3 Review of Ice Sheet Reconstructions based on Geomorphology Mapped from Remotely Sensed Data

3.1 Introduction

The advent of remote sensing allowed the rapid mapping of glacial landforms over large areas, initially using aerial photography (e.g. Prest *et* al, 1968) and later satellite imagery (e.g. Punkari, 1982). They provided a synoptic view, often over remote regions, allowing the identification of small scale features that were unrecognisable from the ground. With the wider availability of these data, theoretical (e.g. Sugden and John, 1976), methodological (e.g. Clark, 1993) and technical (e.g. Clark, 1997) advances in the way glacial reconstructions are performed have been achieved.

The theory used in glacial reconstructions is well developed and practised by several researchers in areas of former ice sheets. Chapter 2 introduced the data sources, techniques and methods employed by these researchers. This chapter aims to make the reader familiar with a range of glacial reconstructions from these different authors. These papers are broadly reviewed by research groups that the principal author falls in (e.g. Punkari in one section and Clark in another). Within each section papers are generally reviewed in chronological order, highlighting methodological advances and discussing particular weaknesses. The chapter concludes with a review of papers that developed the methodological techniques of ice sheet reconstruction.

3.2 EarlyGlacialReconstructions

Glacial reconstructions date to the beginnings of glaciology in the early 1800's (e.g. Agassiz, 1840). Within the UK (my initial study area) it was the geological mapping programmes in the latter half of the 1800's that provided researchers with regional glacial landform data. For example, in Ireland, Close (1867) and Hull (1878) provided early countrywide reconstructions, with numerous other Geological Survey workers discussing regional trends in the memoirs accompanying geological map sheets. However it was not until the 1950's, with the wide spread use of aerial photography by national mapping programmes, that fieldwork was superseded as the predominant tool for mapping glacial landforms over large areas. The mapped data could form the basis of glacial landform maps of entire former ice sheets and so lead on to interpretation and reconstruction. Prest *et al* (1968) used such a method in the reconstruction of the dynamics of the Laurentide Ice Sheet.

The advent of digital imagery, particularly satellite based, later supplemented these data. The relatively low cost and large areal coverage were ideally suited to regional glaciology. Landsat MSS (1:1,000,000 photomosaics) images were first used within a glaciological context by Sugden (1978) to map areas of areal scouring in North America, however it was not until Punkari (1982) that the full potential of satellite imagery for ice sheet reconstruction was implemented.

3.3 Punkari (various), Dongelmans (1997) and Boulton *et al* (2001)

Punkari (1982) used Landsat MSS data (1:100,000 to 1:400,000 paper prints) to map a variety of different glacial landforms in Finland and surrounding areas providing the first satellite based glacial reconstruction. Mapped landforms included lineaments, eskers, end moraines, hummocky moraine, rogen moraines and marginal moraine, incorporating striae, till fabric, erratics and sediment type from the published literature (Figure 3.1). He made particular use of different EM band combinations to highlight vegetational differences (*geobotanical method*) and so enhance lineaments. Due to the restrictions in the sensor spatial resolution (nominally 80m) individual ridge features were difficult to determine, however a general trend (co-linear texture) was apparent. Mapped lineaments were nominally assigned to a flow type of *time transgressive* or *lobate marginal retreat*. Punkari's initial research also highlighted an older flow event which he suggested was preserved under cold based ice. Figure 3.2 illustrates his lineament map and final reconstruction. Punkari (1985) extended his work into Soviet Karelia using the same technical methods. He was able to use winter imagery, noting the particular utility of low solar elevation in detecting lineaments. Soviet airborne radar was found to be

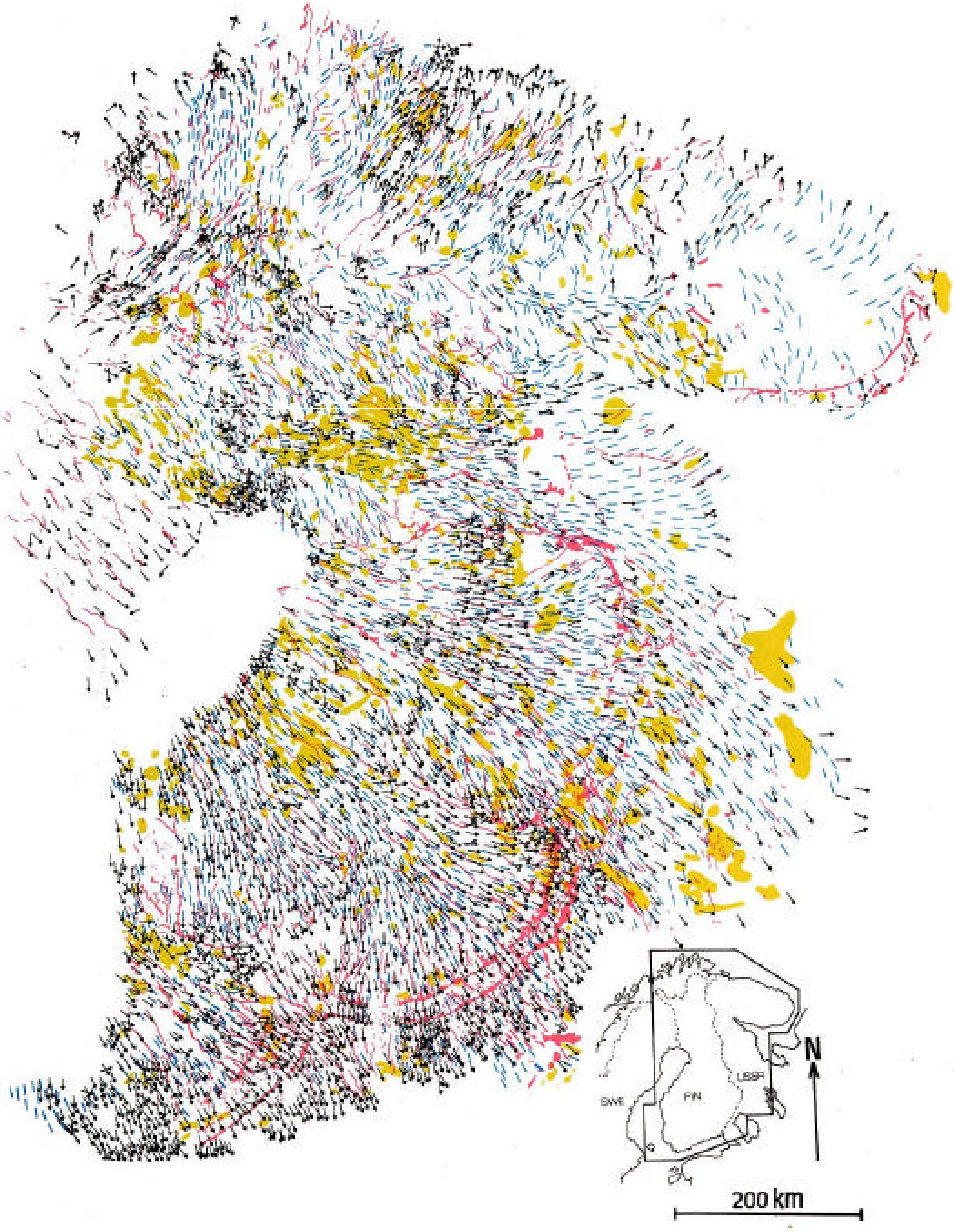


Figure 3.1 Glacial landforms mapped from Landsat MSS satellite imagery (Punkari, 1982) for a large part of Fennoscandia. Landforms are lineaments (blue), end moraines/eskers (red), hummocky moraine (yellow) and striae (black).

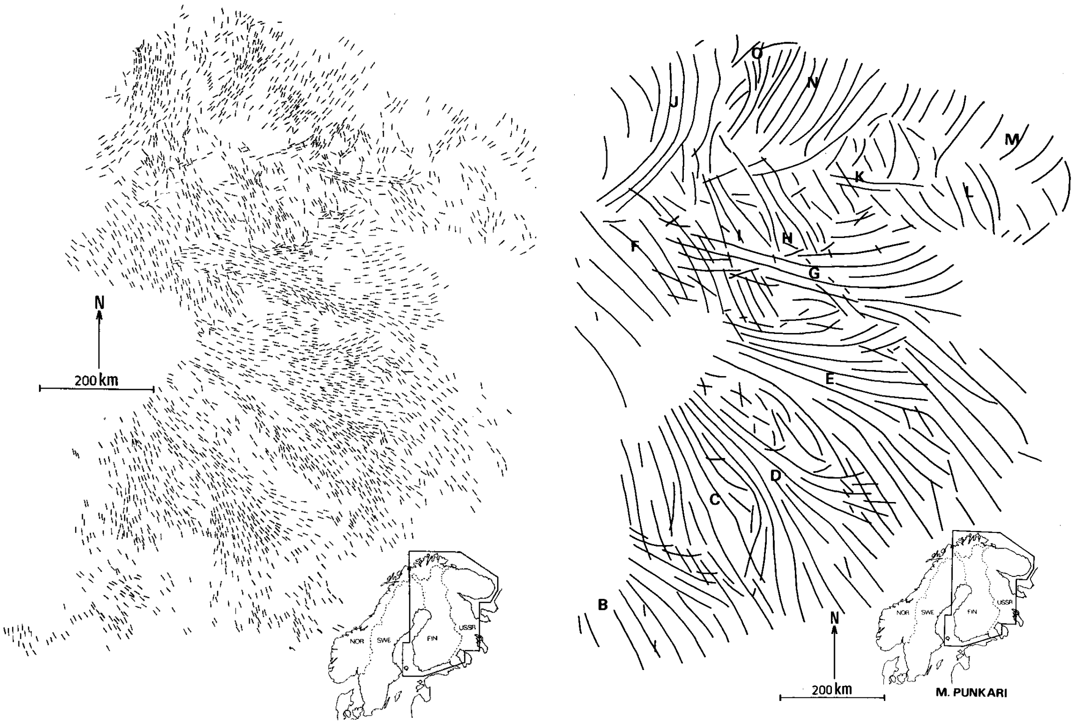


Figure 3.2 Lineaments mapped from Landsat MSS satellite imagery (left) and their corresponding flow patterns (right) for parts of Fennoscandia (Punkari, 1982). Flow patterns are the key element to establishing flow sets prior to a full ice sheet reconstruction. The methods used to produce flow patterns from lineaments are not detailed.

better at detecting glacial lineaments than Landsat MSS, although coverage was limited. This confirmed early work by Ford (1981) that had already shown the usefulness of radar images in detecting glacial landforms. In exceptional cases Punkari was able to extract cross-cutting relationships from superimposed lineaments. Other practical enhancements included cross checking for geological misinterpretation, the use of field work for ground control and the explicit need to consider topography in any reconstruction. Conceptual notions of time transgressive and synchronous flow events were implicitly used.

Punkari (1989) consolidated the above work to produce an overall glacial reconstruction of Scandinavian and Russian Karelia, with the methodology explained in detail in Punkari (1993). This latter report indicated that "general scale" satellite mapping (1:500,000 to 1:1,000,000) was predominantly used (utilising Landsat and SPOT imagery), but incorporated detailed scale (1:20,000) mapping from south-western Finland. This latter mapping was able to identify individual landforms by using topographic maps and aerial photography, supplemented by some field work (principally for logging till fabrics and striae). As a consequence any general scale maps of lineaments are *generalised* from the first stage of mapping, and only in the detailed area of south-western Finland, are individual lineaments identified. Cross-cutting relationships are therefore only available for striae and these are extrapolated and applied to other glacigenic landforms. This work also incorporated the first explicit use of a GIS in ice sheet reconstruction, to digitise landforms and plot histograms of landform orientation.

Punkari (1995) later expanded his mapping of glacial landforms into north-western Russia, again using Landsat MSS 1:300,000 to 1:1,000,000 photomosaics. An explicit theoretical methodology was used and individually mapped features were now digitised and imported into a GIS. Lineaments were directly generalised from the imagery to the map, subjectively taking into account lineament orientation, density and length. In order to analyse lineament orientation, the entire area was segmented into 50km squares and rose diagrams produced (Figure 3.3), following the techniques of Broadgate (1997).

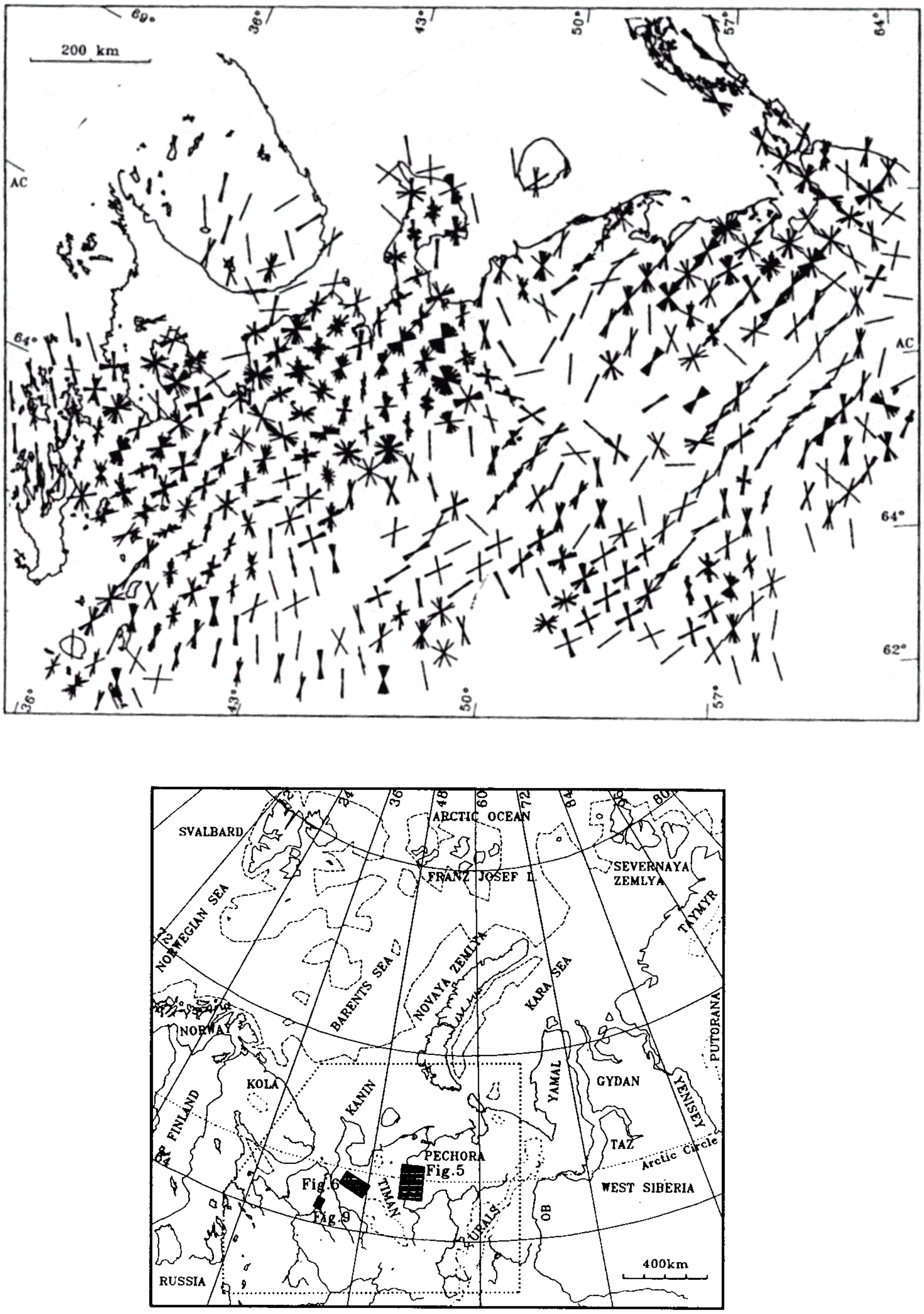


Figure 3.3 Rose diagrams of lineament orientation in NW Russia for 50km^2 grids (Punkari, 1995). Although graphically representing a lot of lineament data, it is difficult to interpret.

Figure 3.4 Frequency histogram (top) of orientation for different glacial landforms, illustrating the use of GIS based data (Punkari, 1993). Bar chart (bottom) of lineament frequency in part of Scandinavia (Punkari, 1993).

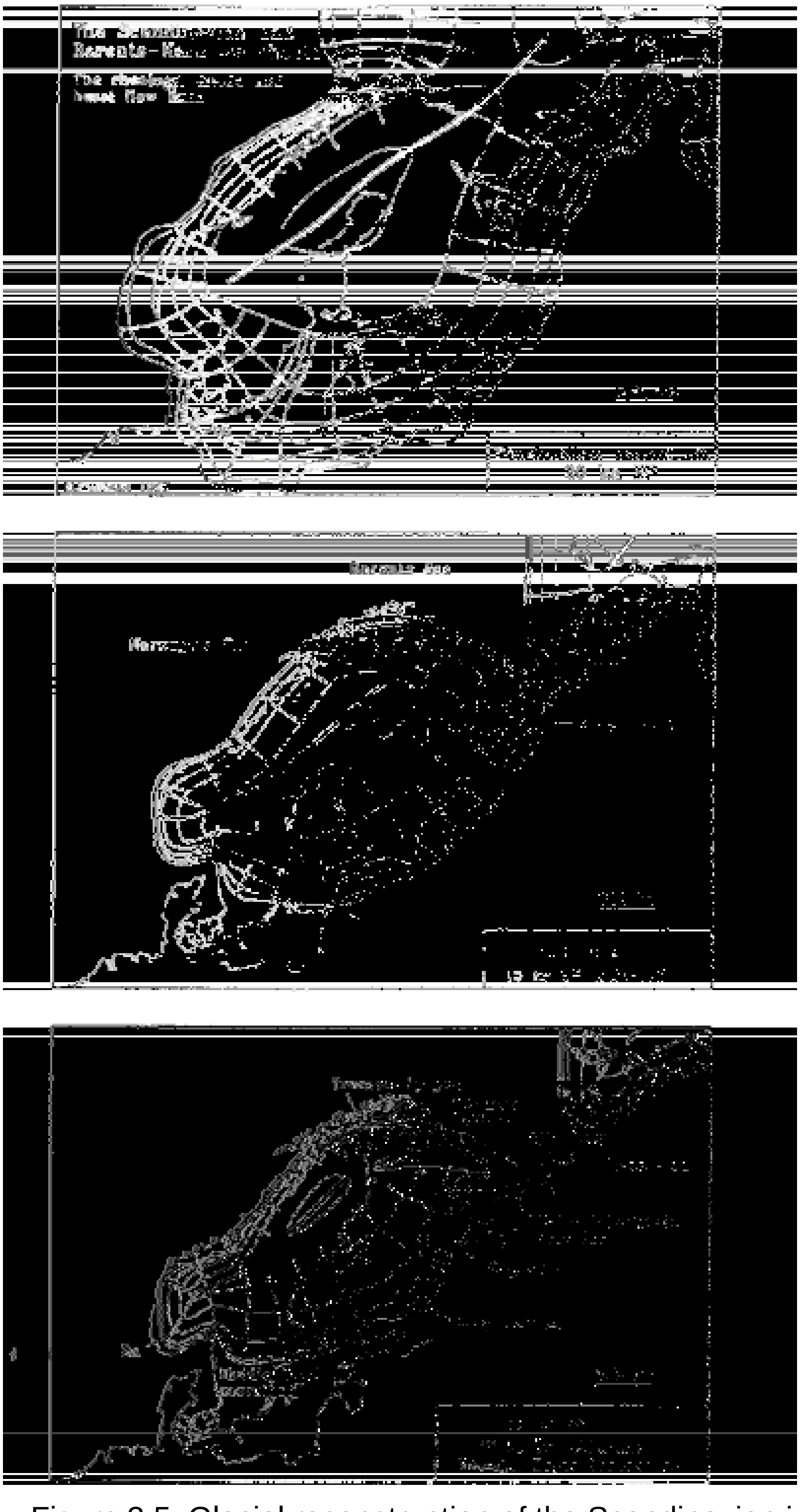


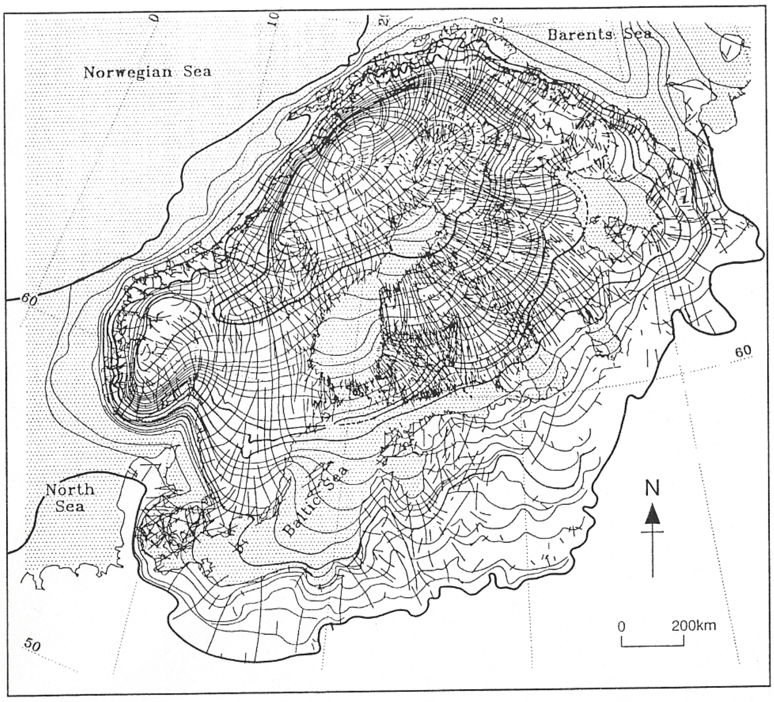
Figure 3.5 Glacial reconstruction of the Scandinavian ice sheet during the last glaciation (Punkari, 1993). Ultimately, glacial landform mapping and interpretation aims to produce a coherent history of the evolution of an ice sheet.

These then aided a reconstruction of the glacial history (e.g. Figure 3.4) to produce a full glacial reconstruction (Figure 3.5). His results concurred with the prevailing view that ice sheet lobes discharged eastwards from the Gulf of Bothnia, however he assumed that evidence of deglaciation was simply imprinted or "stamped" upon the landscape. He did not recognise that retreating ice lobes must be time transgressive and, assuming that lineations are continually formed, cross-cutting must result.

Dongelmans (1997) and Boulton *et al* (2001) produced a reconstruction of the Fennoscandian ice sheet using Landsat MSS 1:1,000,000 photomosaics and a mixture of Landsat MSS (27) and TM (4) scenes. For selected areas where relative chronology was important, 1:150,000 aerial photographs were incorporated. Like Punkari (1982), near-infrared images were used to detect lineaments by highlighting vegetational differences. They mapped eskers, moraines and drumlins (Figure 3.6a), but admit that the Landsat MSS imagery is unable to sufficiently resolve eskers and moraines to perform mapping accurately. Dongelmans does not discuss the process of generalisation, although original interpretations and summary maps are provided. When establishing a "flow" (flow set equivalent) Dongelmans requires lineaments to be "spatially continuous", although this is never defined. Rather than developing methods to cross-check "flow" creation, Boulton *et al* required each author to create their own "flows" and then compared the results. They found no substantive differences and so accepted these results. For display purposes Boulton *et al* performed four iterations of gradual generalisation, ultimately producing a final, ice-sheet wide, generalised map. The lineament and moraine data were linked to the Swedish varve chronology data to allow the authors to infer timescales of ice sheet retreat (Figure 3.6b). The original mapped lineaments were also used to identify major ice sheet structural elements, as idealised in Figure 3.7.

Discussion

Punkari (1982) was the first researcher to attempt to map many different glacial landforms from satellite imagery over a large area and integrate the data with published material in order to develop a glacial reconstruction. Initially the



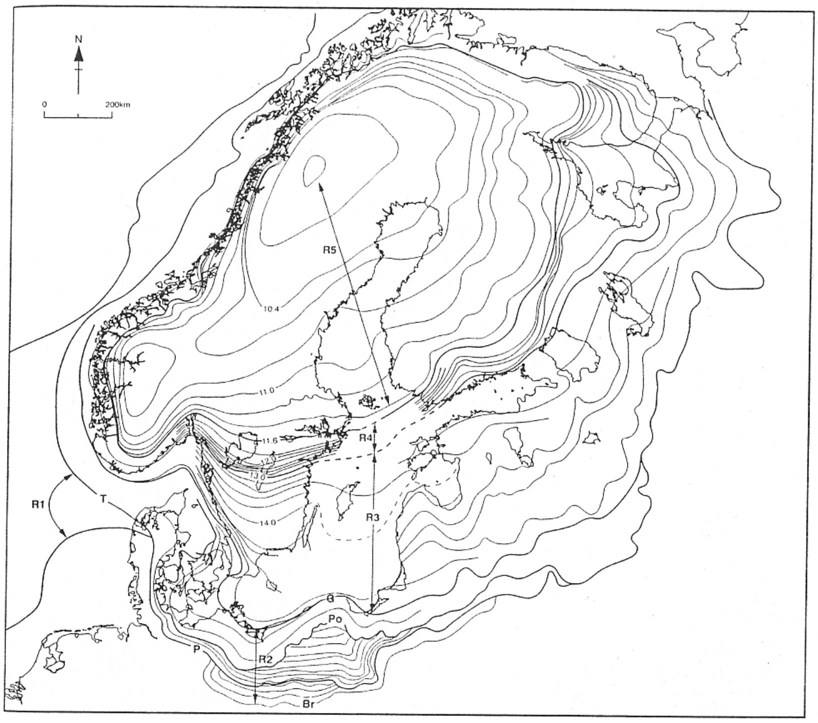


Figure 3.6 a. Major lineament patterns and inferred ice front retreat for the Fennoscandian ice sheet. b. Isochrons of retreat for the last Fennoscandian ice sheet (Boulton *et al*, 2001)

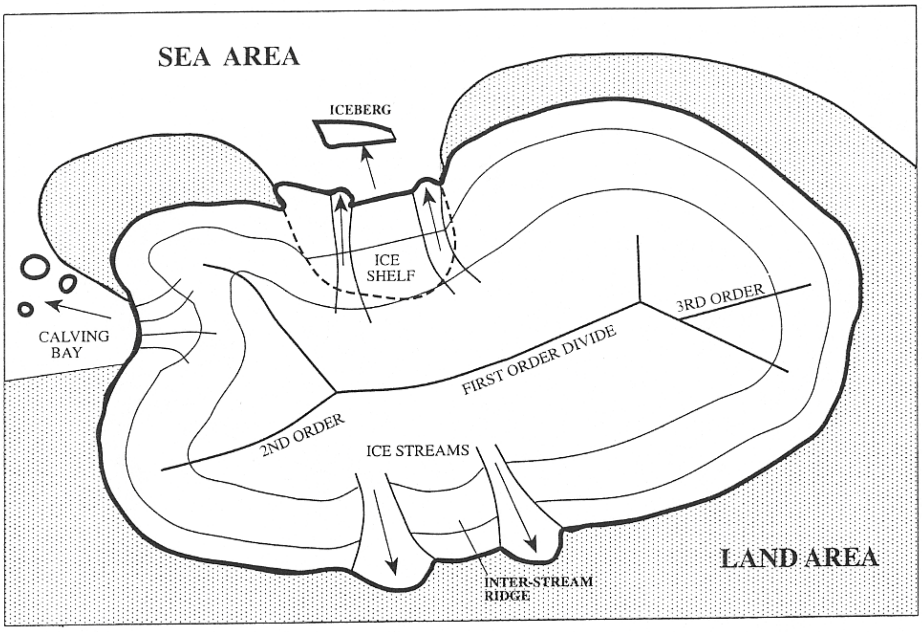


Figure 3.7 Idealised ice sheet structural elements (Boulton *et al*, 2001).

Figure 3.8 Summary lineament mapping for the Laurentide ice sheet (Boulton and Clark, 1990) based upon Canadian NTS (National Topographic System) quadrants.

author had several practical and technical limitations to overcome, exploring many image processing techniques in order to map different landforms. No explicit theoretical methodology was stated, although there were several implicit assumptions concerning the formation of different landforms (e.g. lineaments form subglacially, parallel to flow) and how these combined to produce a glacial reconstruction (e.g. time transgressive). Importantly, he recognised the existence of landforms from the penultimate glaciation, suggesting that these were preserved under cold based ice, however he didn't consider the possibility of multiple flow events within a single glaciation recorded in the morphological record and the implied changes in ice sheet dynamics. As a result he wasn't able to take advantage of developing a chronological history by correlating ice flow indicators across wide areas and using cross-cutting relationships. His ongoing experimentation with SAR and winter imagery was forward thinking, along with the input of mapped data into a GIS. This allowed the integration of a range of published data sources, as well as the development of analysis tools (Broadgate, 1997).

The technical developments implemented by Punkari were not matched by methodological developments. The lack of a framework through which mapped data was interpreted was a weakness in comparison with the methodological advances discussed by Boulton and Clark (1990) and Kleman *et al* (1996). In addition he failed to discuss the assumptions required in his interpretations of the landform evidence, as well as the procedures used to map and generalise the data prior to interpretation. Unfortunately mapping introduces bias into the final dataset used for interpretation. The original satellite image is not fully representative of the landforms on the surface (this is described in more detail in Chapter 4), whilst the observer is biased in the landforms that are mapped. The generalisation of these data, prior to interpretation, also introduces bias. In general, researchers have failed to recognise these deficiencies and account for them.

Dongelmans (1997) and Boulton *et al* (2001) used the same technical and methodological techniques as Punkari, applying them to the Fennoscandian Ice Sheet. Although they introduce the use of cross-cutting lineaments in developing a relative chronology, their discussion fails to incorporate some of the extensive developments made by Boulton and Clark (1990), Kleman *et al* (1996) and Clark (1999). They also do not map the extensive Fennoscandian rogen moraines or discuss the interpretation of these landforms with respect to the thermal regime of the ice-bed interface .

Their reliance upon Landsat MSS imagery is a major deficiency, a general point noted by Clark (1997, p1074) who states that early researchers:

> *used hardcopy prints at small scales and it is likely that many flow patterns were missed and some others erroneously interpreted or confused with geological structure.*

Landsat MSS is also unable to resolve all but the largest cross-cutting relationships. Boulton *et al* did have access to some Landsat TM and selected small scale aerial photography, however the widespread use of Landsat MSS is surprising.

Boulton *et al* (2001) rely upon the interpretation of lineaments as being heavily imprinted on the landscape and more densely grouped in submarginal zones and that this represents the retreat phase of an ice sheet. In addition where divergence of flow is observed at the former ice sheet margins, this is assumed to be indicative of land based ice streaming. They do not consider other glacial interpretations of the data and do not discuss other geomorphological criteria that may be indicative of ice streaming (see Stokes and Clark, 1999 for further discussion).

3.4 Clark (1990), Boulton and Clark (1990), Knight (1996), Clark *et al* (2000) and Clark and Meehan (2001)

Boulton and Clark (1990) used Landsat MSS (1:1,000,000 photomosaics) to map the glacial geomorphology of the former Laurentide ice sheet (Figure 3.8), however for each of the Canadian NTS (National Topographic System) quadrants they mapped, they acquired sample aerial photography to verify relative chronologies (see Chapter 2). Boulton and Clark developed the theoretical ideas of Sugden and John (1976; see §3.7), establishing that traces of previous flow events were visible and were cross-cut by traces of the final event in an area. The cross-cutting relationship provided a relative chronology which could be correlated across large areas. Assuming that previous flow events were preserved under ice divides, divide locations could be estimated and so the dynamics of the ice sheet, through time, constructed (Figure 3.9). Regions where cross-cutting information wasn't available were fitted into different glaciological scenarios to provide a variety of alternative reconstructions. Particular events within a reconstruction could be anchored to time if absolute dates of individual landforms were available. Whereas Boulton and Clark (1990) discuss technical methodological advances in glacial reconstruction, Clark (1993) goes on to describe the geomorphological implications of their results. This approach is later used by Knight (1996) and described in a review by Clark (1997).

In the PhD thesis of Knight (1996), and the subsequent published paper (Clark *et al,* 2000), ERS-1 SAR imagery was used to map glacial lineaments from the Labrador Sector of the Laurentide ice sheet (Figure 3.10). Image hardcopies (unspecified scale) were used to map lineaments. These were digitised, imported into a GIS and added to digitised vector or scanned raster data from published sources. Additional ancillary layers, such as coastlines, rivers and the Canadian National Topographic Grid (Figure 3.11), were also combined. Ground truthing was carried out through the use of 1:50,000 aerial photos (checking drift cover and lineament orientation), selected fieldwork (checking lineament orientation and gathering striae data), image re-interpretation (human interpretation error) and the use of SAR ascending/descending scenes to minimise errors introduced by illumination azimuth.

Individual lineaments were visually generalised into *ice flow trend lines*, with an idealised and actual example shown in Figure 3.12. In the case of multiple lineament patterns, trend lines were grouped into *ice flow line sets*. Although the GIS provided the ability to work seamlessly over the study area at any scale, Knight chose to work with digitised data within the spatial restrictions imposed by the imagery scenes. The creation of *flow sets* involved the extension of ice

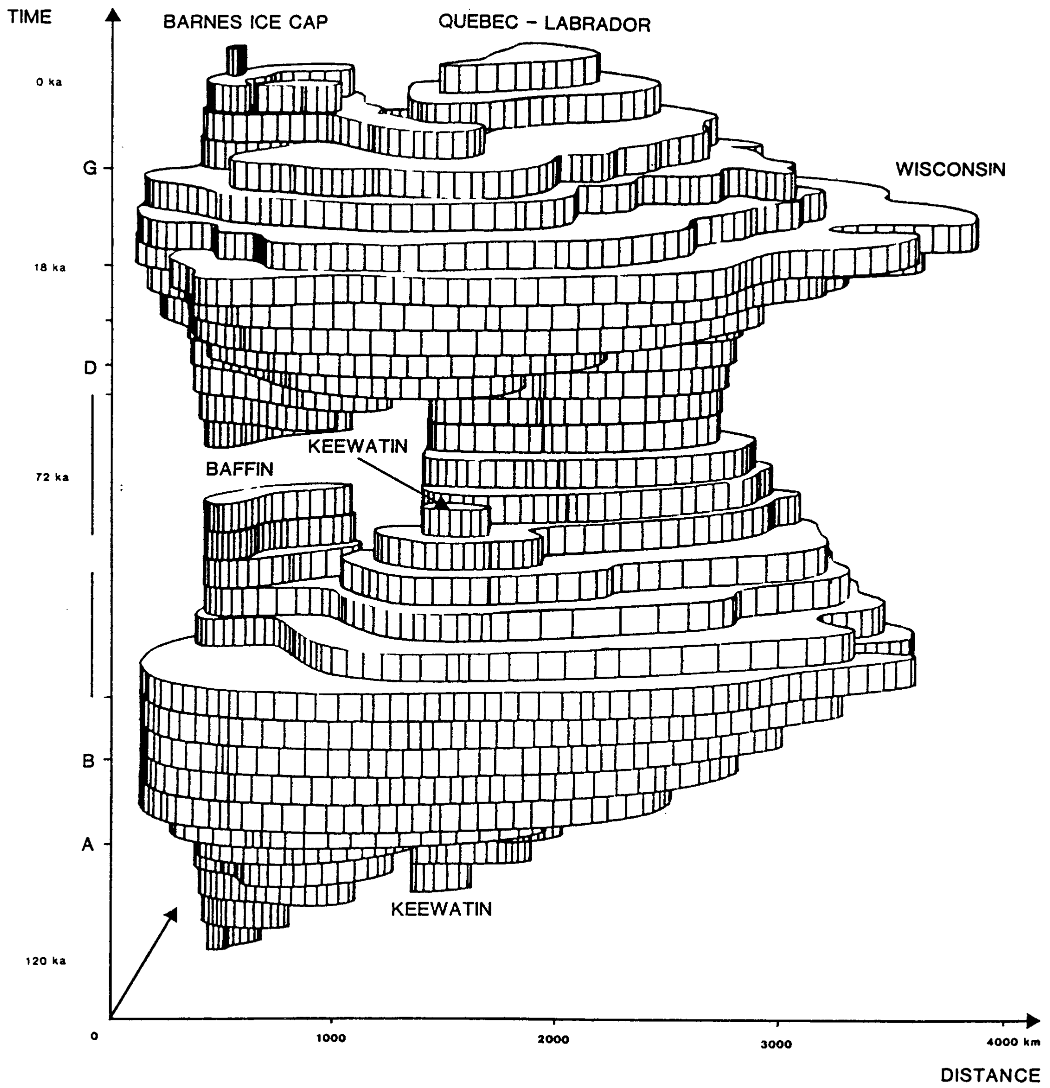


Figure 3.9 Postulated dynamics of the Laurentide ice sheet through the last glacial cycle (Boulton and Clark, 1990), showing the ice sheet border and its waxing and waning.

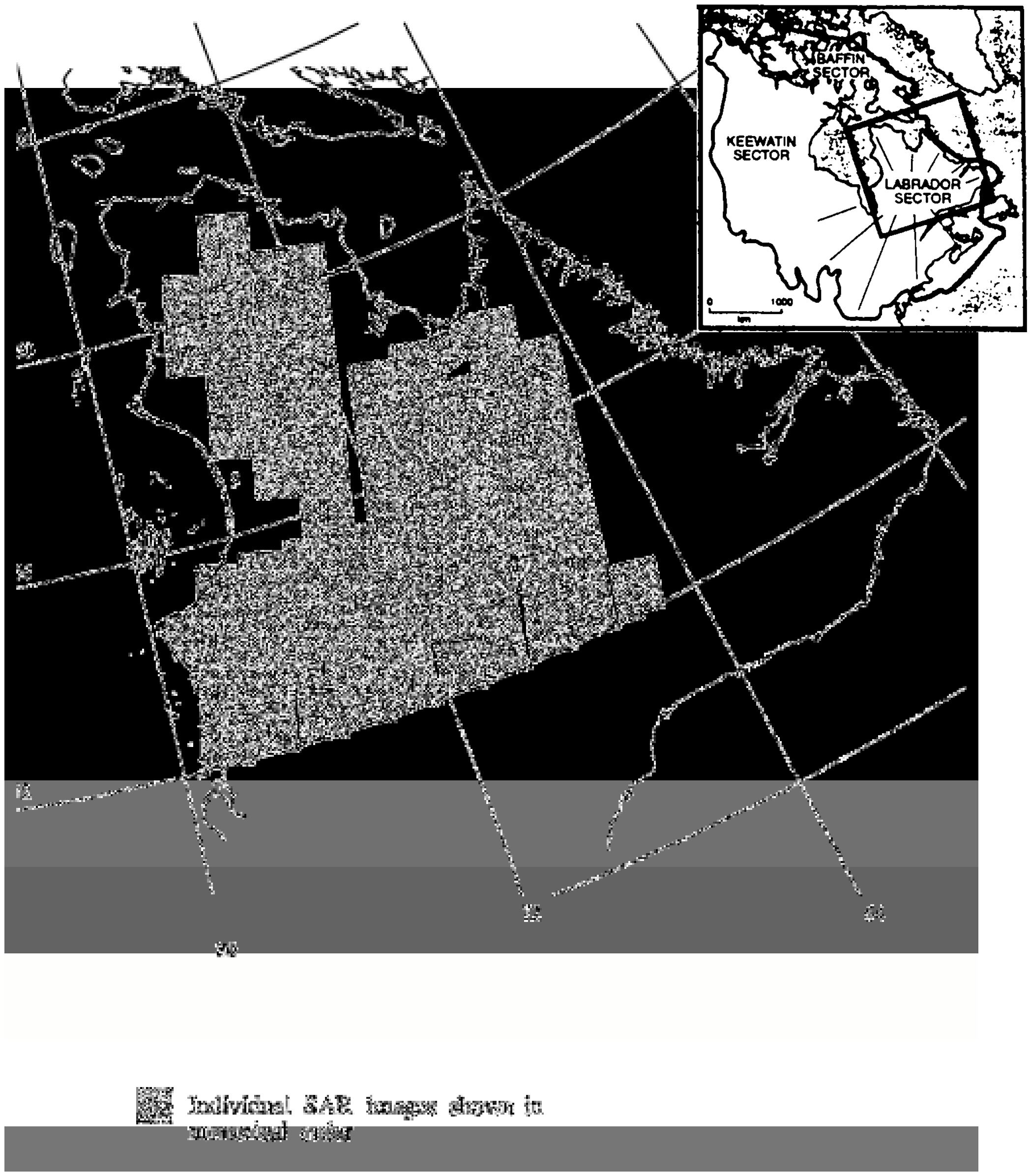


Figure 3.10 Coverage of ERS-1 SAR imagery used to map lineaments for the Labrador sector of the Laurentide ice sheet (after Knight, 1996)

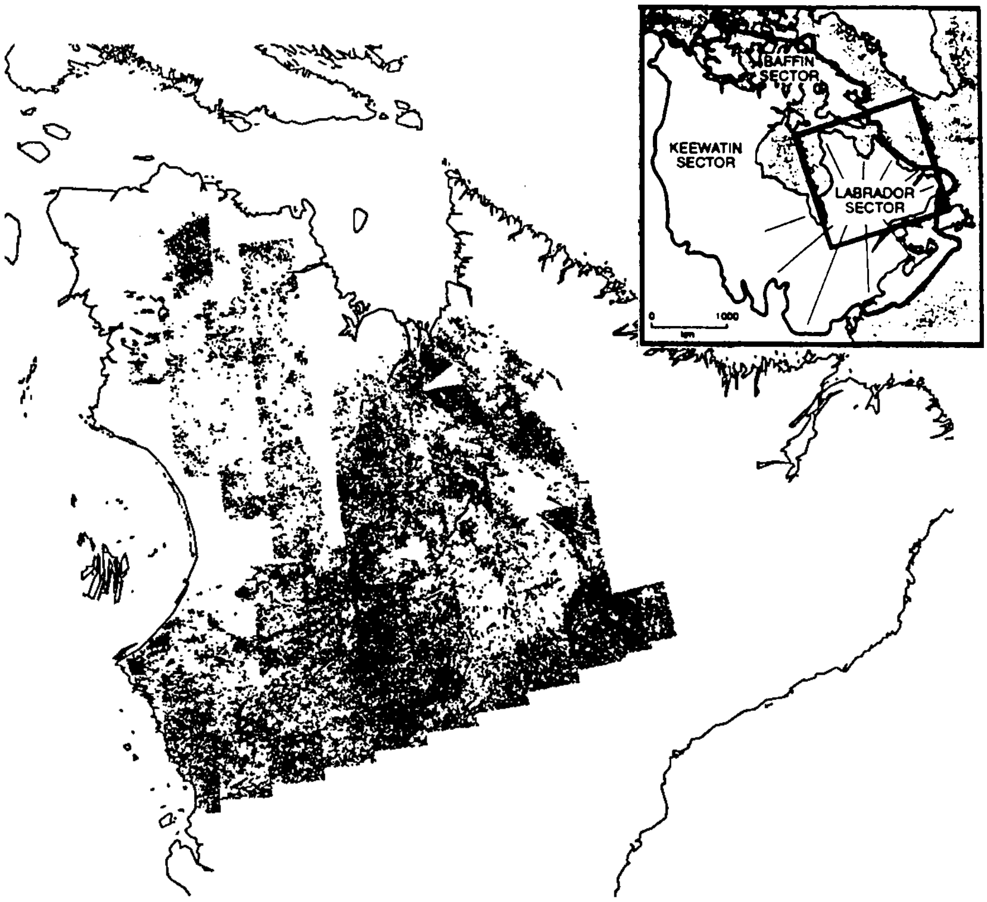


Figure 3.11 Lineaments mapped from the Labrador sector of the Laurentide ice sheet (after Knight, 1996)

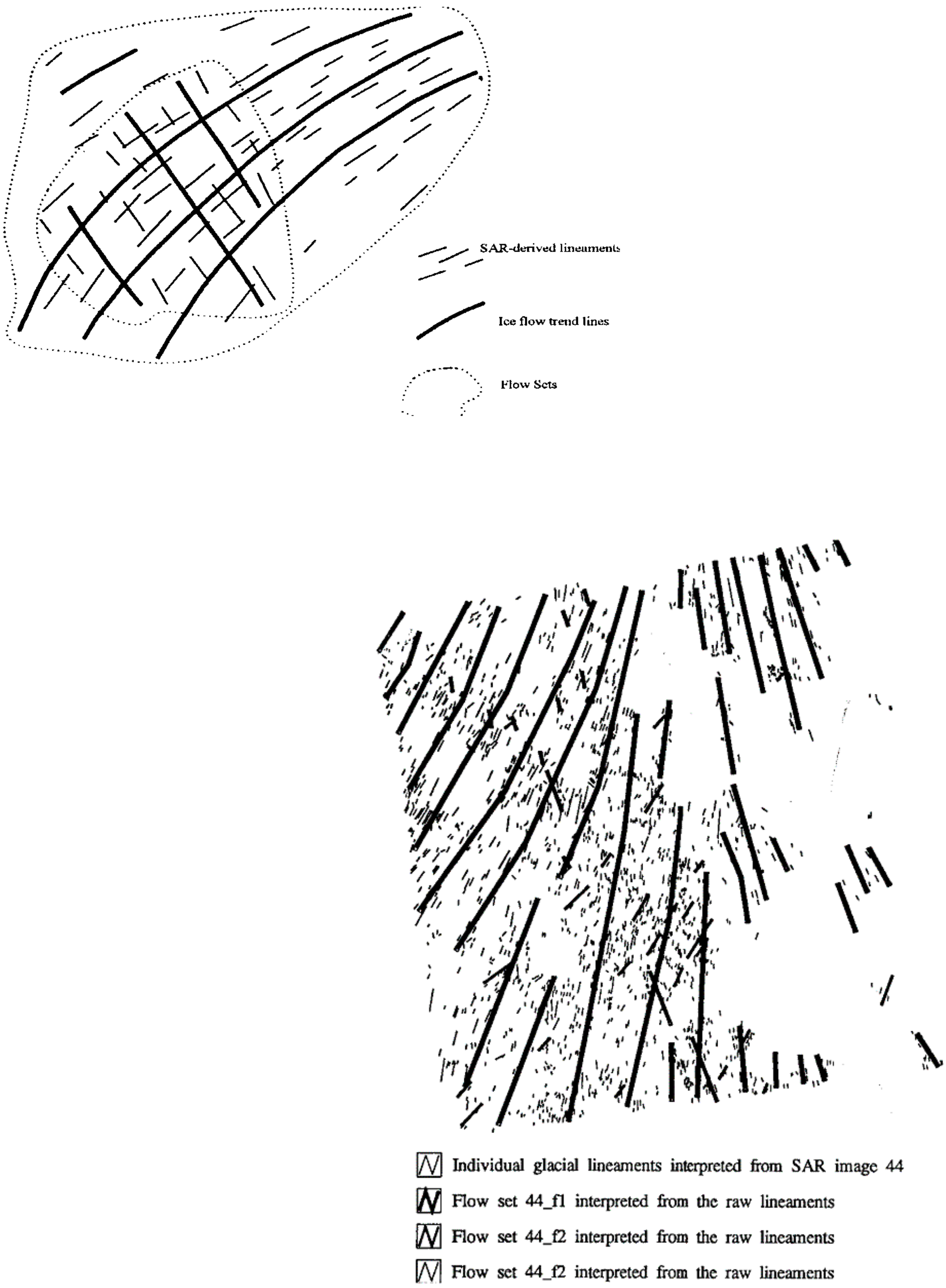


Figure 3.12 Idealised ice flow line creation from raw lineament data (top) and an example of flow lines created from lineaments mapped from one SAR image (Knight, 1996)

flow line sets into adjacent images in an attempt to distinguish discrete palaeo-ice flow events over large areas. The criteria used to establish both ice flow trend lines and flow sets required lineaments to be similarly oriented or with smooth, gradual, continuous change in orientation and no cross-cutting. Knight states that all residual ice flow lines that could not be included in flow sets were disregarded, however their proportion of total lineaments is not recorded. Drift cover and structural geology maps were compared to flow sets to filter out non-glacial data. The glacial reconstruction used lineament (primary data), ribbed moraine and esker (from Prest *et al*, 1968) data.

In her glacial reconstruction. Knight had three main assumptions:
1. Lineaments form synchronously or time transgressively, by subglacial deformation, parallel to ice flow.
2. Eskers form time transgressively recording ice margin retreat.
3. Ribbed moraine form synchronously in ice divide locations.

Knight then assigned flow sets as either synchronous or time transgressive based upon morphological criteria:
1. Synchronous - high parallel alignment and conformity.
2. Time Transgressive - less coherent lineament pattern, with localised cross-cutting, and often a strong alignment with eskers.

Relative ages were then assigned by looking at individual landforms within a flow set and extrapolating their cross-cutting relationships to that of the flow set. Although Knight was able to use SAR, she found aerial photography, fieldwork and published data more reliable. It would have been useful to break down the total number of relative age data points, by category, per flow set and so provide a quality assessment on relative age assignments.

Clark and Meehan (2001) go on to reconstruct different phases of the Irish Ice Sheet using a mixture of satellite imagery and DEMs (see also §2.4). Landform mapping was performed from a high resolution DEM, that was further supplemented by satellite imagery and field mapping. Using the methods of

Clark (1997) they went on to create flow sets from the mapped lineaments and ribbed moraine, before producing a reconstruction.

Discussion

Like the work of Punkari, Boulton and Clark (1990) made use of Landsat MSS photomosaics: they accepted that individual lineaments were usually not visible, but were able to make use of lineament “grains”. Consequently aerial photography was used to determine cross-cutting relationships. Although the photomosaics were a mixture of MSS imagery from different seasons and years, they did not discuss the potential for low solar elevation to aid detecting glacial lineaments. Boulton and Clark made significant methodological advances, recognising the preservation of glacial landforms in the landscape and using this evidence to build a chronology of events. They also discussed the effect that assumptions about landform development have on the interpreted sequence of events. By providing the original data, the known chronology and the assumptions used in their interpretation, the work was open to scrutiny and re-interpretation by other researchers. Their work was also able to take advantage of the large Canadian aerial photography archives in order to verify cross-cutting relationships.

Knight (1996) and Clark *et al* (2000) were the first researchers to make use of SAR data for lineament mapping, whilst Clark and Knight (1994) assessed the utility of SAR for lineament mapping and Vencatasawmy (1998) developed SAR image processing techniques for geomorphological mapping. Knight explicitly states the techniques employed in the research, making full use of aerial photos, fieldwork, ascending/descending SAR scenes and image re-interpretation in order to minimise bias and increase accuracy, however no assessment of the accuracy was performed. The methods of generalisation to provide the final dataset for interpretation are also discussed.

Finally, Clark and Meehan (2001) are one of the first users of high resolution DEM data for mapping glacial landforms and interpreting that data to produce a glacial reconstruction. In addition, they supplement this data with a Landsat TM purposefully acquired to have low solar elevation in order to enhance topographic features. They also briefly discuss (and highlight) some of the processing required of the DEM data in order to avoid mapping landforms from a biased dataset.

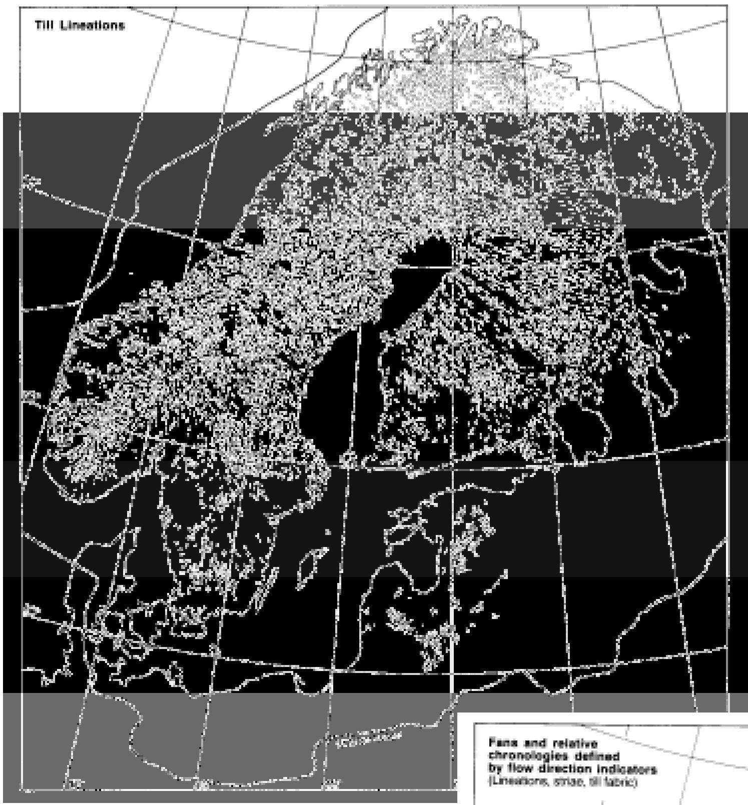
3.5 Hättestrand (1997) and Kleman *et al* (1997)

Hättestrand (1997) made use of 1:150,000 panchromatic aerial photographic coverage of central and northern Sweden to map glacial landforms. The small scale, high altitude photography made the project similar to mapping carried out from satellite imagery. These included ribbed moraine, De Geer moraine, end and lateral moraines, Veicki moraine, eskers, meltwater channels and lineations. The aerial photography coverage was 35km by 35km (although less for stereopairs) with a nominal spatial resolution of 5m. The author was able to make good use of the stereoscopic viewing and high resolution, however the small areal coverage per stereopair meant that many photos were required in order to map large areas. A mirror stereoscope was used for mapping and, although not providing the accuracy of an analytical plotter, was adequate for the requirements of geomorphological mapping, particularly in low lying areas where the effect of relief displacement is minimal.

The above work formed part of a wider research project that culminated in the reconstruction of the Fennoscandian ice sheet (Kleman, *et al*; 1997). In addition to the above mapping, they also utilised stereoscopic satellite prints of the Kola peninsula and incorporated much published literature, including the mapping performed by Punkari for Finland and Russia. Once the data had been mapped, cross-cutting relationships were established (Figure 3.13). This was achieved through reference to published striae and till fabric data, as well as their own observations of cross-cutting landforms.

<u>Discussion</u>

The methodology used in this research is clearly defined with an explicit set of assumptions, following Kleman *et al* (1996). However there were many details concerning the precise techniques used that were not discussed. As noted above, the method of generalisation is vital to the delineation of flow sets (or



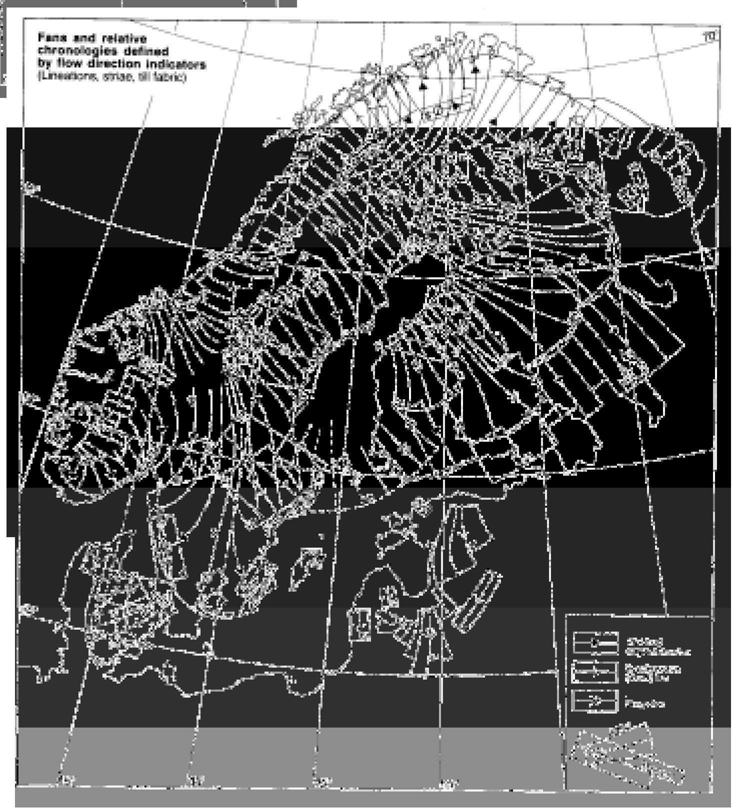


Figure 3.13 Summary lineaments mapped from aerial photography and collated from various sources (top) and their corresponding flow sets (bottom) from Kleman *at al* (1997).

fans), yet it was not clear what methods were used. The construction of relative chronologies was also problematic as there was little information on how this was performed from the fan data. Intriguingly Kleman *et al* (1997) discuss only 29 of the stated 56 fans. Relative chronologies were assigned according to individual landform evidence, relying heavily on striae data. In areas of low relief with few flow directions, correlating cross-cutting striae with other palaeo-flow indicators is acceptable, however in areas of high relief and many flow directions this is not satisfactory. Some relative chronologies were assigned purely on the basis of till fabric data. These can only be used reliably if one till sheet overlies another (e.g. Hill and Prior, 1968). Clast orientation is not strongly correlated to ice flow direction (Syverson, 1994) and may be misleading if there have been multiple ice flow events. Strong glaciotectonism may also alter clast orientation.

As part of Hättestrand's work, Goodwillie (1995) mapped and interpreted lineaments in the Kiruna region of northern Sweden. This work gave a fuller account of the procedures used in their reconstruction. Part of this work involved the division of the study area into 50km grid squares and the production of a lineament orientation histogram per square. These were used to identify dominant lineament orientations. This technique was used by Boulton and Clark (1990) and Punkari (1995). Clark (pers. comm, 1997) discarded its use as it simply identified visually dominant lineament orientations.

3.6 Knight and McCabe (1997a, 1997b) and McCabe *et al* (1998)

Knight and McCabe (1997a) utilised satellite imagery (Landsat MSS 1:250,000 paper prints) to map lineaments in Donegal Bay, Ireland, presenting a generalised diagram (Figure 3.14). They were concerned with the relationship between individual lineament morphology and sedimentology in order to infer the depositional environment. They recognised the presence of cross-cutting lineaments and that lineament morphology is composed of a continuum of forms that vary according sediment supply and depositional environment. The authors therefore use the concept of a relative chronology and that this requires a mechanism for lineament preservation.

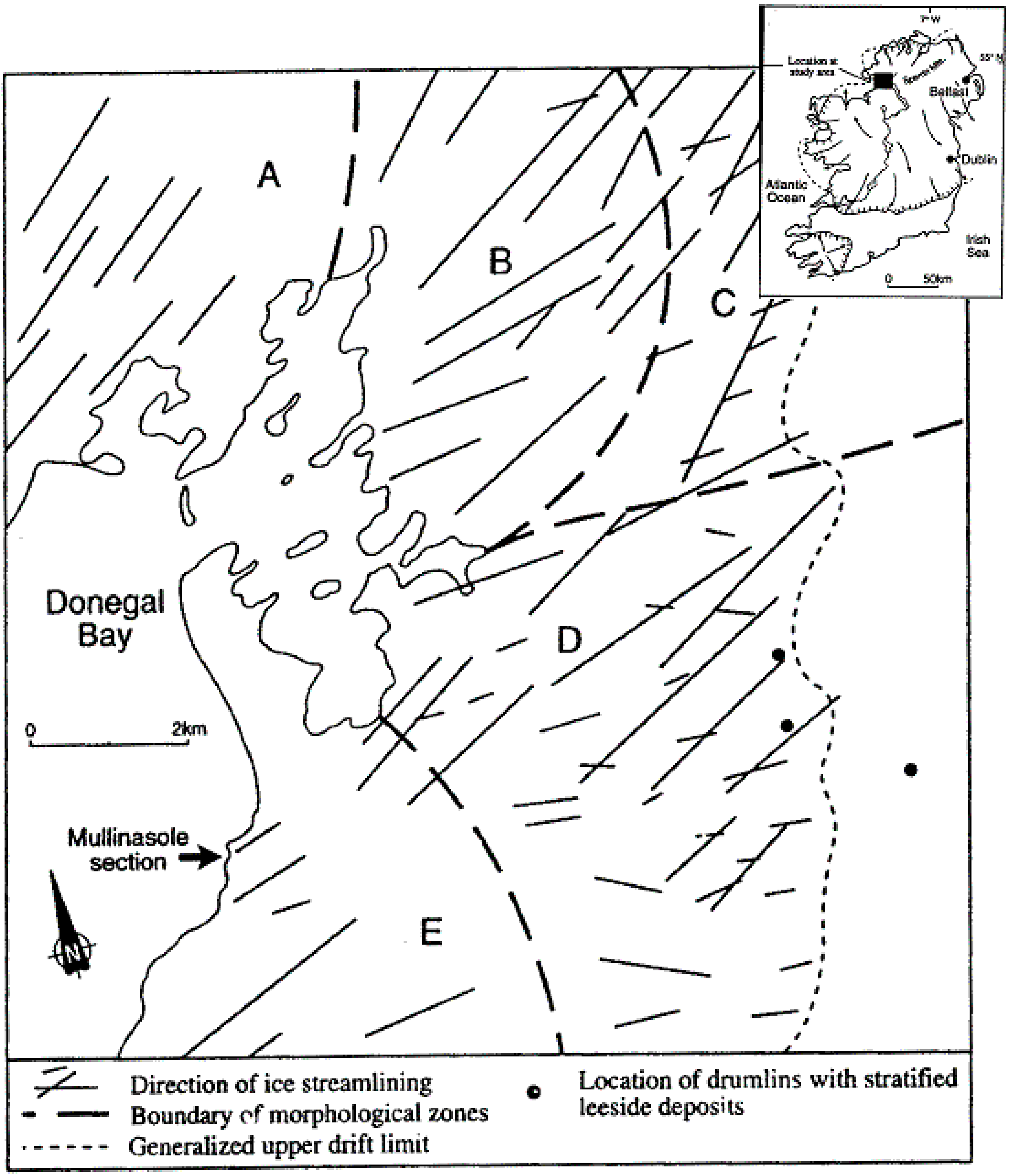


Figure 3.14 Generalised lineaments mapped from Landsat TM satellite imagery (Knight *et al*, 1997).

Knight and McCabe (1997b) extended the above mapping into the Irish Midlands, using a Landsat TM 1:250,000 paper print to map glacial landforms. Image mapping was used to complement detailed field surveying, although they were for two separate field areas. For illustration they presented satellite mapped data (ribbed moraine) of their field area and a sample image of a different area.

McCabe *et al* (1998) used Landsat TM paper prints to map glacial bedforms in north-central Ireland, this is supplemented by an unspecified use of aerial photography and field work. Their reconstruction uses mapped data and published evidence, to describe four distinct ice flow stages, however they do not use the methodological techniques (e.g. flow set creation) developed by Clark (1993) and Kleman *et al* (1996). The lack of a rigorous methodological basis from which landform data can be interpreted to flow sets does not provide a solid morphological base from which to interpret their data. They also fail to discuss the distinction between time transgressive and synchronous flow sets; for example they describe a pattern of curving flow as indicative of ice streaming, however this flow pattern can be explained by either flow set type, each providing a different glacial scenario.

Initially they interpret landform data purely as directional indicators, however they assume that ice sheet marginal bedforms are indicators of fast ice flow and consequently representative of net-erosional processes. This is used to develop the idea of transverse ridge erosion followed by streamlining. They go on to suggest that ribbed moraine cross-cut by lineaments are representative of a change in basal thermal regime, the former explained by Lundqvist's (1989) theory of ribbed moraine formation, and the latter evidenced by coastal moraines representative of the high erosional processes.

Discussion

It is disappointing that the papers of Knight and McCabe do not follow the methodological techniques of Boulton and Clark (1990) and Clark (1993, 1994) for their glacial reconstructions. No assumptions are outlined and the conclusions are based around discussion points, rather than providing an objective review of the evidence and the production of alternative interpretations.

3.7 TheoreticalandTechnicalMethodologicalDevelopment

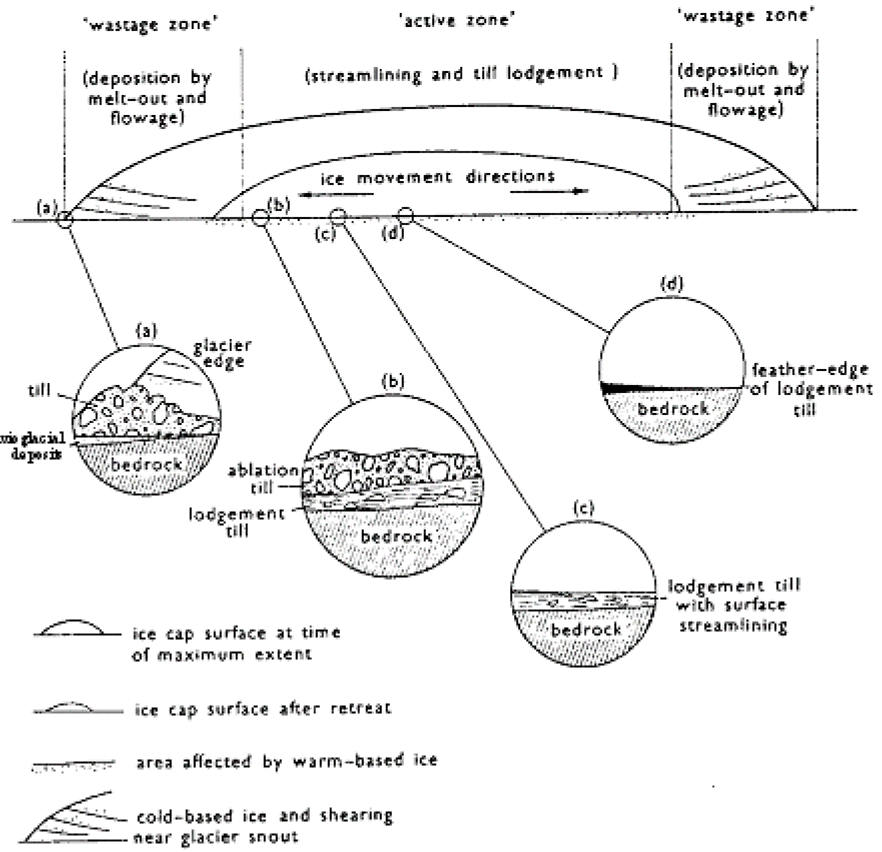
The traditional method of reconstructing palaeo-glacial environments involves the up-scaling of processes that form individual landforms, within a study area, to that of the ice sheet. This approach usually involves *a priori* assumptions concerning landform processes, as well as their scalability. In addition, it assumes that all landforms within the study area were created similarly and that this can be extrapolated to other regions. The weaknesses introduced by the above assumptions become more apparent at smaller and smaller scales and consequently the methodology has evolved into an approach that uses appropriately scaled techniques to reconstruct former ice sheets. These techniques are based around two main approaches, or models, to geomorphology. The first, termed the ***landsystems model*** is defined by Benn and Evans (1998) as an:

> *holistic approach to terrain evaluation, wherein the geomorphology and subsurface materials that characterise a landscape are genetically related to the processes involved in their development.*

This is distinct from the ***process-form model*** where spatial variation in morphology are used to infer changes in process. The palimpsest landscapes investigated by the glaciologist will display morphological variations that are a result of both *landsystems* and *process-form* changes and an understanding of these models and their implications will allow a more complete study of past glacial environments.

Sugden and John (1976) used the process-form model to investigate ice sheet reconstructions within the context of the Laurentide ice sheet. They idealised an ice cap in cross-section (Figure 3.15a) with two broad zones; a *wastage zone* towards the ice cap margins where sediments are deposited and an *active zone* where faster flowing ice both erodes and deposits, shaping the landscape. The wastage zone identifies moraine, dumping and melt-out landforms. The active zone is dominated by deposition towards its margins, with erosion towards the ice cap centre. They briefly discussed the effect of multiple glaciations on the landscape, but concentrated on sedimentary sequences rather than morphology. It is natural to develop associations between different processes and changes in landform morphology. Indeed, given a morphological association in their genesis, this link can feed back into an understanding of the processes that formed them. Sugden and John (1976) concluded with a generalised model of drift landscapes that moves from erosion, to active, to wastage zones, with transition areas between, and the landforms associated with those zones (Figure 3.15b).

The advent of satellite imagery allowed the expansion of landform mapping to larger areas and so closer scrutiny of landform associations. It was not until Boulton and Clark (1990), Clark (1993) and Clark (1994) that an attempt at an objective methodology was explicitly implemented. This incorporated assumptions about landform formation, the discovery and use of a relative chronology from cross-cutting landforms, a discussion of “grain” features and the discovery of mega-scale glacial lineations. Perhaps most importantly the glaciological implications of cross-cutting lineations were explored. This included the method of cross-cutting (superimposition or remoulding) and how this related to ice velocity, residence time and sediment supply. Clark (1993) envisaged a continuum from a lineament with no modification, through superimposition and minor remoulding to complete realignment (Figure 2.4). The degree of modification is reliant upon a combination of ice velocity and time of exposure in relation to sediment availability. Within an ice sheet, velocity is very low at the divide, with no supply of sediment. Towards the margins velocities increase and so the potential for strong deformation is high. Using lineament correlation over large areas and relative and absolute dating, Boulton and Clark (1990) considered the majority of cross-cutting landforms in the Laurentide Ice Sheet could only occur if the ice divide had shifted. This assumes all lineaments are from one glaciation, the alternative a result of multiple glaciations. This work provided evidence of dynamically shifting ice divides and how this is reflected in the landscape. This model assumes that lineaments are formed synchronously, however many cross-cutting lineaments in marginal areas would require a complex series of re-advances in order to



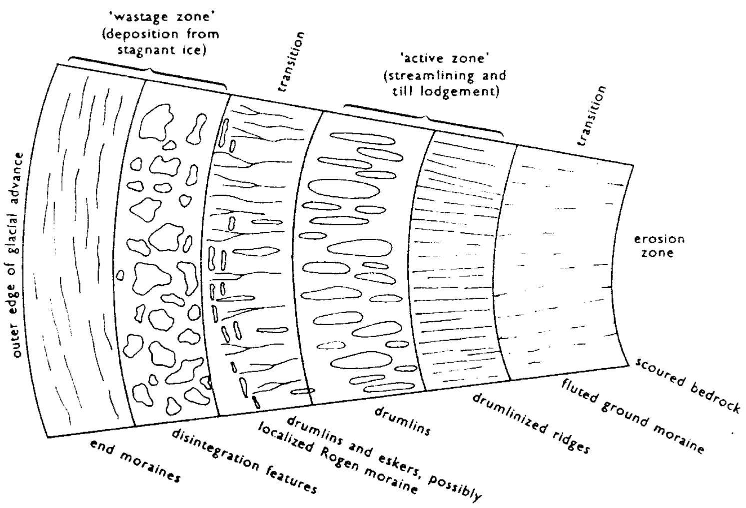


Figure 3.15 a. Generalised model of drift landscapes (Sugden and John, 1976). There is erosion in subcentral parts of the ice sheet (the “active” zone) that changes to deposition in submarginal regions (the “wastage” zone) b. Landforms associated with these zones.

explain such patterns. Clark (1997) suggests that the “on-off” activation of ice streams may produce cross-cuts (Figure 2.6). He also provides a detailed discussion of the type of imagery suitable for lineament mapping and the image processing techniques that are available.

Clark (1999) focuses more specifically on the interpretation of mapped lineament data by asking the following questions:

- *What were the processes of generation?*
- *What was the glaciodynamic context?*

Investigations into landform generation have been numerous, but are inhibited by problems in directly studying these processes. At the lowest level, glacial landforms provide information on palaeo-ice flow direction. Any further inferences are based directly upon theoretical assumptions.

Understanding of the *context of generation* has received little attention. Although both inquiries are linked, geometric and contextual landform data can be used to provide a great deal of information on the location of formation.

Whereas flow patterns are simply the large scale grouping of landforms (in this instance lineaments), flow sets operate over much larger areas where there are often several different interpretations available to the researcher (§2.3.6). These interpretations are strongly influenced by the assessment of lineament formation as isochronous or time-transgressive (§2.3.4). Clark goes onto develop seven glacial contexts where lineaments may be formed, primarily classified as time-transgressive or isochronous (Figure 3.16). The application of a context within specific situations is intended to provide a further tool for understanding the dynamics of previous ice sheets.

This discussion highlights the necessity to distinguish between time-transgressive and isochronous lineament patterns. Clark considers ice thickness, flow topology and stability to be the main controlling variables, visualised in the following manner:

- **Time-transgressive -** formed close behind retreating ice margin and consequently unstable conditions, thin ice and variable flow conditions.
- **Isochronous -** formed some distance from the ice margin and consequently beneath thicker ice, with a more stable flow pattern.

Clark goes on to list distinguishing parameters for each type of configuration. Isochronous flow events will display lineaments with similar orientation and morphometry, whereas time-transgressive events will produce a less well ordered pattern, perhaps with obvious discontinuities. A special case of this latter event is that produced at a retreating ice margin. This produces a distinctive pattern of splayed lobes that accrue as the margin retreats. The low profile of the ice produces landforms that are partially controlled by topography. These factors produce a complex record of cross-cutting lineaments, broadly emplaced within splayed lobes.

Although these criteria are a good starting point, visually identifying such flow sets and separating them from isochronous ones is difficult. The assignment of flow set type is a procedure concurrent with the creation of those flow sets and as such this tandem process is somewhat iterative as it attempts to account for as many flow sets as possible within a single scenario.

Building on the methodology outlined above, Kleman *et al* (1996) further developed glacial reconstruction methodology, following techniques originally developed for striae data (Kleman, 1990) and investigations into the morphological record of landforms and methods of preservation (Kleman, 1994). The space-time cube (Figure 3.17) depicts the present day suite of glacial landforms (the top surface of the cube). Each “layer” within the cube represents the state of the surface during earlier periods. The area covered by ice constantly changes, as does the type, number and magnitude of landforms “recorded” on the surface. Relict landforms will also be present, but can be combined with contemporary landforms forming composite ones or entirely removed.

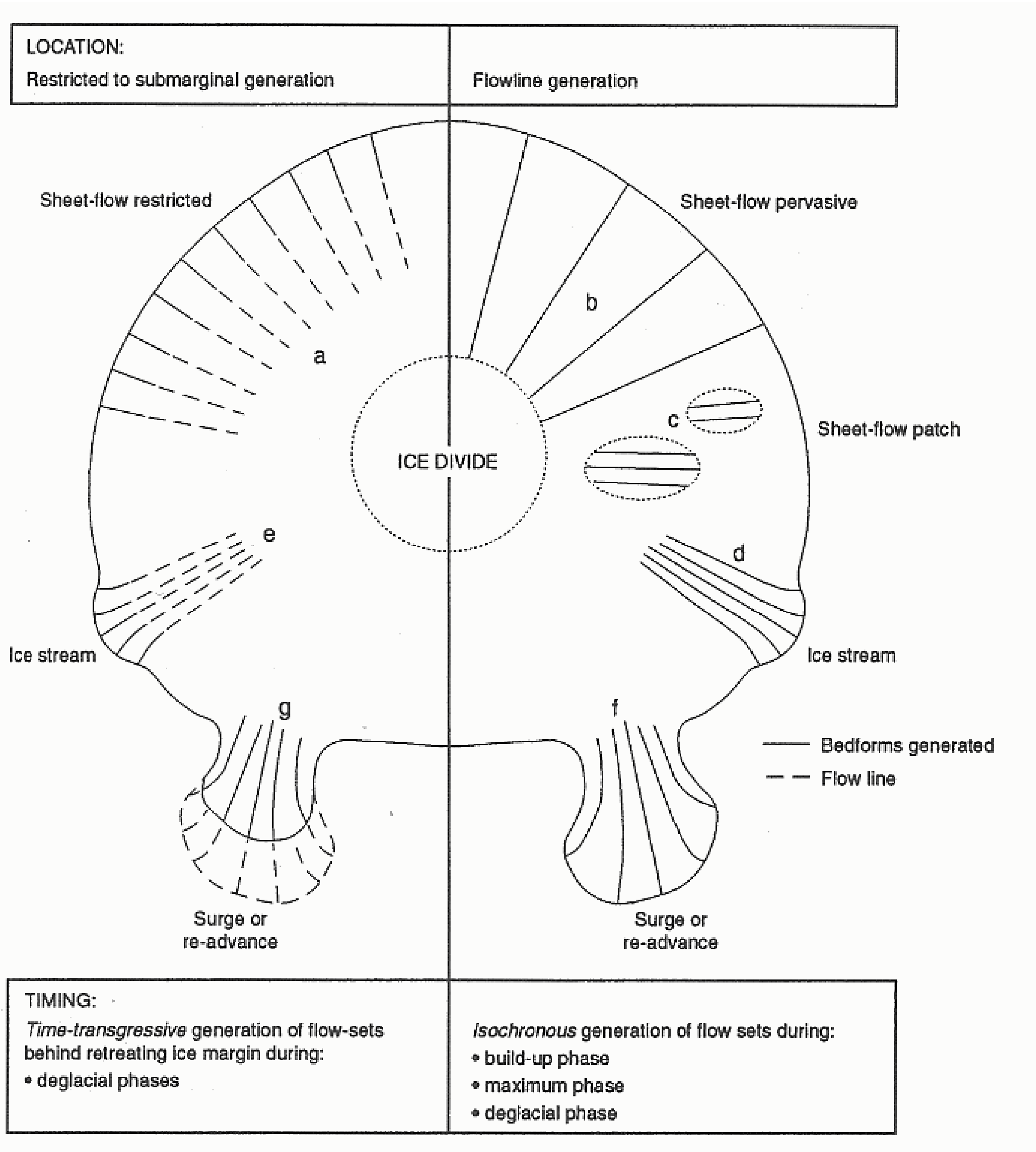


Figure 3.16 a. Different glaciodynamic contexts under which lineaments can be generated (Clark, 1999). These can be grouped under generation *isochronously* or *time-transgressively*.

Ice sheet reconstructions were originally based upon interpreting all landform data (the top surface) as representative of conditions at the last glacial maximum (LGM). However the challenge now is to unravel the history of a region by interpreting landform suites into individual landforms and the events that formed them. This can be further aided by the use of dating methods to constrain both the extent of glaciation through time and individual events.

After the grouping of landforms into flow events, the associations between landforms within these events and whether they are synchronous or time-transgressive, allows their classification into one of five categories (Figure 3.18). Although this methodology aims to provide an overall theoretical and techniques based framework for further work, Kleman *et al* (1997) state that it is less suitable for areas with mountainous terrain. This is because one of the assumptions for the conglomeration of features into fans is their spatial continuity, which cannot be maintained in high relief areas, a point noted by Punkari (1985). However this element can be incorporated through the use of relief (i.e. a DEM) to help assess spatial continuity, a task suited to a GIS. This example highlights the problems involved in the methodology.

Benn and Evans (1998) prefer a landsystems approach (Eyles, 1985) to reconstruction, suggesting that bed strength and hydraulic conductivity, basal thermal regime, meltwater availability, ice velocity, shear stress and effective overburden pressure influence the formation of subglacial sediments and landforms. This complex interaction produces the palimpsest terrain viewed today, which typically produces distinct landform zonation, although this can later be modified by further advances and retreats of the ice margin. An integrated, small scale, methodology remains to be developed, that can combine the landform mapping from satellite imagery with detailed sediment logging.

3.8 Conclusions

Remotely sensed images have been used within palaeo-glaciology for nearly 25 years and during this time remarkable changes in their use have been made. These developments have been made in tandem with technological ones

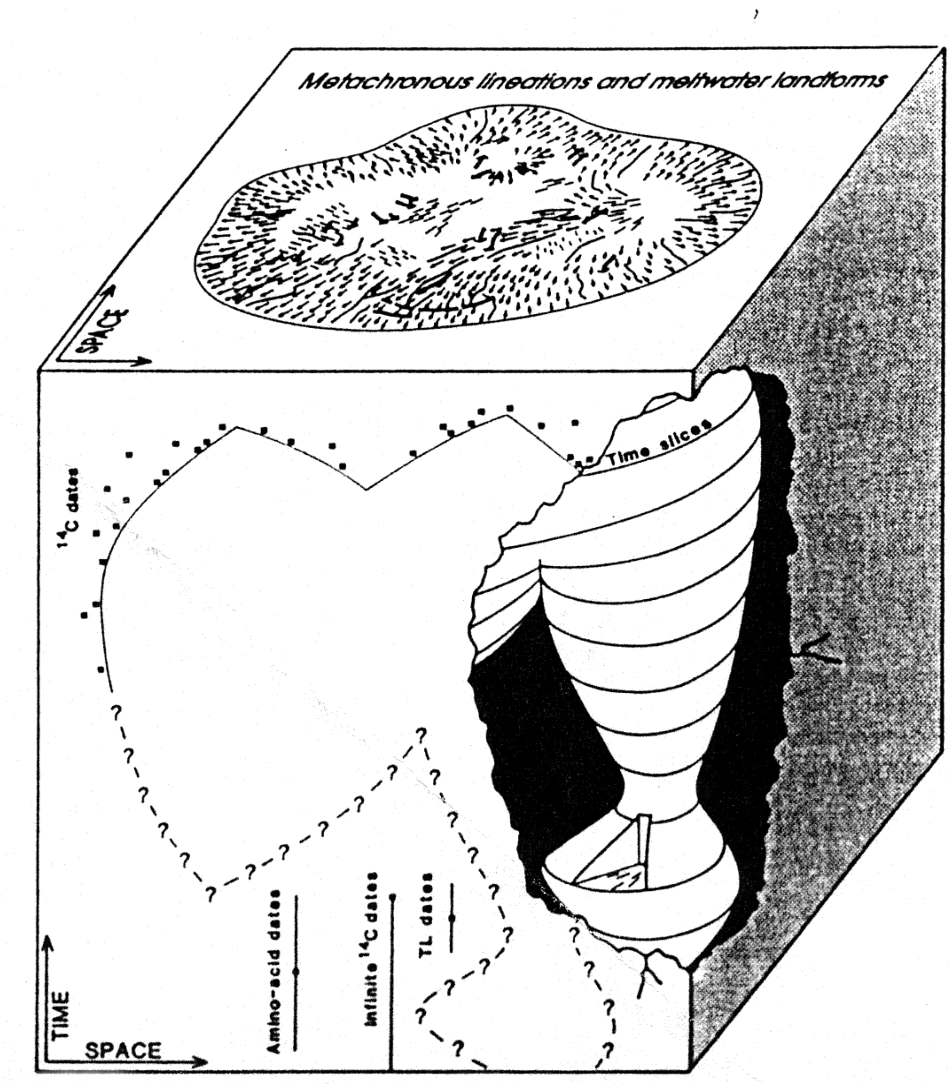


Figure 3.17 Space-Time cube showing an idealised, contemporary, geomorphological surface (top of cube) and the inferred ice sheet behaviour required to have generated this (Kleman *et al*, 1996).

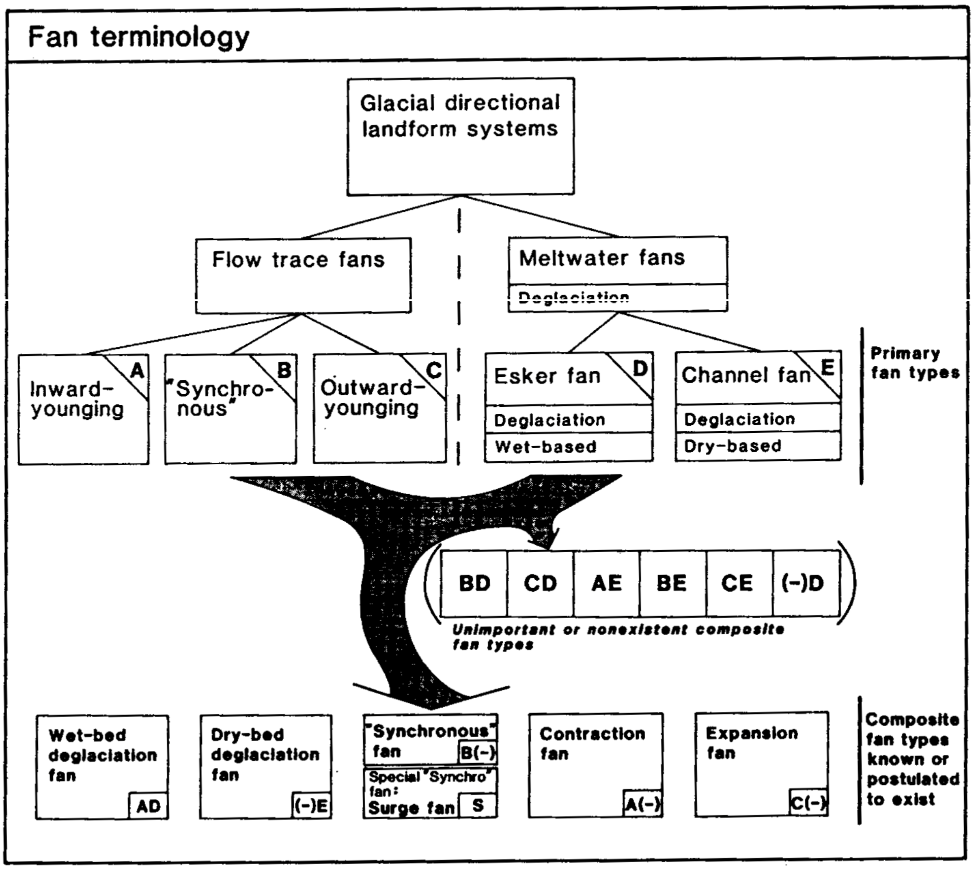


Figure 3.18 Table showing postulated fans that can logically exist (top) and those that are known or postulated to exist (bottom) (both diagrams after Kleman *et al*, 1996).

deriving from the launch of new satellites. More detailed data are being collected, allowing the morphological mapping of glacial landforms, over large areas, at relatively economic costs. Until the advent of such technology, the mapping of landforms across an area previously covered by an ice sheet, was almost unheard of due to the scale of project needed to complete such a task. Indeed this work unequivocally showed that the present day landform assemblages can record multiple ice flow events. This realisation has forced a complete re-evaluation of the way in which palimpsest data are interpreted. Unfortunately, these methodological developments require the *process* of landform generation to be understood, as well as its *context*. Given the difficulty in studying sub-glacial processes beneath present day ice sheets, these are purely hypothesised and will require on-going refinement.

This chapter has highlighted the importance of satellite imagery within ice sheet reconstruction research and traced the technological and methodological developments that have taken place. It has also emphasised the weaknesses and inconsistencies, within research, that need addressing. Unfortunately this is not confined to earlier research, but equally affects more recent work. It is important that any future research is able to acquire appropriate satellite imagery and map glacial landforms in a consistent and appropriate manner. These data then need to be generalised into a simpler information set that can be interpreted. The following chapter highlights areas of weakness within this current workflow and these are then addressed later in this thesis.