions through which high contrast images depicting lineaments are obtained (e.g. Slaney, 1981). In general they conclude that a low solar elevation produces ideal imaging conditions.

Synthetic aperture radar (SAR) imagery is also used for mapping landforms but here the controls on detectability are different because of the different viewing geometry. SAR imagery is good at detecting topographic variation due to the oblique viewing angle of the sensor, as opposed to the near-vertical viewing angle of visible and near infra-red (VIR) sensors (Figure 4.4). An advantage of SAR data is that it is acquired with fixed illumination and azimuth angles providing a consistent data source. This is unlike optical data (e.g. Landsat) which will have varying angles on different images according to the date and time of day (i.e. the sun position varies).

Figure 4.1a and b Landsat ETM+ Multispectral (left) and Panchromatic (right) images showing the effect of sensor spatial resolution (15m and 30m respectively) on lineament detection.

Figure 4.2 Illustration of the effect of azimuth biasing on landform detection. The two images are extracted from a relief shaded DEM (Lough Gara, Ireland), illuminated from different azimuths. Arrows indicate azimuth angle.

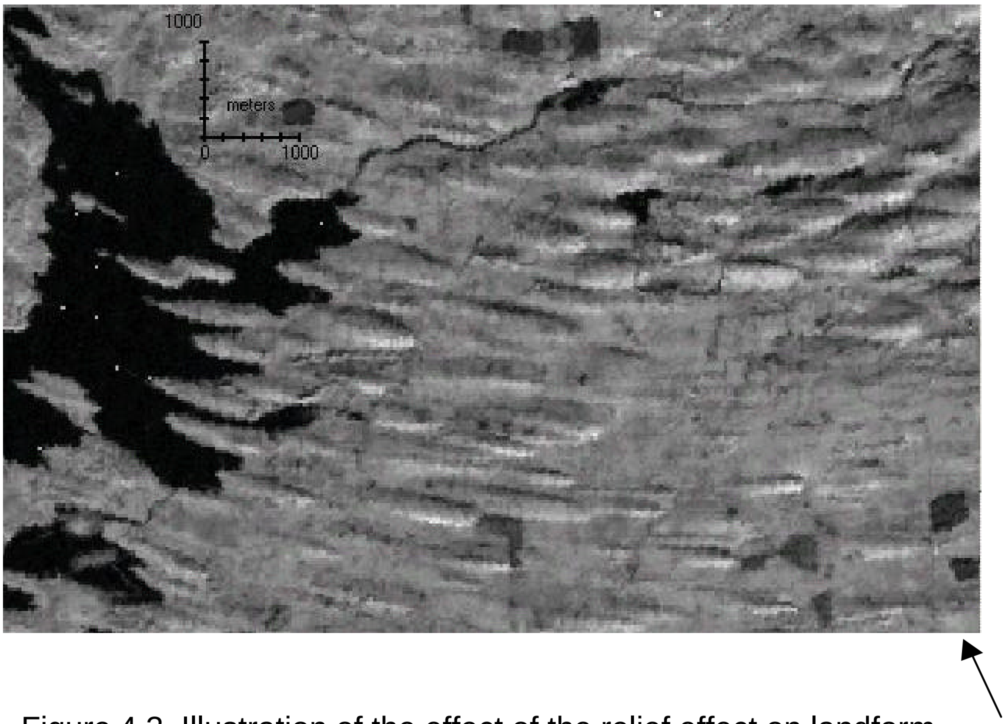

Figure 4.3 Illustration of the effect of the relief effect on landform detection. The image shows lineaments highlighted by the shadows they cast, a result of low solar elevation. Arrow indicates azimuth angle.

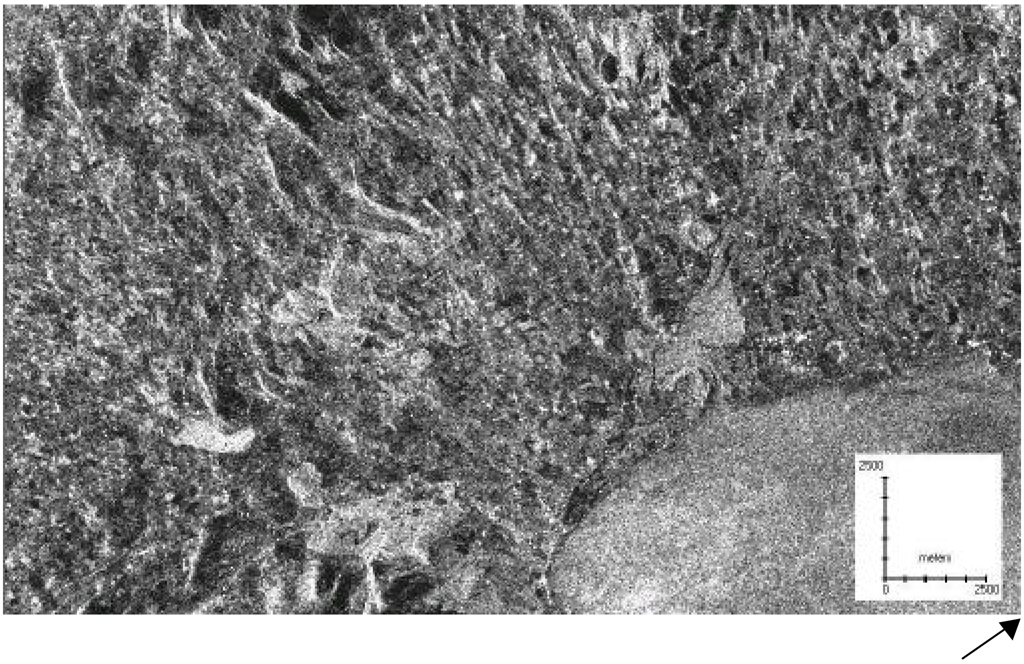

Figure 4.4 ERS-1 SAR image highlighting lineaments on the right hand side oriented north-south. Note the rollover effect the side-looking radar has on the steep, mountainous terrain in the centre. Arrow indicates azimuth angle.

The greater the difference in reflectance properties of the surface cover of the lineament when compared to surrounding terrain and the greater the relief effect (for VIR imagery), the greater the tonal differentiation of the lineament on the image (see Clark, 1997 and Aber et al, 1993 for further discussion). As lineaments are often composed of the same material as the surrounding terrain, spectral differentiation is of limited use in these situations. However, Punkari (1982) and Dongelmans (1996) have successfully used spectral differentiation by taking advantage of certain regions where drumlinised terrain enhances the collection of moisture in inter-drumlin areas. This variability in surface moisture affects surface cover (i.e. inter-drumlin regions become boggy) and allows drumlin identification.

Meteorological conditions can also be important for landform representation in VIR imagery. Atmospheric interference can reduce the sharpness of imagery by diffusing direct radiation, whilst antecedent conditions may affect surface reflectance properties and so alter lineament tonal differentiation. This is especially true for SAR data which is highly sensitive to variations in moisture such as from rainfall events or dew.

The interaction of the above variables produce a complex representation of an imaged surface. In order to interpret data mapped from imagery it is essential to understand the nature of the imagery from which that data has been acquired so that inherent errors can be accounted for. This is dependent upon the aims of the research and consequently the level of spatial accuracy and completeness required. If a morphological map of a selected region is required, then mapping with high spatial accuracy and completeness is necessary. Conversely, generalised flow patterns of a palaeo-ice sheet require lower spatial accuracy and completeness.

In summary, there is a minimum resolvable landform size and a range of lineament orientations that an individual sensor will be able to represent. In addition, the *definition* of these landforms is dependent upon the surface cover (affected by antecedent meteorological conditions) and relief effect (for VIR imagery). Optimum conditions for definition (e.g. Aber *et al*, 1993) will allow the representation of some landforms and easier interpretation of others.

4.2.2 Observer Ability

Image interpretation is the qualitative (manual) identification of features of interest within an image and an appraisal of their significance. The ability of an observer to interpret a remotely sensed image is dependent upon the experience in using interpretive techniques, as well as specialist information pertaining to the area of interest.

Different interpretive techniques have been developed since the availability of aerial photography and have consequently been the focus of much research (e.g. Colwell, 1960). With the advent of infra-red and radar photography these techniques were expanded (e.g. Oslon, 1960) and this process continued with the introduction of space photography and digital imagery (e.g. Colwell, 1983). Traditional techniques (Colwell, 1960) include the assessment of shape, size, tone, texture, shadow, pattern, location and association. A “convergence of evidence” allows the successful identification of an object. Estes *et al* (1983) ordered the above techniques, so providing a hierarchical framework to image interpretation methodology. This was extended by Black (1995) who categorised this hierarchy, suggesting that higher order techniques provided the most effective methods of identification and so should form the basis of an image enhancement strategy (Figure 4.5). Black suggests traditional interpretation techniques allow “perception” and “cognition”, however higher order techniques lead to “recognition” and ultimately “identification.” By focusing lineament mapping and image enhancement techniques on these higher orders, high accuracy mapping should be attainable. His principal datasets were Landsat TM imagery and DEM data created from 1:10560 and 1:50000 digitised contour data. The latter were used to create slope and aspect maps, as well as alternately relief shaded images. Although he recommends image processing techniques for satellite imagery, he states that the DEM and derived data were the best primary data source, however the exact technique used for mapping from the DEM data is not explained.

The specialist experience of an observer is central to their ability to interpret imagery. In glaciology, the ability to identify glacial landforms in different locations and environments is fundamental to the achievement of complete mapping.

Lineament mapping has formed a major area of research, particularly during early geologic applications of Landsat MSS imagery (Pohl *et al*, 1998). This has attracted work on the enhancement of lineaments within imagery (e.g. Clark, 1997; Black, 1995), as well as the reproducibility of results by one observer and between observers. The former topic was briefly described above, whilst the latter topic will now be touched upon.

Siegal (1977) built a scaled model of a landscape and used vertical photographs (with four different illumination azimuths) to test the variability between specialist geological observers. He explicitly focused on geological lineaments and chose to provide no definition of “lineament” to the observers. Given that observer variability is expected, it is not surprising that his results reflect this. He found that there was high variability in the number of lineaments mapped, with 22% of the variation of total lineament length attributable to observer variability, whilst illumination azimuth accounted for just 2%. The remaining variability is a result of observer-azimuth interaction and other unaccountable errors. Siegal went on to perform a comparison of lineament coincidence between observers and found that there was less than 5% coincidence between all 5 observers, with 50% of all mapped lineaments not coincident at all. However overall accuracy could not be gauged as a higher accuracy map was not used to test against.

Podwysocki (1975) compared the lineament mapping of four geologists using Landsat MSS imagery, having provided them with an explicit definition of a lineament beforehand. Less than 1% of lineaments were coincident between all four operators, however Podwysocki had no access to higher quality data and admitted that the study area was not ideal.

These results are perhaps not surprising given the very broad remit with regard to mapping. Within geological lineaments both topographic and non-topographic forms will be mapped, with lineament lengths often varying across several orders of magnitude. This can result in the inclusion of nearly all linear features as requiring mapping. The lineaments mapped will therefore depend on the mapping style and experience of each individual observer. Within the context of a glacial environment, lineaments (i.e. drumlins) are purely topographic forms, principally spanning the 200-2000m range, although longer and shorter lineaments do exist. Given their topographic representation, other ancillary evidence often exists with which to corroborate an identification. For detailed morphological mapping, it is desirable to perform break-of-slope mapping and then subsequently identify lineaments. With careful mapping procedures operator inter-variability should be minimal.

4.2.3 Summary

Landform detectability is dependent upon the representation of a surface by a satellite sensor and the ability of an observer to map those landforms. This then raises the following questions:

- Does the available image represent all, or a large proportion, of the landforms present?
- Is the observer able to map these landforms or are errors of omission and commission present?

The latter question has been briefly touched upon above, but is yet to receive specific examination with respect to glacial landforms. Indeed, recent research (e.g. Vencatasawmy, 1997) has looked at the ability to automate the process of lineament mapping. Chapter 5 aims to investigate the former question and whilst observer variability in mapping is a problem, this is assumed to be minimal through consistency produced by one observer.

4.3 DEM Visualisation

4.3.1 Introduction

The two-dimensional visualisation of three-dimensional terrain has been a common problem within geography, dating back to early map making. Perspective views (Figure 4.6a) are a common method used to introduce a sense of depth, however it is not appropriate for maps as they are generally orthographic (i.e. scale invariant with a vertical view). Map makers came up with alternative methods which included hachuring, contours and relief shading (Figure 4.6). Other less common techniques that were developed included vacuum-formed maps (i.e. three-dimensional surface models created using the vacuum-formed process), illuminated contours (relief shading with contours), physiographic diagrams and inclined contours (perspectively viewed contours which are planimetrically correct). These are depicted in Figure 4.7.

Since the advent of computer graphics and computer based mapping, the graphical recreation of a real word scene through numerical modelling and visualisation on a computer monitor has been the focus of much research (See Appendix 1 for further discussion). A number of techniques have been developed to perform this and are broadly referred to as *rendering*. These are either predominantly physically or visually based and can provide an orthographic or perspective view. The more complex techniques produce photo-realistic results which are designed to be indistinguishable from real landscapes, as evidenced by computer based special effects used by film makers. The simpler techniques leverage their ability to produce results very quickly and so allow real-time, interactive, visualisation. Aircraft flight simulators clearly fall within this category.

Within map based disciplines, these latter methods are predominant as they allow rapid evaluation of terrain for a variety of purposes. For example Tragheim (1996) illustrates the use of digital photogrammetry within the British Geological Survey. After the acquisition of standard aerial photography, the photos are scanned into a digital photogrammetric workstation and a DEM produced. This can then have the original rectified image draped over it and allow the operator to “fly” through the landscape. Interactive viewing can allow

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the operator to distinguish relationships which may not be readily visible either from the ground or through using traditional aerial photography. Unfortunately it was not possible to digitise using a perspective view so that it was recorded correctly on an orthographic basemap, however there is no reason why this technology cannot be readily developed. Figure 4.8 shows examples of relief shading, colour shading, contouring and perspective viewing in computer based mapping.

4.3.2 Storage Techniques

Three dimensional spatial data have traditionally been stored in two ways; either vector based (commonly Triangulated Irregular Networks or TINs) or raster based (grids). These techniques need to satisfactorily model the following criteria of surfaces:

- continually varying
- space exhausting
- spatially autocorrelated

Early storage techniques needed to be efficient, as well as interoperate with contemporary datasets (typically contour data). TINs are vector polygon based surfaces that apply varying height data across their facets in order to map the surface they represent (Figure 4.9). Each polygon is constructed to accurately represent the surface beneath it and is size variable. This takes advantage of spatial autocorrelation in that “smooth” landscapes can be described by larger polygons and so involve less storage. In addition, due to their construction, each polygon includes slope and aspect attribute data, as well as location.

The raster grid storage technique is commonly called a DEM (for surfaces) or Digital Terrain Model (DTM for terrain). Each cell within the grid is assigned a height value for the location it represents. Given the nature of a grid, if cell dimensions and the co-ordinates of the origin are known, then each cell location can implicitly be calculated.

Although less efficient than TINs (they are essentially a regular sampling technique), DEMs are the storage medium of choice as storage is now relatively inexpensive and much earth science data (e.g. satellite imagery) is collected in this manner. DEM research dates to the late 1960s (Evans, 1972) with most work based upon contour data converted to raster grids. The launch of Landsat 1 by NASA in 1972 brought grid based data to the earth sciences. In addition to the abundance of remotely sensed data (and the processing techniques that have developed in tandem), DEM data is now becoming widely available. In Europe this began with the conversion of existing map data to DEMs. For example, in the UK the Ordnance Survey (OS) created 50m resolution DEMs based upon its 1:50000 map products. More recently they have generated 10m resolution data based upon their 1:10000 products.

The Irish Ordnance Survey (IOS) have generated a country wide DEM using digital photogrammetry, showing the move from traditional survey techniques to digital mapping. However it is the advent of satellite based techniques that are producing the greatest revolution. The UK now has the Landmap DEM (Kitmitto *et al*, 2000) based upon ERS-1 interferometric SAR (inSAR) data of the UK and Ireland. Of more interest is the Shuttle Radar Topography Mission (Rolando *et al*, 1996) or SRTM, which aims to deliver a near global DTM from 56°S to 60°N. This is also based upon inSAR, with data collected by the Space Shuttle. Data products will eventually include 90m resolution global data and 30m resolution data upon request.

This, however, still leaves large unmapped landmasses north of the 60°N latitude. Photogrammetry was previously the only technique for producing DEMs, however researchers have experimented with creating them from satellite imagery. Limited experimentation began with early Landsat imagery, however the advent of SPOT allowed this to become a reality through the use of their side-looking HRV sensor. This is expensive and currently has sporadic coverage. Much more success has been had with ERS SAR data (e.g. Landmap). The recent fully operational status of the ASTER sensor aboard NASA’s Terra satellite has altered this now. This uses twin, nadir and aft looking, visible and near infra-red, sensors to collect data for the creation of DEMs (30m resolution).

The preceding discussion has highlighted the different storage techniques available for three dimensional surface visualisation, showing that the availability of global high quality, inexpensive, DEM data is rapidly approaching. For landform mapping, the move away from the sole use of field mapping, aerial photography or satellite imagery has begun. Many researchers are unfamiliar with the use of DEMs and may not be aware of data accuracy issues and visualisation problems. The following section briefly discusses some of the methods commonly used in surface visualisation (focusing on DEMs) and highlights some of the problems in their use.

4.3.3 Surface representation: Relief shading

Relief shading is perhaps the most popular 3D visualisation technique used within computer mapping software as it is quick to render and readily recognisable by most operators. This method simulates the shadow thrown by an apparent light source shining from one (or more) directions across a three-dimensional landscape. The azimuth of the light source is variable, although it is usually fixed in the north-west as, visually, this provides the most desirable image (Lidmar-Bergström *et al*, 1991).

The similarities between the use of relief shaded and satellite images in visualisation is striking. It is even more so when you consider that both incorporate vertical viewing and a single illuminating light source. As a result DEMs suffer from exactly the same biases as satellite imagery (as described in §4.2.1). More specifically *relative size* is principally dependent upon the resolution of the DEM data. For most high resolution DEMs this is currently between 10m and 50m. *Azimuth biasing* is directly dependent upon the azimuth of the illuminating source, although with a DEM this can be set by the operator. Finally, real world (solar based) effects on *landform signal strength* are very sensitive to changes in illumination elevation. Although such changes can be made to the illumination source within a DEM, this generally has the effect of increasing or reducing the ambient light visible within the rendered image, rather than producing the more complex atmospheric and surface interactions that take place within a real landscape.

4.4 Generalisation

4.4.1 Introduction

Chapter 2 introduced the main stages performed during an ice sheet reconstruction (Figure 2.1). Once landform data has been satisfactorily mapped, they are then required to be generalised. This is a data reduction stage that reduces the amount of overall data, whilst retaining the essential patterns of lineament orientations required to meaningfully interpret the data. It allows the interpreter to untangle the complexity of individual lineaments by representing them with broad lineament patterns. A good example of this is the Glacial Map of Canada (Prest *et al*, 1968) which is based upon mapping individual glacial landforms but has been very broadly generalised both for cartographic purposes, as well as to make its interpretation much easier.

Generalisation is a qualitative and subjective technique, relying upon the abilities of the observer. Given that the aim is to identify broad patterns, prior to interpretation, it is preferable that this stage should be as objective as possible. This would not only allow more objective generalisation, but also introduce consistency both by a single observer and between observers. In order to appreciate the complexity of the generalisation process, this section introduces its broad application within cartography and then reviews its use within satellite image based ice sheet reconstructions.

4.4.2 Cartographic Approaches

Generalisation involves the simplification or removal of detail. At a methodological level, generalisation is purely a data reduction (or data compression) stage as it involves going from more to less information. As a consequence of data reduction, the procedure also removes noise and random effects from the data set, so aiding interpretation. The original mapped data represent abstracted objects of reality (*simplification*) and the process of generalisation further abstracts these objects. It is the method of *selecting* mapped features for abstraction that is integral to the informational context of

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the generalised map, at the desired scale, and the consequent *reduction* in the amount of information, such that the generalised map presented to the end user is clear and concise.

The process of generalisation has traditionally been performed by cartographers and uses their preconceptions, experience and knowledge of heuristics (object symbolisation). These factors, and their overall combination, produce the finished mapped product. Jones (1997) suggests generalisation involves two stages; *semantic* and *geometric* generalisation. *Semantic generalisation* is the selection of objects that are necessary to convey the theme of the map at the appropriate scale. *Geometric generalisation* is concerned with the processes by which those selected objects are informationally reduced, whilst retaining their essential characteristics, for their presentation in a mapped product. During the generalisation of mapped lineaments, it is *geometric generalisation* that is of interest.

The process of generalisation has been particularly difficult to automate due to the complex interplay of visual and attribute phenomena related to, and between, the mapped objects. Overall design heuristics, coupled with the map purpose and consequent relative importance of objects within that map, require the processing of much related information. As Jones (1997) states *"successful generalisation requires a holistic approach in which the interaction between cartographic objects can be monitored... at present this is usually achieved by the human eye."*

As spatial data are increasingly being collected with greater precision, generalisation becomes important both in terms of data reduction and the presentation of data for different purposes. Muller (1991) warns that higher precision could well lead to further errors in observations as there is a greater likelihood of perturbation by high frequency random errors. Generalisation is therefore a necessary step as, although it reduces resolution, it filters out error and emphasises trends within the data. This is precisely the purpose of generalising mapped lineament data for interpretation.

4.4.3 The use of generalisation in ice-sheet reconstructions

In general, researchers apply a manual, visually based, technique in order to group lineaments. By generalising they want to remove unnecessary detail, leaving a simplified representation of their original data set. Figure 4.10 shows summary lineaments mapped from aerial photography by Kleman *et al* (1997). Generalisation is designed to remove the detail apparent in 4.10a and allow the observer to move on to group flow patterns into meaningful flow sets, as shown in Figure 4.10b. Generalisation therefore needs to group “similar” lineaments together, whilst retaining much of the essential information. Phrases such as “coherent lineament pattern”, “parallel conformity”, “spatially coherent” and “internally homogenous” attempt to describe the visual techniques applied. These imply a dependence upon a similarity in orientation, although covers other factors such as length and density, however their descriptive nature is vague and implies a lack of procedures for generalisation. Scale is integral to the process of generalisation, yet these phrases imply different techniques at different scales. Published research has tended to concentrate on the glacial implications of mapped data or the techniques used to either acquire the satellite imagery or interpret the results, rather than the methods of generalisation. This section briefly reviews the use of generalisation in previous research work, broadly ordered by the same research groups discussed in Chapter 3.

Punkari (1982) almost certainly needed to generalise his data but did not discuss the issue. Punkari (1985, 1993, 1996) later mentions generalisation in relation to mapping presentation, but does not discuss it. In Punkari (1995) he intimates that “trend lines” are produced by using principal lineament orientations from rose diagrams for 50 x 50 km^2 grid squares (Figure 3.3). To help with his grouping into flowsets he also used cross-sectional histograms of different landforms (Figure 3.4). Dongelmans (1996) suggests that lineaments should have “*corresponding trends and spatial continuity*”, however his method goes from observation data to fully interpreted flow sets

Boulton and Clark (1990) “*simplified by summarising parallel flow patterns by a few more continuous ‘ice flow’ lines.*” They combined flow lines to create flow

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sets. They valued the degree of “lineament alignment” as an important attribute, but only briefly addressed the issue. Knight (1996) states that the formation of flow sets requires an intermediate (generalisation) stage where *ice flow trend lines* are formed (Figure 3.12). Clark (1997) suggests grouping into “*sub-parallel sets whose topology and extent is glaciologically plausible*.”

Kleman (1990) advises “*regionalisation based on ... internal homogeneity*” and Kleman *et al* (1996) suggest that any generalisation should require lineaments to be “*spatially coherent*.” In applying the *Inversion Model* of Kleman *et al* (1996), Kleman *et al* (1997) define their generalised lineaments as “*temporary tools”* designed to “*simplify and spatially delineate map representations of glacial landform swarms*.” They are defined “*on the basis of spatial continuity and the resemblance to a glaciologically plausible pattern, i.e. a minimum-complexity assumption*.”

McCabe *et al* (1998) combine the processes of generalisation and interpretation. They go on to suggest that alignment, location, morphological attributes and cross-cutting relationships are important factors in the formation of flow sets. However, combining these procedures is inappropriate as it is not possible to derive unique flow sets from complex and cross-cutting lineament patterns (Clark, 1997) and consequently any results obtained using this method should be viewed as the authors preferred interpretation, rather than an objective evaluation of all the landform evidence.

Clark (1999) stresses that grouping landforms into similar sets requires recognition of three criteria; *parallel conformity*, *proximity* and *morphometry*. As with other workers, similarity of orientation is important. Clark also suggests that close proximity is a useful criteria; this is dependent upon the size of landform and, ultimately, the scale of processes operating at the ice sheet base, although Clark *et al* (2000) state that this will be of the order of up to 2-3 times the dimension of the landform. Density might be a more appropriate criteria. The final criteria, morphometry, is very general and could refer to many individual and shape related measurements, although landforms should display similarity.

All of the above work address generalisation, however the degree and scope of discussion is varied. Figure 4.11 clearly illustrates how one set of mapped lineaments can be alternately interpreted. An objective understanding of the characteristics of the data would make generalising them easier and more objective. The following paragraphs (see Figure 4.12) provide an example from the Storkerson Peninsular, Canada, using a simple set of lineament data (after Stokes, 2001). The lineaments can all be intuitively grouped together primarily using similarity in orientation (or "parallel conformity"). This attribute is universally accepted by all researchers, provided that any grouping based upon it is within a plausible glacial scenario. The lineaments are not all of a similar orientation, but rather show a gradual change from north to south. Lineament length is also considered useful. In this example the eye is drawn to the relatively large number of large lineaments, however upon closer inspection there are also a large number of medium and small sized forms which are equally spaced between the larger forms. This is to be expected and lends to the overall visual impression that this group of lineaments share a common form of origin. Further visual inspection suggests that mean lineament length may decrease from north to south. This is perhaps influenced by the impression of a decrease in lineament density from north to south. These last two points are both glacially plausible and highlight the further point that lineament groupings are dynamic forms and would be expected to change.

Other attributes, such as plan-form/cross-sectional morphometry and cross-cutting are often neglected or only briefly touched upon. Indeed the admission that the same data can provide a variety of glaciologically plausible scenarios suggests that generalisation is subjective, based upon a variety of criteria that vary between researchers and which operate at different scales. At the very least these alternative scenarios should be investigated.

4.4.4 Conclusions

Generalisation is an essential stage of data reduction, performed in order to highlight trends within datasets used for glacial reconstruction. This section has described the general cartographic approaches to generalisation and then gone onto review how researchers have applied *geometric* generalisation techniques

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prior to the interpretative stages of the reconstruction process. Although there has been the development of grid based statistics to help in the process, these have largely remained unused with reliance being placed upon the visual acuity of the observer.

With the development of new methodological techniques, researchers have become increasingly aware that landform assemblages are a complex mix of landforms created during different periods of time and contextually located at different positions under and around an ice sheet. The land surface simply represents the dynamic intermixing of different processes, in different contexts, at different times. In order to interpret these data, a reduction in their complexity and the development of trends is essential. Not only is generalisation an essential stage, but it needs to be as objective as possible in order to allow reproducibility.

4.5 Conclusions

This chapter has presented the three key research areas within ice sheet reconstruction research that require addressing. Initial exploratory lineament mapping in Ireland suggested that landform representation varied between different types of satellite imagery. This chapter has outlined the basis for variability in landform mapping which include *landform representation* and *operator variability*. Although such variability can never be entirely removed, it should be possible to minimise their effects within a study and, given suitable mapping methods, even between studies. Of more concern is the variability in landform representation between satellite imagery due to relative size, azimuth biasing and landform signal strength. It is important for an interpreter to know if the available imagery is representing all or some lineaments within a study area. If some lineaments are not being represented, are these errors systematic or random? Chapter 5 provides a review of landform representation errors within satellite imagery. In addition to giving measures of the effects of each of the variables discussed in this chapter, it concludes with a summary of the main problems and gives detailed advice on the most appropriate methods and sensors with which to acquire imagery.

DEMs have traditionally been viewed using relief shading, however this suffers from the same azimuth biasing that effects satellite imagery. Although landform signal strength is not a problem (there are artificially high levels of light used in relief shading), relative size still is. It is therefore important to understand the different visualisation options that are available to interpreters and which ones provide the greatest levels of completeness. Chapter 6 reviews these problems and then provides a case study to show a practical use of the methods developed.

During the process of ice sheet reconstruction, once landform data have been mapped, it is necessary to generalise this data before any interpretation can begin. §4.4 showed past approaches to generalisation within the reconstruction literature. It is essential that generalisation is as quantitative as possible, such that it can be verified and reproduced by other researchers. This requires either a fully automated approach or a manual approach which provides quantitative information about mapped data to aid generalisation and goes onto give statistical feedback. Chapter 7 develops these techniques and provides a summary of “best practice” for interpreters.

Chapters 5, 6 and 7 are complementary work and provide a holistic view of ice sheet reconstruction techniques. This is reviewed by investigating satellite imagery and DEM based mapping methods and the techniques used to take this “raw” data to make it ready for interpretation.