2 Overview of Ice Sheet Reconstruction from Geomorphological Evidence

2.1 Introduction

Satellite images can be used to map glacial landforms and have been a good supplement to aerial photography due to their wide coverage and synoptic scale. A reconstruction of the glacial history of a region involves four stages:

- mapping individual landforms from satellite imagery.
- generalisation of individual landforms into distinctive flow patterns
- interpretation of flow patterns into distinctive flow sets
- palaeo-glacial interpretation of all glacial landform data to produce a reconstruction of ice sheet geometry, extent and changes through time.

This chapter will outline the image processing and mapping techniques currently used by researchers, as well as the methodological framework for landform interpretation. This is followed by a discussion of the palaeo-evidence provided by different landforms, the use of relative chronological data and the variation in interpretation of landforms and their implications for ice sheet reconstructions. The chapter is concluded with an example of an ice sheet reconstruction.

2.2 MethodologicalOverview

Ice sheet reconstructions have been a focus for research since the late 1800's and involve the collection and interpretation of landform data related to ice flow direction and marginal positions. It is an incremental procedure whereby knowledge slowly accumulates as more landforms are mapped. Researchers tend to collect and interpret their own geomorphological evidence (primary data), augmenting it with published literature (secondary data).

The acquisition of primary data was originally achieved through field work (e.g. striae mapping), later augmented with aerial photography and digital satellite imagery. Satellite imagery is particularly useful for ice sheet reconstructions as it allows a synoptic scale view of former glaciated areas and provides global coverage. Interpretation relies upon the use (and development) of theories concerning landform formation.

Geomorphology attempts to provide further understanding of the real world through a “systematic process of investigation” (Rhoads and Thorn, 1993). This invariably takes place through observation of the physical system (or part thereof) being studied and the creation or testing of theory. Theory that is able to model the full complexity of the real world is closest to achievement on very small temporal and spatial scales, such as fluid dynamics (e.g. Jackson and Steyn, 1993). For larger spatial and temporal scales less information is available, leading to a greater subjective assessment of data. It is this problem that faces glacial reconstruction. More specifically, relict features are used to infer possible processes, through indirect empirical methods or, as Rhoads and Thorn (1993) state, historical retrodictive abduction.

Geomorphological landforms are formed through the interaction of one, or several, physical processes on the Earth’s surface. By studying currently active processes it is possible to learn the conditions and controls on landform development. When relict landforms are discovered we can then use this knowledge to infer the environmental conditions at the time of their formation. An example is the formation of striae through the abrasion of rocks embedded in the base of a warm based ice sheet as it passes over bedrock. The direction of ice flow can be inferred by striae orientation. However this method cannot be extended to landforms where their formational processes have not been observed. Drumlins fall into such a category and consequently theoretical development is reliant upon the study of relict landforms. These landforms are also used in the reconstruction of former ice sheets.

Boulton *et al* (2001) describe this area of research as *palaeoglaciology* and suggest that the following steps are required:

- characterise ice sheet dynamic elements
- identify geological features that reflect these elements
- interpret and integrate these features to recreate the behaviour of former ice sheets.

These steps can specifically be applied to reconstructions based upon satellite imagery (Figure 1.1) and are principally accomplished through the mapping of glacial lineaments (particularly drumlins and mega-lineaments). This technique is well established, having been used by Punkari (1982), Boulton and Clark (1990), Knight (1996), Dongelmans (1996) and discussed in detail by Clark (1997). Once complete, the lineament data is generalised. This is a data reduction stage designed to make the interpretation of regional ice flow patterns easier. Once a series of ice flow patterns are delimited, the observer finally produces a single, or series of, ice sheet reconstructions. There is a well developed theoretical framework for the reconstruction of past glacial environments (Clark, 1994,1999 and Kleman *et al*, 1996) using geomorphological landforms. These stages are discussed in more detail in the following sections. It should be born in mind that these techniques apply specifically to satellite imagery based investigations, however they are directly applicable to aerial photography, DEM and field work investigations. Aerial photography is still a valuable resource and satellite imagery should be viewed as a supplement to these data. Their higher resolution and ability to view terrain stereoscopically are used effectively by many researchers (e.g. Kleman *et al*, 1996), however these benefits must be weighed against the relative large scale (in general) of images (typically 1:40000 or less). The financial and labour investment often means that aerial photography is not a cost effective method for mapping glacial landforms over large areas.

2.3 Methodological Techniques

2.3.1 Satellite Imagery and Image Processing

The mapping of glacial landforms requires the acquisition of appropriate imagery for the area of interest. Although there are many active earth resources sensors, there are only a handful that are suitable for landform mapping (Table 2.1). There are two main types of sensor; Visible and Infra-Red (VIR) or Synthetic Aperture Radar (SAR). The former images are in the VIR part of the electromagnetic (EM) spectrum, whilst the latter images are in the microwave part of the EM spectrum. Landsat Multi-Spectral Scanner (MSS) has been used extensively as it has been available the longest, however its low spatial resolution makes it unsuitable for detecting individual landforms. Landsat Thematic Mapper (TM) provides good resolving capabilities, whilst both Landsat Enhanced Thematic Mapper (ETM+) and SPOT Panchromatic sensors provide excellent imaging of glacial landforms. Landsat ETM+ is the most desirable VIR imagery at present and is relatively inexpensive. Landsat MSS is very cheap and consequently provides an economical medium for low cost landform mapping. SAR imagery provides a good resolution, however more knowledge is required during image processing due to technical considerations. In addition interpretation is more difficult, requiring an experienced observer.

For VIR imagery, representation of linear landforms can be enhanced by obtaining images during periods of low solar elevation so that fore slopes are illuminated slightly more than lee slopes (Slaney, 1981), highlighting topographic differences. It may also be possible to highlight moisture differences (spectral differentiation) between lineaments and the surrounding terrain (*geobotanical method*) through the use of band combinations (e.g. Punkari, 1982). Figure 2.1 shows two Landsat TM images of Lough Gara, Ireland. These images illustrate the advantages of using winter (bottom) imagery with low solar elevation, over summer (top) imagery.

VIR imagery require cloud free conditions in order to image the Earth. The use of low solar elevation to enhance lineaments, places constraints upon the timing of image acquisition. For mid-latitude regions this will be in mid-winter, making cloud free images difficult to obtain. This becomes more complex in high latitudes where it is also desirable to obtain snow free images so that landforms are not obscured.

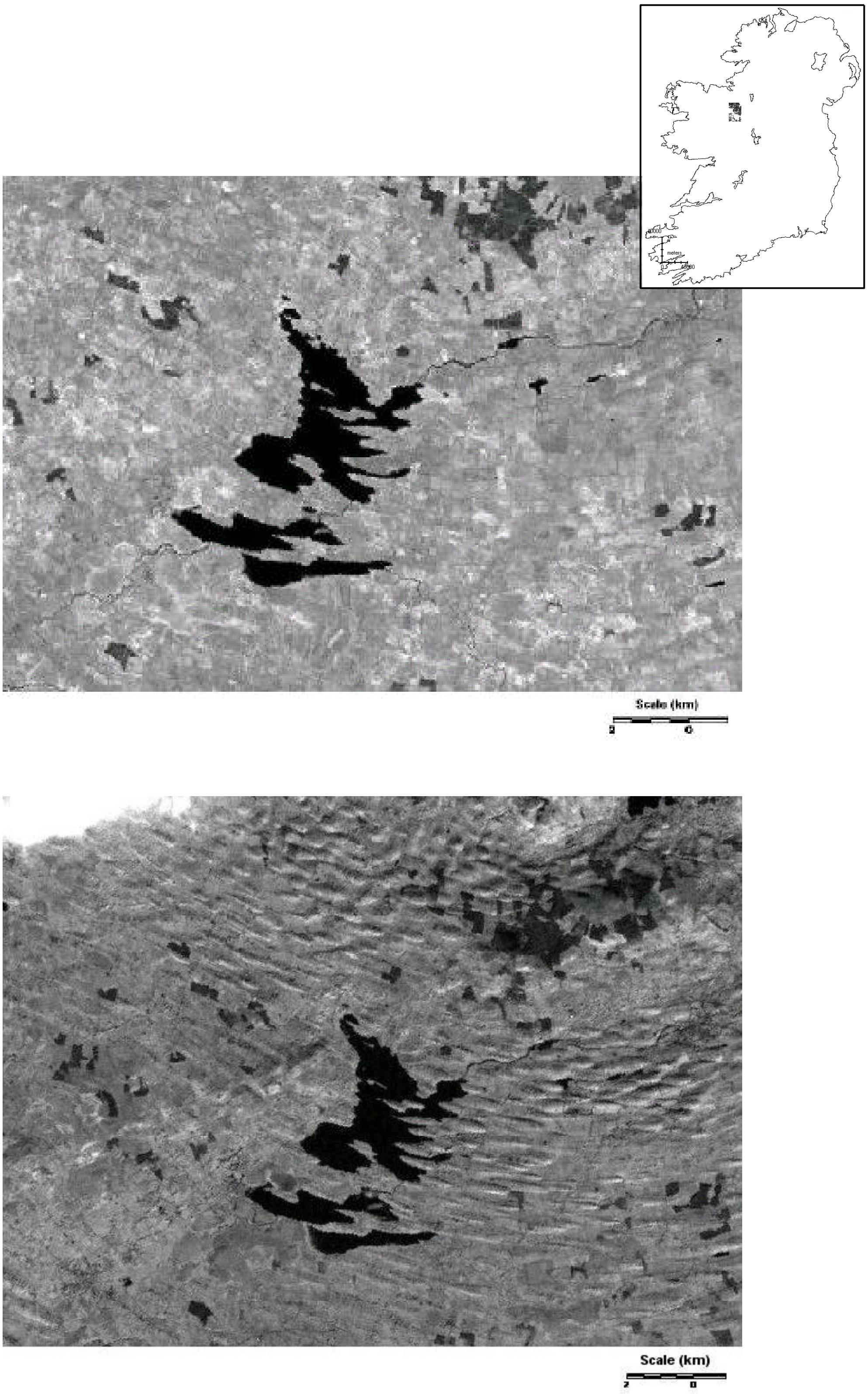


Figure 2.1a and b Landsat TM images of Lough Gara, Ireland, with a summer image (top; high solar elevation angle) and winter image (bottom; low solar elevation angle).

Satellite	Sensor	Nominal Resolution (m)	Image Size (km)
Landsat	MSS	80	185×185
Landsat	TM	30	185×185
Landsat	ETM+	15/30	185×185
SPOT	XS	20	60×60
SPOT	Pan	10	60×60
SEASAT	SAR	25	100×100
ERS	SAR	25	100×100
Radarsat	SAR	9-100	Swath width 50-500
Terra	Aster	15	60×60

Table 2.1 Earth resources satellites used in glacial reconstructions.

Clark (1997) reviews image pre-processing techniques used to enhance glacial landforms. For VIR images these include contrast stretching, convolution filtering and de-striping, as well as experimentation with colour composites in areas with mixed surface cover. Processing techniques for SAR are different as it is a microwave, rather than optical sensor. Vencatasawmy *et al* (1998) and Clark (1997) report specific recommendations for geomorphological applications. These involve de-speckling, data reduction and contrast improvements.

Pre-processing is followed by the geocorrection of the imagery to known geographic co-ordinates. For sub-pixel accuracy in geocorrection, topographic maps with high spatial accuracy are required and, if in mountainous terrain, a high resolution digital elevation model (DEM) is required to correct for relief displacement. Often neither of these requirements are met in glaciated terrain and so accuracy of the order of 5 pixels is attained. If topographic maps are not available for the selected region then it will require the simple correction using the corner co-ordinates supplied with the image; this will provide an accuracy of the order of 15-20 pixels. This order of accuracy is satisfactory for the synoptic mapping of glacial landforms in the production of generalised flow events for a region.

2.3.2 Palaeoglaciological Landform Mapping

Once geocorrection is complete, glacial landforms, particularly lineaments, eskers, ribbed moraine, moraines and hummocky bedforms, need to be identified and mapped. This can be achieved by hand, on paper print-outs of the imagery and then manipulated on paper or later entered into a Geographic Information System (GIS). Alternatively landforms can be digitised on-screen within a GIS using thematic layers. This latter approach is more flexible as it allows viewing of the imagery at all scales and later digital manipulation.

Identification and digitisation is best performed at different scales to allow the recognition of different size landforms, although this is dependent upon the nominal resolution of the imagery. For Landsat MSS the most detailed mapping scale is 1:120,000, however for other imagery it is desirable to initially map at 1:75,000. This is followed by mapping at 1:150,000, with less intensive mapping at 1:300,000 and even 1:600,000. Once completed, a single image can contain several thousand lineaments. It is then important to check against the broad regional geology for spurious correlations with fault lines, drift covered rock ridges (scarps), bedding and major changes in lithology.

Mapping can be viewed as the initial interpretation (or abstraction) of the observations of an unknown surface imaged by a satellite sensor. It is the qualitative (manual) identification of landforms within an image and an appraisal of their significance. In addition, the observer requires experience at interpreting satellite imagery as well as in the subject area of interest.

2.3.3 Flowset Construction (Figure 2.2)

Before the interpretation of lineament patterns can begin, the original mapped lineaments are generalised or grouped into summary lines, termed **flow patterns**. Flow patterns represent groups of glacial lineaments, with high parallel conformity and similar morphometry (e.g. length, spacing), reducing the amount of data for interpretation. Spatially coherent flow patterns are then taken and interpreted into distinct flow events termed **flow sets** (Boulton and Clark,

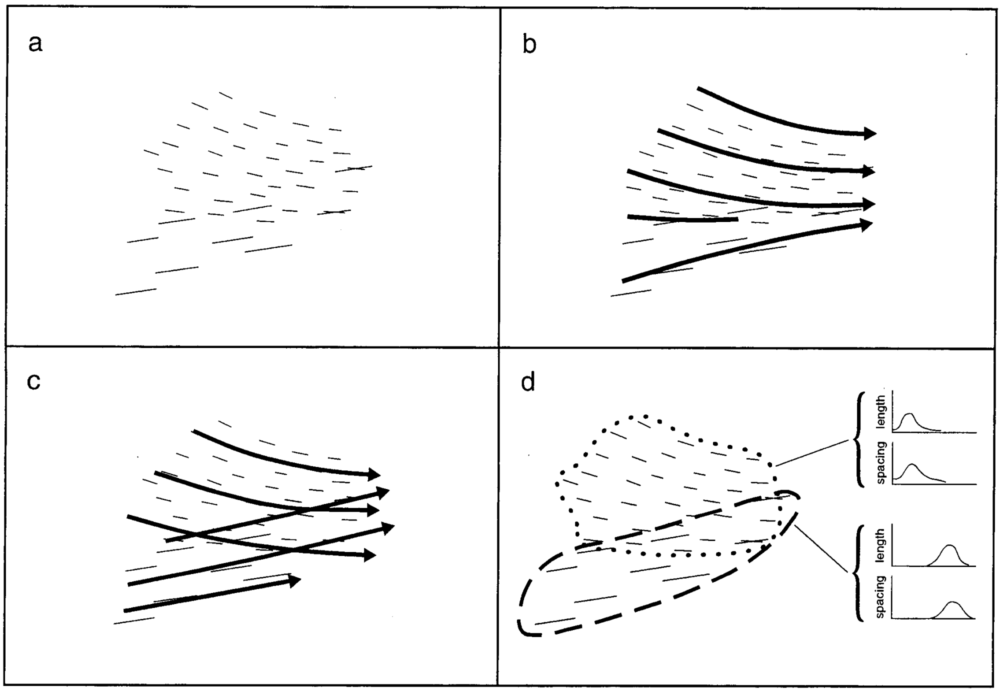


Figure 2.2 (a) shows individual mapped lineaments, whilst (b) and (c) show two alternative interpretations of their formation. (d) illustrates that by grouping lineaments and reviewing their characteristics (e.g. spacing and length), there can be a basis for interpretation (Clark, 1993).

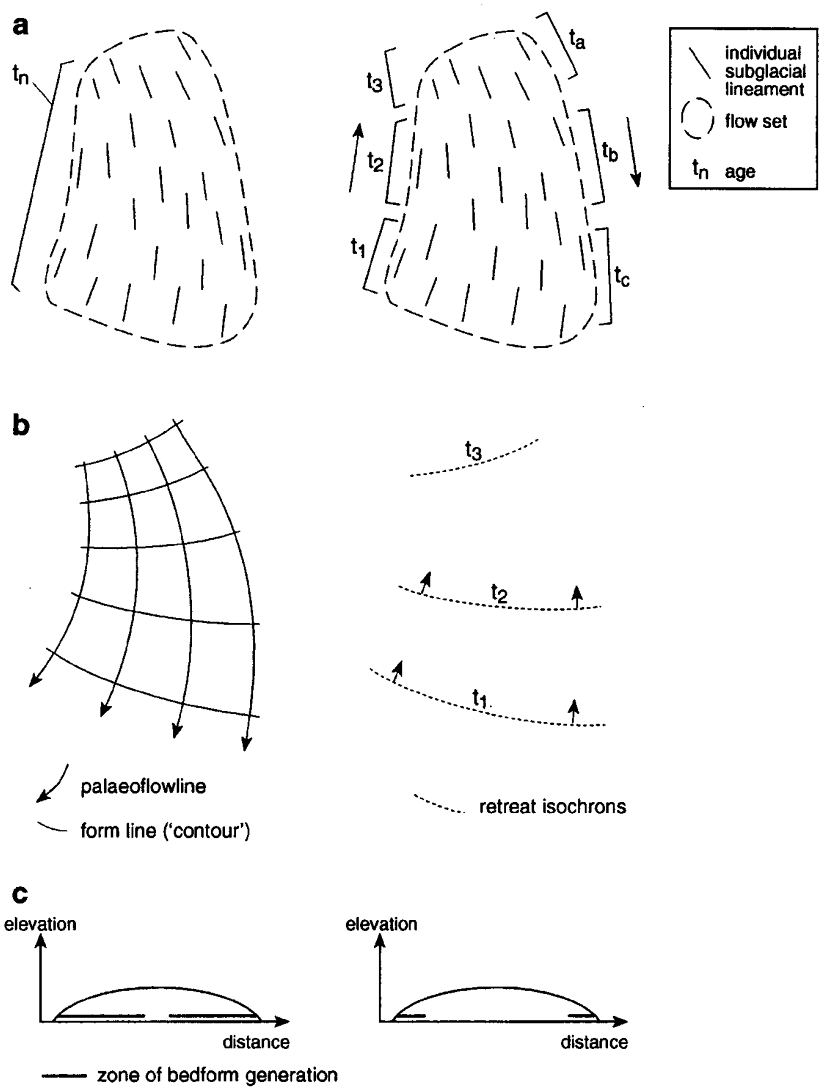


Figure 2.3 Illustration of isochronous (left) and time-transgressive (right) flow set formation. The isochronous lineaments are formed at time t_n (a) and can be represented by palaeo ice flow lines (b). Time transgressive lineaments are shown in (a), with the retreat pattern they represent at t_1, t_2 and t_3 (b). Their location of formation is shown in (c) (Clark, 1999).

1990). As flow sets are interpreted features, it is important to consider all glaciologically plausible scenarios in their grouping. The construction of flowsets is a process that devolves landform assemblages into flow event building blocks from which a reconstruction can be based.

2.3.4 Synchroneity of Formation

Once flow sets have been created their mode of emplacement needs to be ascertained. This can be categorised (Figure 2.3) as either **time transgressive** (formed over a period of time) or **synchronous** (formed at a point in time). Synchronous flow sets exhibit high parallel conformity and similarity of morphology over small areas, with gradual and systematic changes over larger areas.

Time transgressive flow sets are formed during periods of *varying* flow patterns and consequently display obvious discordancy, with lower parallel conformity, changes in morphology and unsystematic cross-cutting (Clark, 1999). Lineament patterns formed time transgressively typically form behind a retreating ice margin.

2.3.5 Cross-cutting flow traces

With the establishment of ice sheet wide flow sets, cross-cutting data (see §2.3.6) are extrapolated from individual landforms to flow sets and then used to establish a **relative chronology** of flow sets. This provides information on the changing ice dynamics through time. Clark (1993) stresses that it is not possible to asses relative age by assuming the newest lineations produce the dominant or “freshest” patterns. The appearance of cross-cutting sets is controlled by sediment supply to a re-advancing ice sheet margin. If there is a ready supply of sediment then one flow set can be **superimposed** upon another. However if there is a small, or no, sediment supply then **re-moulding** of the pre-existing flow set will occur. Clark (1993) suggests that the degree of re-moulding is dependent upon ice velocity (Figure 2.4) and consequently can be used to determine the velocity zones of former ice sheets (i.e. lineaments are related to relative high velocity zones which are located at the ice sheet margin). Other researchers (e.g. Sugden and John, 1976) arrive at similar conclusions.

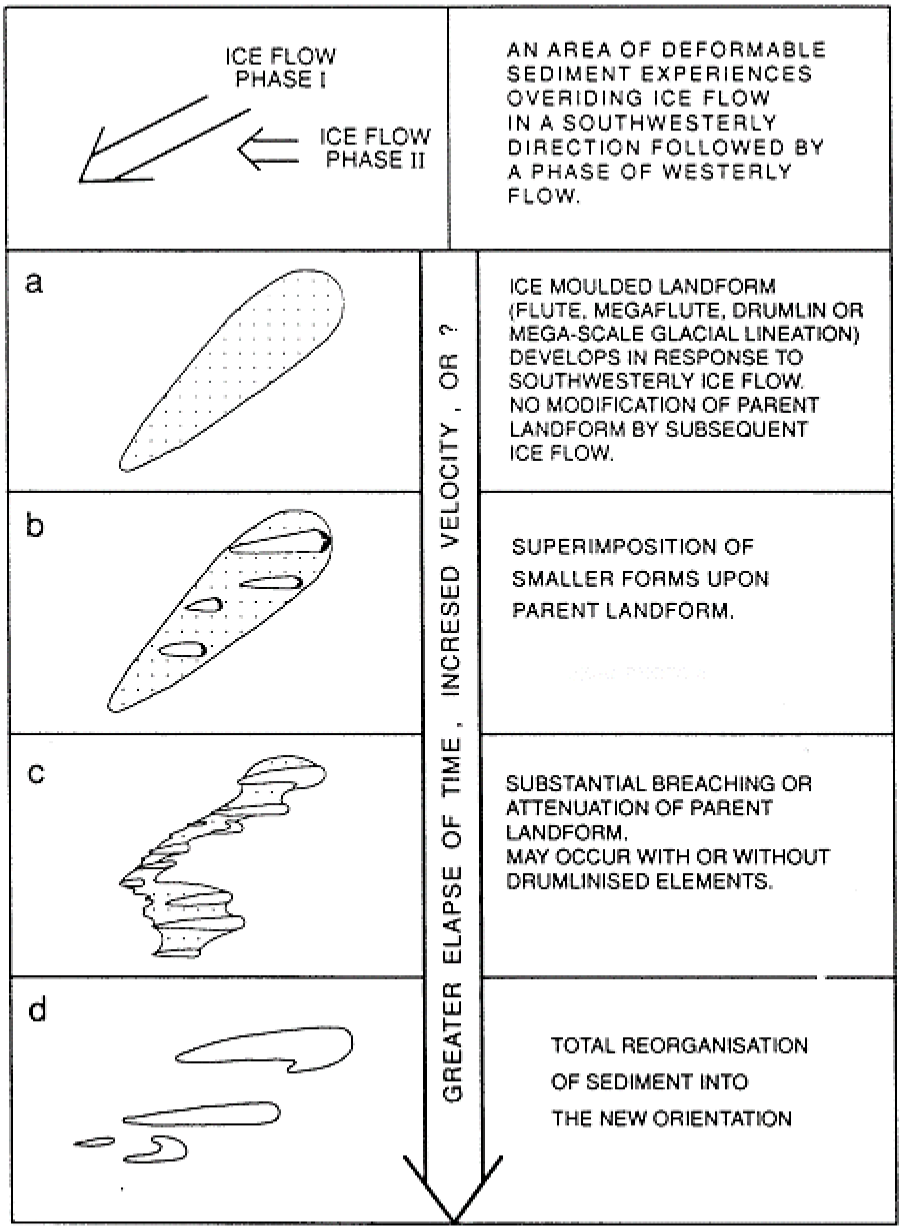


Figure 2.4 The glacial record shows that cross-cutting lineaments form a variety of shapes with superimposed and remoulded forms as end members. The greater the residence time and velocity of the ice sheet, in addition to a low sediment supply, the more likely remoulding is to occur (Clark, 1993).

Published field studies that provide dating evidence for landforms mapped from the satellite imagery can also be used (e.g. radio carbon dates for till horizons). These allow the determination of an absolute age for a particular site, so providing an **absolute age assessment**. This information can be combined with the relative age assessment, however it is unlikely that all the flow sets will be constrained by absolute dates. Rather, it is likely that some sites will be dated and so provide broad dates between which certain flow events are known to have occurred.

2.3.6 Relative Age

Boulton and Clark (1990) noted that glacial lineaments often exhibit cross-cutting relationships (e.g. Figure 2.5). It had previously been thought that all glacial lineaments were formed during the last glacial advance, however the discovery of cross-cutting relationships demonstrates that older patterns can be preserved (see §3.7.8). Figure 2.2 shows how flow patterns would originally have been explained and how they can subsequently be interpreted with reference to cross-cutting. Cross-cutting patterns of bedforms, in a single glaciation, can occur due to (refer to Figure 2.6):

1. **Ice Divide Migration** - movement of the ice divide position changes ice flow geometries and as a result causes cross-cutting. In general the closer to the current ice divide that cross-cutting patterns are found, the greater the angular difference between cross-cuts. This theory was used as sole explanation for cross-cutting patterns by Boulton and Clark (1990) in their reconstruction of the Laurentide ice sheet.

2. **Ice Stream Activation** – ice streams are fast flowing channels of ice, that initially converges from an ice sheet interior. They exhibit a strictly confined zone of parallel flow. Once an ice stream is activated it may cross-cut previously formed lineaments.

3. **Lobate Margin Retreat** - as an ice sheet recedes, lobate margins will pull back in a slow, irregular, manner. Retreat patterns can be complex and may

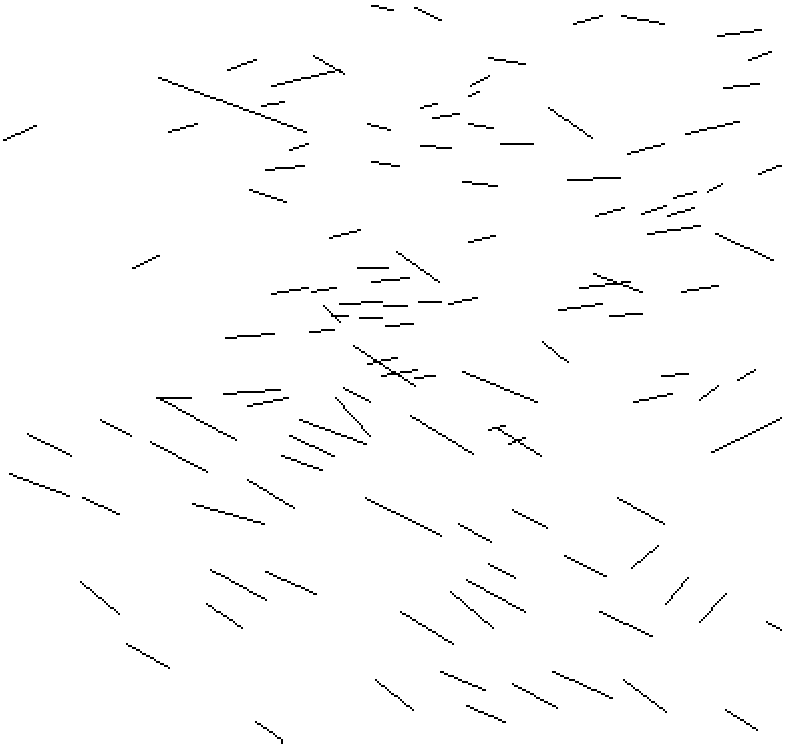
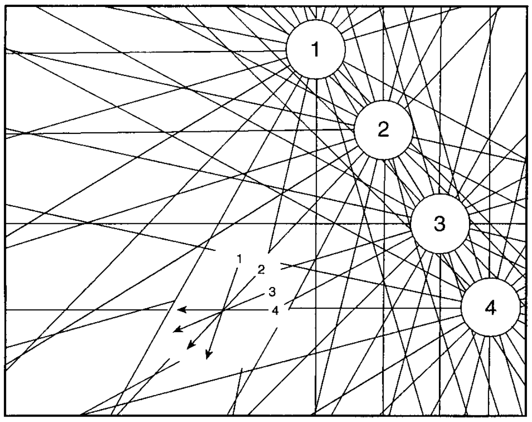
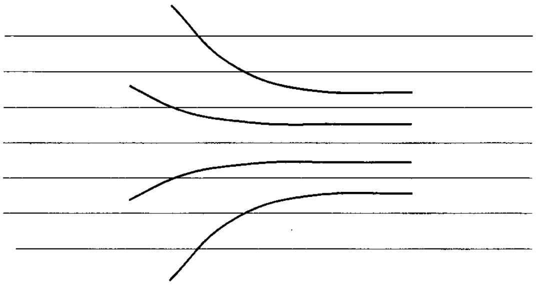


Figure 2.5 a. Example of cross-cutting lineaments depicted on SPOT satellite imagery (Lough Gara, Ireland). The arrows in the top diagram highlight two dominant lineament directions. The circled region shows cross-cutting lineaments. The image is 8.5km across. b. The bottom diagram shows lineaments that have been mapped from the above image.

Ice Divide Migration :



Ice Stream Activation :



Lobate Margin Retreat :

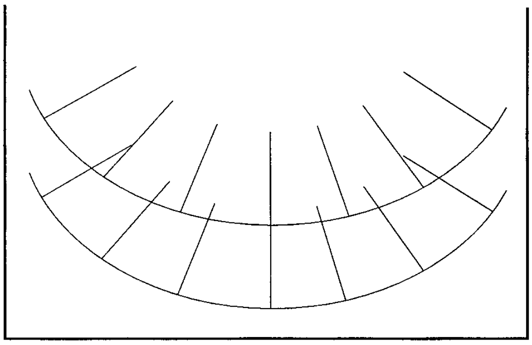


Figure 2.6 Three main glaciological scenarios through which cross-cutting lineaments can be generated (Clark, 1997). Ice divide migration, ice stream activation and lobate margin retreat all allow for the change in ice flow direction.

leave a record of flow patterns if still drumlin forming. In the latter case, cross-cutting lineaments will mark the retreat of the margin. In an idealised situation, towards the central axis of a lobe lineaments will be aligned conformably, whilst towards the edges of the margin there will be a greater angular difference (Figure 2.6). However, this hides what will actually appear to be a very complicated area of flow; the resulting pattern will be a complex mix of cross-cutting lineaments with little appearance of conformity as ice sheets rarely retreat in a steady, orderly, pattern. Sections of the ice will retreat faster than others and then re-advance, further complicating the flow trace.

2.3.7 Summary

This section has presented the different types of satellite imagery appropriate for mapping glacial landforms to be used in a full ice sheet reconstruction. The methods by which these are mapped and then identified as contiguous landform assemblages was described. Flow sets are the final part of this process. Using this information, and given the constraints of topography, the position of cold-based regions and ice divides can be inferred (i.e. areas where no lineations were formed and preservation of pre-existing landforms occurs). The evidence can finally be pieced together to provide a single reconstruction or, more likely, a number of alternative reconstructions. These reconstructions are based upon mapped and published geomorphological and sedimentary evidence. Table 2.2 provides a summary of how this evidence can be used to infer the conditions that were prevalent during glaciation. The following section illustrates how all the stages of a ice sheet reconstruction fit together through the use of a case study.

2.4 Reconstruction Case Study – The Irish Midlands

This section provides an example of an ice sheet reconstruction for the Irish Midlands, based upon Clark and Meehan (2001).

2.4.1 Methodology

Ireland has perhaps one of the longest traditions in glacial research owing to the presence of one of Europe’s largest drumlin fields in the Midlands. However it is

T2.2

poorly mapped due to fragmented research from a variety of authors. The lack of a glacial map for Ireland has hindered research and the authors attempt to help redress this balance. The authors used a high quality Landsat TM image (180km by 180km) and a high resolution (25m pixel) DEM (100km by 100km) for the Irish Midlands. These two data sources were used to produce a glacial landform map for this region. Both data sets were provided in digital form allowing on-screen digitising of landforms. Initial investigations identified the presence of a large number of ribbed moraines, in addition to the lineaments. These were mapped as polygons (marking the break of slope) and single lines (marking ridge crests) respectively on the DEM (Figure 2.7). The Landsat TM image involved mapping broad lineament and ribbed moraine patterns rather than individual landforms. The primary data were supplemented with field mapping and sedimentology, as well as selected erratic trains.

With the mapping phase complete, the authors go on to describe the broad characteristics and pattern of ribbed moraine and drumlins. The former comprises two separate patterns. The first, a single contiguous field, covers almost the entire area, whilst the second is oriented transverse to the first and occupies a small region in the NW corner. Drumlins occur across the entire region with considerable overprinting on the ribbed moraine. Indeed the close association between the two suggests the drumlins were formed shortly after the ribbed moraine. They argue that the strong parallel conformity of drumlins (and association with the ribbed moraine) in this area suggests they form a single phase of drumlin creation that was probably isochronous (flowing from the NW to SE). Drumlins also overtop relief up to 200m, without deflection, which negates their creation at a receding margin. They identify two further patterns in the NW (flowing SW to NE) and SE (flowing SW to NE) respectively which are identified by a marked change in orientation (although no cross-cutting is present) and drumlin morphometry. Traditional stoss and lee relationships for drumlins were used to identify flow direction.

2.4.2 Ice Sheet Reconstruction

With the creation of flow patterns complete, the authors go on to develop drumlin and ribbed moraine flow sets (Figure 2.8) identifying 6 lineament and 8 ribbed moraine flow sets based upon parallel conformity and morphometry. These are then sorted into known relative ages based upon cross-cutting relationships noted on the original imagery (Table 2.3).

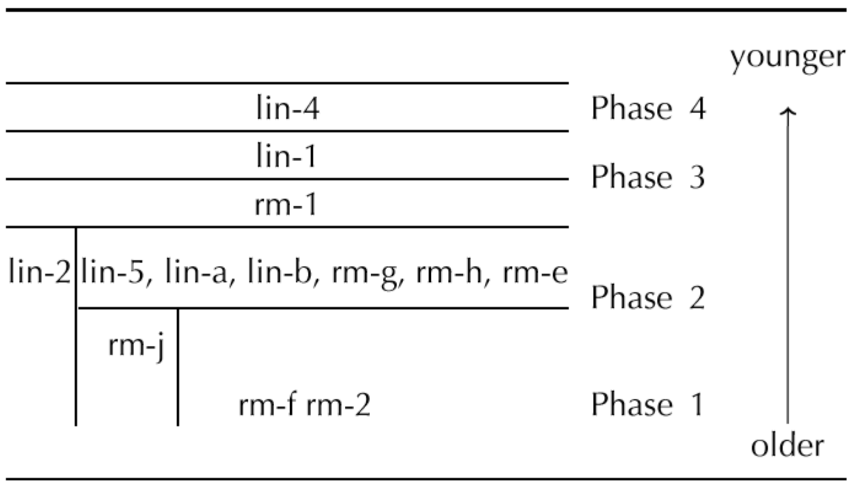


Table 2.3 Relative chronology of interpreted flow sets and how they relate to the different Phases of the ice sheet reconstruction.

Using this information the authors suggests four main phases based upon their evidence (refer to Table 2.3 and Figure 2.9). These are:

Phase 1 – rm-2 and rm-f form the earliest phase representing ice flow from the NE. As relief (up to 200m) has little effect on their creation, they cannot have formed under thin ice or close to the margins. They infer these forms as representative of expansion of an ice cap centred upon NE Ireland, possibly after invasion by Scottish ice.

Phase 2 – seven flow sets comprise this phase; some are not influenced by topography, whilst others are. They are grouped together (due to their orientation) as representative of this period, not because they all formed synchronously. Their orientation suggests a linear N-S ice divide. This position of cold based ice beneath the divide would have also helped preserve the flow sets in Phase 1. From this evidence they infer a worsening in climatic conditions leading to the development of a large ice cap. Given the landforms record a large ice cap at a relatively southern latitude, it is assumed this represented the Last Glacial Maximum (LGM).

Phase 3 – the flow sets identified here are the most dominant in Ireland. The drumlins closely match the ribbed moraine, as well as cross-cutting them. They can safely be grouped together, with the drumlins formed shortly after the

F2.7

F2.8

F2.9

ribbed moraine. This then infers an ice divide located in NW Ireland, possibly extending out on to the continental shelf. This was a major phase of drumlinisation which would have erased all older landforms beneath it.
Phase 4 – the final, and youngest, drumlin pattern is left, being strongly controlled by topography. This appears to indicate ice flow *towards* the NE, almost a complete reversal of the previous phase. The two inferences are that a Galloway based ice cap invaded and extended towards the north or, more likely, this phase represented a fragmentation of the ice sheet into smaller ice caps and that this simply records deglaciation.

The above phases represent the authors' preferred interpretation of the available primary evidence. However it is discussed in relation to existing literature and there is room, within these phases, for flexibility. They suggest that the relative age of events is stable, although absolute ages are far less so. To this extent, they provide an alternative interpretation which would equally fit evidence. This suggests that Phases 1 and 2 represent the build of ice and that Phase 3 is representative of the LGM. Once sea ice was established in the Irish Sea, it is possible that the ice divide migrated towards the higher northern region helped by precipitation from the Atlantic.

The above section represents the application of the four main stages of an ice sheet reconstruction by Clark and Meehan. That is, the mapping of individual landforms from satellite imagery and DEM data, following by their generalisation into distinctive flow patterns. Once completed the authors used these patterns to generate distinctive flow sets which could be placed within a relative chronology and assessed as to whether they were time-transgressive or isochronous. Using all this evidence a reconstruction of ice sheet geometry, extent and changes through time was produced. This is completed with a discussion of implications relating to the surrounding regions that are not directly evidenced in the research. In addition, previous literature needs to be examined in order to note and explain differences between conclusions.

2.5 Summary

This chapter has discussed the techniques and methodology currently used in ice sheet reconstructions. Although the diversity of satellite imagery is still relatively restricted, the current variability provides a wide range in the quality of data available and consequently the interpretation of any landforms that are mapped. The methodology described above allows the implementation of techniques to integrate diverse palaeo-evidence, recognising the importance of cross-cutting data and the alternative scenarios of interpretation. Indeed the methods are specifically designed to embrace all data and interpretations. This reduces data precision but highlights strong synoptic trends such that complementary evidence can be used to discard improbable or implausible scenarios. Although the work of Sugden (1976), Boulton and Clark (1990) and Kleman and Börgstrom (1996) have made significant improvements to these methods, there are still weaknesses which are highlighted in the following chapter through a review of previous satellite imagery based glacial reconstructions. Chapter 4 then goes on to formulate specific key issues on which the research of this thesis is based.