8 Conclusions

8.1 Introduction

Ice sheet reconstructions are an important part of glaciology, serving to provide information on how palaeo ice sheets both responded to, and influenced, climate change. This thesis has provided a study of the methods by which ice sheet reconstructions are performed through geomorphological mapping and has highlighted areas where improvements to this methodology could be made. The following sections summarise the results of this research and suggest future research topics.

8.2 ResultsSummary

8.2.1 Primary Data Acquisition: Satellite Imagery

Chapter 5 investigated the sensitivity of *relative size*, *landform signal strength* and *azimuth biasing* on satellite imagery with respect to landform mapping. Broadly, the results can summarised as:

- **Relative Size** - the effects of relative size are commonly appreciated (and compensated for) by researchers (i.e. higher spatial resolution data is required to map spatially smaller landforms). Early studies could not map individual landforms, however higher resolution satellite imagery now means detailed mapping is possible. The Russian study area showed a 170% increase in the number of lineaments mapped as a result of increasing the spatial resolution from 30m to 15m. For the Lough Gara region, relative size was the dominant control on landform detectability, resulting in a 220% increase in the number of lineaments mapped when resolution was increased from 80m to 10m. The effect of relative size is not considered a problem for the current range of earth resources satellites used by glacial researchers to perform landform mapping. Resolutions of <30m produce reliable results.

- **Landform Signal Strength** - is generally linked to the illumination elevation. For VIR imagery, low solar elevation is required and, as satellite overpass time is fixed, it means that seasonal changes must be used in order to achieve variation in elevation. Solar elevation needs to be in the 5º-20º range in order to provide sufficient contrast to perform mapping. Solar elevations as low as 5º are available, but require optimum imaging conditions. For mid-latitudes this is difficult to achieve due to the high frequency of low pressure weather systems (i.e. cloudy days). For high latitudes, heavy snow cover will typically be present and may mask the terrain. Close investigation of archives will be necessary in order to select the best imagery.

- **Azimuth Biasing -** the illumination of an image *parallel* to the dominant lineament orientation causes those lineaments to appear altered in shape or to disappear altogether. In comparison to the dataset representative of all lineaments around Lough Gara ("truth"), the relief shaded DEM data illuminated orthogonal and parallel to the dominant lineament direction represented 84% and 40% of all lineaments, respectively. This dramatic difference is solely attributable to azimuth biasing and is unsatisfactory as it selectively removes information from the data used for landform mapping such that important features might be missed. This can be mitigated against by acquiring alternately illuminated imagery (either SAR or DEM data) or by having a broad knowledge of the study area. It is important to note that the parallel image selectively highlighted transverse landforms that *were not* visible on the orthogonal image.

It is recommended to use Landsat ETM+ imagery as it delivers the most appropriate data, however it may be necessary to use Landsat TM or MSS where satisfactory imagery is not available or there are economic constraints. To this end, the accompanying CD (and Appendix 2) provides the details necessary to calculate solar azimuth and elevation. This allows the researcher to highlight the best time of year to acquire imagery for, as well as note possible azimuth biasing effects. Although these results are principally aimed at VIR satellite imagery, the special case of SAR imagery is briefly addressed.

- **Synthetic Aperture Radar (SAR)** - this is particularly appropriate for mapping topographic features due to the side-looking sensor, however landform detectability is also affected by relative size, landform signal strength (although this is fixed) and azimuth biasing. Whilst the 25m resolution of the sensor is satisfactory for landform mapping, azimuth biasing can be a serious problem. The case study around Strangford Lough, Ireland, showed a dramatic difference in the lineaments represented for SAR and Landsat TM, with a vector mean of 141º and 98º respectively. In addition, the results of lineament mapping in Ireland were very poor and, in this instance, SAR was not an appropriate data source, although it has been used successfully elsewhere (e.g. Clark *et al*, 2000).

8.2.2 Primary Data Acquisition: DEM Data

DEM data have been available in various formats for over 30 years, initially based upon contour maps, but now directly measured. For the glacial researcher the issue is not whether data is available or how best to go about converting height data into a DEM, but rather *which* data is best suited to the research task and how to utilise it. The former question has a much wider remit to anyone using height data and is therefore beyond the scope of this thesis (this is discussed further in the final section), however the latter topic has pertinence within landform mapping itself. That is, we have absolute data concerning surface elevation (within set accuracy constraints); how do we best visualise this surface to allow accurate and consistent landform mapping. This might initially appear a simple task as almost all GIS, remote sensing and heightfield software allow the rendering of “2.5D” data through the use of relief shading. However this introduces an illumination source and therefore suffers very similar problems to those discussed above for satellite imagery. Clearly then we need to use height data in a robust manner.

Chapter 6 assessed the ability of a variety of standard and developed methods to visualise the landscape. Methods that were assessed included relief shading (parallel and orthogonal to the dominant lineament direction), principal components analysis (PCA), false colour composites, animated relief shading, slope curvature, 3D viewing and localised spatial enhancements. Ideally a single visualisation method is required that optimally enhances the terrain, but without introducing bias. However no single visualisation method was able to provide optimal viewing. The following broad results were obtained:

- **Azimuth Biased:** relief shading is based upon an illuminated landscape and so contains azimuth biasing. Parallel and orthogonal relief shaded images contained 40% and 84% of the lineaments mapped on truth. Whilst landforms oriented parallel to the illumination azimuth were selectively diminished, those oriented perpendicular were selectively *enhanced*. So although individual relief shaded images were not satisfactory alone, in combination they have great utility.
- **Non-Azimuth Biased:** slope curvature, overhead illumination, PCA and localised spatial enhancements are preferable as they do not introduce illumination bias'. They contained 82%, 60%, 61% and 62%, respectively, of the lineaments mapped on truth. Whilst slope curvature performed well, the remaining methods were unsatisfactory.

Overall recommendations are that non-azimuth biased methods should be used for initial landform mapping. Azimuth biased methods can then be used to complete the mapping procedure. This method was then used to map glacial landforms, including over 2,600 lineaments, for the Lake District. After initial trial and error in their application, a satisfactory workflow was established in their use, finally producing the first complete bedform map of the Lake District. In comparison to published data, there are many more lineaments identified, including the presence of previously unmapped cross-cutting patterns and ribbed moraine.

8.2.3 Generalisation

The generalisation of landform data into summary flow patterns is currently a visual, qualitative, method. Chapter 7 developed a technique based around the provision of a set of maps that generalise the raw lineament data. These maps are interpolated surfaces based upon the length and orientation of the original lineaments. They are straight forward to interpret and allow the researcher to make informed decisions during the generalisation process. Once the lineaments have been “split” into individual flow patterns, they can be visualised using the same method. This should help confirm that the flow patterns can be established as genuine. If not, they allow the process to be repeated. This is an important technique as it allows this stage of an ice sheet reconstruction to be objectively verified.

The above technique is implemented on the set of data mapped from the Lake District in chapter 6. The complex series of landforms proved difficult to generalise, however the 2,600 lineaments were reduced to a series of 12 flow patterns. Initial investigation suggests that this may reduce to as few as 3 flow sets that show a shift in ice mass away from the Lake District (towards the Pennines) before an increase, and expansion, in the dominance of Lake District ice. To conclude the chapter, a “proof-of-concept” algorithm was developed to show that it should be possible to automate such a procedure, however further development is required.

8.3 Future Research

During this work I have identified further avenues of research which would be appropriate to pursue and these are now discussed.

1. **Comparison of Landform Mapping Methods** - satellite images are one of several earth observation techniques that include, aerial photography, DEMs and field mapping. With regards to landform mapping, each method has its own strengths and weaknesses. The large areal coverage, low cost and manageability make satellite imagery ideal for rapidly mapping landforms over large areas. The opposite is true for field mapping which is slow, high cost and very detailed. Although these generalisations are broadly correct, this research has highlighted how satellite imagery can have serious errors of omission. Can similar problems affect the use of aerial photography or field mapping? For instance, aerial photos are normally acquired with high solar elevations and (in the northern hemisphere) with solar azimuth from the south. These effects seriously reduce the benefits of the high spatial resolution. It would be constructive and informative to compare landform mapping for these four methods over the same area. Although satellite

imagery can detect broad regional trends in landform assemblages, are all methods comparative when detailed morphometric information is collected? Might it be more appropriate to use DEMs for regional mapping and aerial photography for detailed mapping to confirm, for instance, cross-cutting and ice flow direction

2. **Comparison of DEM Data** – the different types of DEM data have briefly been discussed, however it is the source from which it is produced that determines their appropriateness and therefore usability for a particular purpose. The data used in this research was the Ordnance Survey's Panorama™ data, which is a 50m resolution product produced from original contour map data. The contour data is based upon a product that is designed to represent a "bald earth", that is, an earth surface devoid of buildings and vegetation. And because it's a bald earth and generated from contour data, the DEM surface has been smoothed. The same is not true of radar generated DEMs which generally measure a "visible surface". That is, they include buildings and vegetation (and anything else on the surface). Clearly, if a surface of interest is heavily forested, then the detectability of landforms will be severely degraded. Even in "clean" areas (i.e. bald) the difference in the type of point sampling used and method of collection means that landscapes can appear differently. Further work would be required to review the different types of DEM products available and then compare and contrast their applicability for landform mapping.

3. **Automated Lineament Generalisation** - Chapter 7 provided initial "proof-of-concept" development of an algorithm that can be used for generating flow patterns. This could potentially be automated and would allow a fast and truly interactive and iterative approach to flow pattern development. As such it is a computer programming exercise that would require refinement within the problem areas identified in Chapter 7.

8.4 Final Thoughts

This research began as an exercise in the application of a set of techniques and has progressed through to a refinement of these techniques. The previous section highlights the areas where research can be pursued and all are based around technical enhancements, particularly in the arena of DEM data. DEMs will undoubtedly become one of the most important research tools of the next decade and further understanding of their use and weaknesses is vital to their acceptance by the greater research community. One topic which hasn't been touched upon is the original aim of this thesis; that is the reconstruction of the British and Irish ice sheet. This still awaits to be done, although Clark and Meehan (2001) have made a start, utilising DEMs rather than satellite imagery, whilst the BRITICE project (Clark, 2002) is making a contribution to the summation of mapped glacial landforms in the UK. The availability of OS Panorama™ and Landmap DEM data for Britain and Ireland means that there is now a free (for academic use) source of data available. All that is required is the appropriate mapping of landforms.