1 Introduction

1.1 Introduction

Palaeo-environmental studies are an important part of geography as they provide a means by which we can understand our surroundings. By using our understanding of current processes we can look at landforms generated in the past and then infer the environment in which they were created. Although this assumes that current processes are good proxies for past ones, it is a powerful method as it not only allows us to provide a history, one which may inform us of singular events, but we can then use that information to help predict how our environment might operate in the future.

1.2 Use of Ice Sheet Reconstructions

The most widely publicised predictive studies are based around global environmental issues, such as global warming. General circulation models attempt to enter current environmental variables and predict future climatic states. Clearly the development of such models is based upon an understanding of contemporary processes, however there is great utility in calibrating or testing them using palaeo-environmental data. The reconstruction of past glacial environments clearly falls within this remit

Ice sheet reconstructions specifically try to recreate dynamics through time. This deals with the location and migration of ice sheets and divides, as well as the dating of changes in their configuration. It can then be postulated what were the causes of these changes. Ice sheets can be an important aid in determining the extent and degree of interaction between the atmosphere, geosphere and cryosphere and are believed to be the one of the most important feedback mechanisms that have modulated climate change over the last 2 million years. Once an ice sheet has been reconstructed in time and space, this can be compared with known or inferred behaviours of the ocean and atmosphere. Given the current poor level of knowledge of the dynamical change of the cryosphere, an ice sheet reconstruction should provide more insight into climate change through the combined inputs of the atmosphere (particularly changing precipitation patterns), ocean (particularly the switching on and off of the oceanic deep water currents), cryosphere (particularly the extent and cause of Heinrich events) and external forcing (Milankovitch cycles).

1.3 Techniques for Ice Sheet Reconstruction

The use of remotely sensed data to perform ice sheet reconstructions is a relatively new technique. Prior to this, field mapping and aerial photography were the primary data sources. Using these techniques, it was difficult to acquire ice-sheet wide landform evidence and, as a result, processes inferred as operating over small areas of investigation were scaled up to the ice sheet level and extrapolated to cover wider regions. Ice sheet reconstructions tended to be syntheses combining evidence from different researchers who used different techniques and methodologies.

Mapping from remotely sensed data solved the issue of acquiring ice sheet wide landform evidence, however it introduced methodological problems concerning their integration and interpretation. Methods have gradually been developed to solve these issues, whilst newer, and better, primary data sources have been made available. Figure 1.1 presents a broad outline of the steps involved in an ice sheet reconstruction. After acquisition of a primary data source, glacial landforms are mapped by an observer. These are then generalised into summary flow patterns so that their interpretation into flow sets (glaciologically plausible scenarios) is easier. This then allows the production of a final, or several, reconstructions.

The last 20 years have seen a major shift in the way ice sheet reconstructions are performed. Rather than using piecemeal evidence that is hung together using an authors preferred interpretation, there is now an explicit methodology, with flow sets the key building blocks to data synthesis. Figure 1.2 shows a space-time diagram for an idealised region that has been glaciated. The top surface represents the present day land surface that has imprinted upon it evidence of former ice flow. Using this evidence it should be possible to infer the dynamics of an ice sheet through time. Geomorphologically based ice sheet reconstructions aim to do this.

Although the methodology by which these reconstructions are produced is well established (e.g. Clark, 1997), the primary source data can contain random or systematic errors which then become reproduced in the research. Additionally, the techniques used involve subjective or qualitative stages which can introduce biases through their application. At best this makes comparison between researchers and regions difficult, at worst it can make the results unreliable.

1.4 Aims and Objectives

The research for this PhD began with the intention of producing an ice sheet reconstruction for the United Kingdom and Ireland. Being an almost self-contained unit, Ireland was an obvious location to begin landform mapping. This was initially pursued using ERS-1 SAR imagery (satellite based radar) and later extended to include limited Landsat TM (satellite based visual/near infra-red) and digital elevation model (DEM) data. It quickly became apparent that not only were there differences between the different data sources, but in certain locations there was little similarity. It was clear that further landform mapping could not be pursued until these issues were resolved and this also called into question previous landform mapping exercises.

This research has therefore developed into an understanding of the above problems, as well as a refinement to some of the techniques used as part of a glacial reconstruction. This work can be divided into three broad research topics:

- **Aim 1: Investigate the presence of bias within satellite imagery**

Satellite imagery depicts topographic glacial landforms through the recording of reflected light on an illuminated surface. The detail of the images, and the manner in which the landscape is illuminated, controls how these landforms are depicted. This introduces both random and systematic biases into the imagery. The nature of this biasing is explored, with recommendations for their mitigation.

- **Aim 2: Explore visualisation techniques for DEM data**

DEMs are rapidly becoming an important primary data source for landform mapping. They have traditionally been visualised through relief shading, however this introduces biasing in a manner similar to those identified for satellite imagery. This section explores and assesses a variety of techniques for visualising DEMs.

- **Aim 3: Improvement of techniques for lineament generalisation**

The final part of the thesis is concerned with the generalisation of landform data from individually mapped landforms to coherent patterns that can be interpreted as part of ice-sheet wide events. This stage has traditionally been performed visually by the researcher and can introduce subjective bias at an early stage. A technique for quantitatively verifying this manual generalisation stage is introduced.

1.5 ThesisStructure

The next chapter introduces the broad methodology by which an ice sheet reconstruction is performed, introducing the reader to the technical and methodological techniques currently in use, as well as familiarising them with how an understanding of the processes that created landforms can be used to infer conditions in past environments. This is followed by a review of satellite imagery based ice sheet reconstructions (Chapter 3), with a particular emphasis on the techniques and methodologies used. Chapter 4 goes on to introduce the key research issues highlighted in Chapter 3 and how they might be investigated. Chapter 5 investigates the problems in using both VIR and radar satellite imagery in landform mapping exercises and concludes with recommendations for best practice. Chapter 6 goes on to review and develop different DEM visualisation techniques, with suggestions for performing mapping exercises. The final research chapter develops techniques to aid the generalisation of landforms into flow patterns. These can be iteratively refined and quantitatively verified.

Although this research began as an ice sheet reconstruction, it has developed into a refinement of the techniques used to perform them. Initial exploratory work clearly identified weaknesses in current approaches. It is hoped that these improvements will allow better mapping, a greater take up in the use of DEM data and the better development of flow patterns and the resultant reconstructions.

Primary Data (e.g. field mapping, satellite imagery)

Stage 1: Subglacial bedform mapping. Ideally objective.

Raw subglacial bedform maps

Stage 2: Generalisation of 'raw' lineament data in fewer, summary, "flow patterns." Ideally objective.

Generalised "flow pattern" maps

Stage 3: Interpretation of flow patterns into glaciologically plausible "flow sets." Subjective.

"Flow set" maps

Stage 4: Organisation of flow sets into one, or several, ice sheet histories.

Ice sheet reconstruction

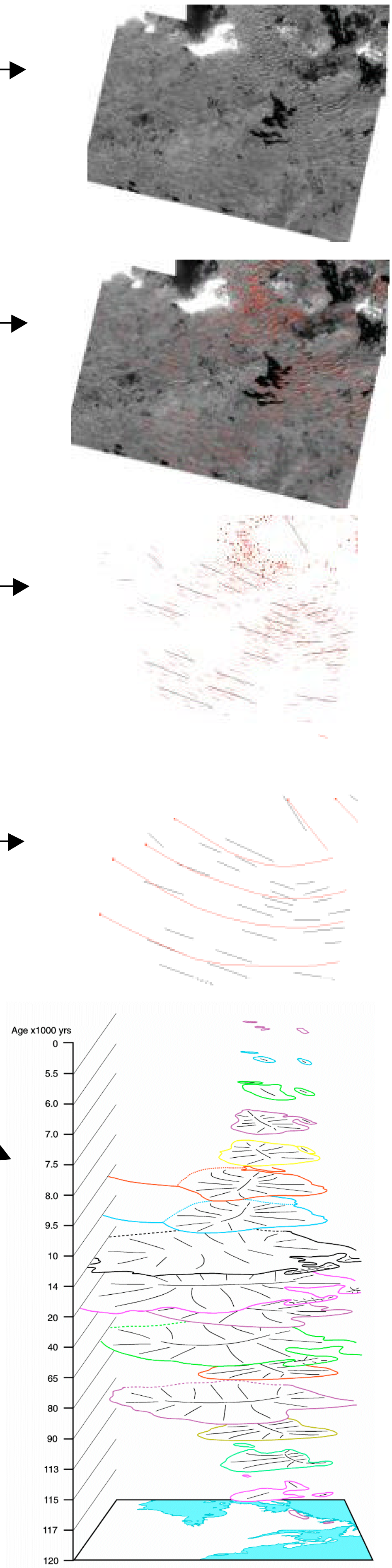

Figure 1.1 Flow chart demonstrating the stages performed during an ice-sheet reconstruction (left) and illustrated diagrammatically (right). After the acquisition of primary data, individual landforms are mapped and then generalised in to summary flow patterns. These then form the basis of interpreted flow sets which are used in the final reconstruction of flow geometry and ice divide configuration (ice sheet reconstruction after Clark, unpublished).

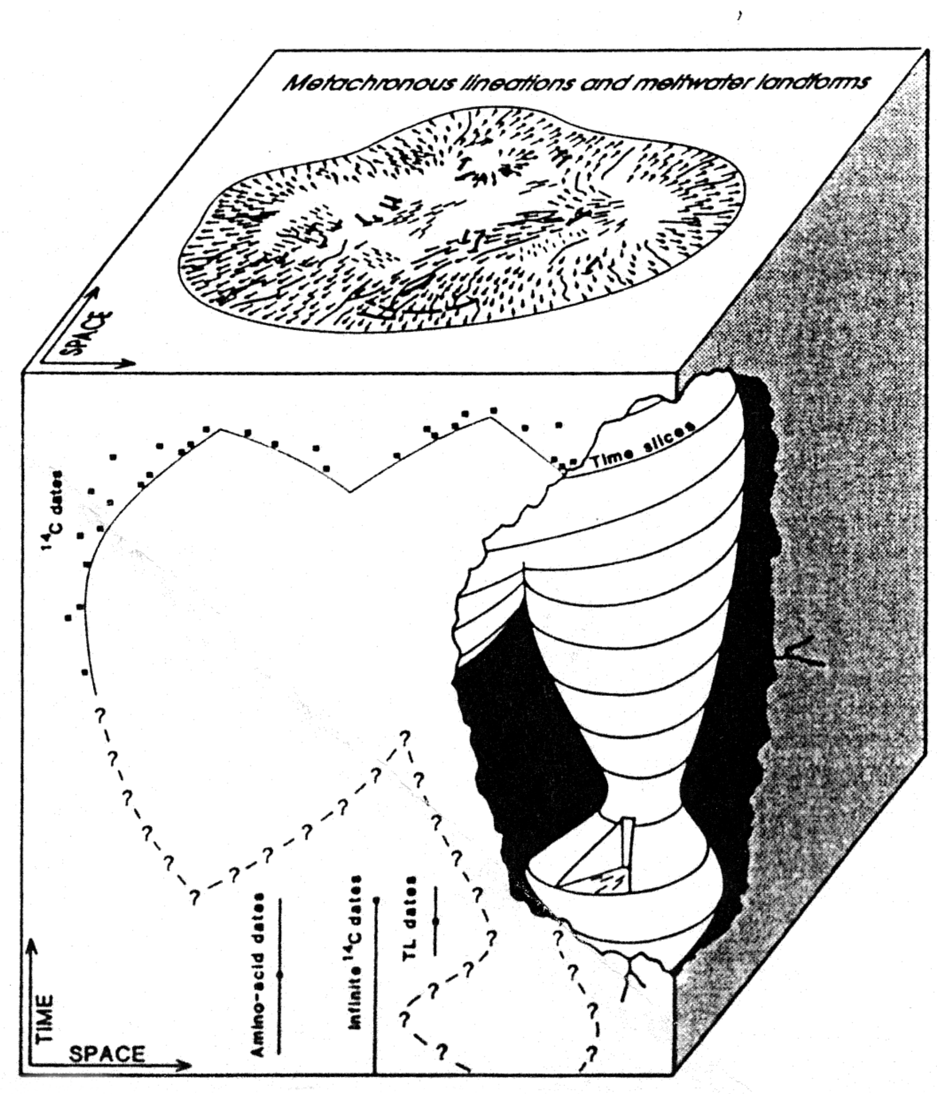

Figure 1.2 Space-Time cube showing the current geomorphological surface (top of cube) and the postulated ice sheet behaviour required to have generated this (Kleman *et al*, 1996). The "vase" in the centre of the cube provides an hypothesised reconstruction of the ice sheet through time. The front face shows how landform evidence can be used to mark the maximum extent of the ice sheet through time, whilst, where available, dating indicators match this to an absolute time scale.