An Integrated Approach to Palaeoenvironmental Reconstruction Using GIS

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ABSTRACT

The last interglacial/glacial cycle is the key period for understanding the nature of long-term environmental change, and the complex interplay between the atmosphere, oceans, glaciers, the lithosphere and vegetation. It is the cycle for which most information is available, and the only one for which there is any hope of reconstructing a detailed history. Major obstacles to utilising the available data are the volume of complex, disparately located information, the difficulty of relating earlier observations to new models, and the increasingly global nature of investigations. There is a fundamental and pressing need for a way of optimising the co-ordination of research, and the organisation and analysis of data. Information Technology (IT) in general, and Geographical Information Systems (GIS) Science, in particular, offer a powerful means by which this can be achieved.

Despite recent advances in palaeoenvironmental research methodologies, significant improvements may be realised through better data management and a more rigorous approach to spatial data analysis. Geographic Information Science research offers methods and techniques for handling large volumes of complex, multi-source, spatial data which require an understanding of spatial theory and scientific organisational structures. Research in this area combines computer science, social science, geography, geodesy, cartography and cognitive psychology to address these issues.

Analyses of the data and methodologies employed in palaeoenvironmental reconstruction reveal particular areas where GIS might increase scientific understanding. Glacial geomorphological and sea level data sets provide very different palaeoenvironmental reconstruction challenges through which the issues of current practices, and the benefits of GIS techniques, can be explored. GIS data analysis and management methods considerably improved the potential for using this data in reconstruction of the NW European palaeoenvironment during the last glacial cycle. A spatial framework was developed, which facilitated data integration and quantitative analysis for regional datasets. The accuracy and speed with which this was achieved using GIS has hitherto been impossible using manual methods. However, several issues have emerged which highlight the limitations inherent in current palaeoenvironmental practices, and the shortfalls in GIS knowledge and technological development. This suggests that a change in the current research paradigm is needed.

An object oriented approach to palaeoenvironmental reconstruction addressed limitations imposed by the current research paradigm and has been developed into the PaleoEnvironmental Reconstruction and Information System (PERIS) model. Changes in research practices are required to improve palaeoenvironmental research methods. These changes would support the PERIS model and are discussed in terms of a palaeoenvironmental infrastructural research strategy.

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Wachowicz, M. and Broadgate, M.L., 1993. A significant Challenge: Prediction of environmental changes using a temporal GIS. *Proceedings AGI 93.*

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* Maps in back pocket of binding

Chapter 1 Introduction

1.1 Palaeoenvironments and global change

In the current climate of unease about the future of the earth system and the impact of humans on global change, it has become imperative to find out more about the mechanisms of change and to understand which parameters play key roles. It is necessary to know the magnitudes, spatial patterns and rates of change, and to address the question of climatic evolution at different temporal and spatial scales. Importantly, the current changes being monitored in the earth's climate must be elucidated in relation to the overall pattern of climate change over a long time-scale. The question is whether current changes are part of a broader pattern of natural cycles, or if human impact is perturbing the long-term cycles to a degree which is of concern. Historical instrumental records provide only a narrow sample of possible changes. It is therefore important to know how these climatic variations compare with the major climate changes in the geological record (Crowley, 1989). Knowledge of past environmental evolution can also be used to understand the processes of long-term climatic change.

Information is required for policy making and planning. Understanding earth and climatic processes is a prerequisite for informed management of the environment (Lillesand, 1993). Pressing problems include how far green house gas emissions must be curbed to limit their impact on climate, and the capacity of oceanic and terrestrial systems to accommodate the dumping of hazardous waste. The safety of nuclear waste disposal, for example, has implications for future generations, because of the timescale of nuclear waste activity. There is concern over the impact of future glaciations on proposed underground repositories through glacial erosion and meltwater subrosion (Boulton & Payne, 1992a). Therefore studies of past climate have taken on a new importance in helping to address these issues.

The last interglacial/glacial cycle holds the best opportunity for uncovering the large-scale, long-term mechanisms of climatic change (Mangerud, 1991a, 1991b). It is the geological period for which the most detailed climatic records exist, making it possible to reconstruct significant environmental changes such as sea level and vegetation variations, and the waxing and waning of large continental ice masses. Thus the role of palaeoenvironmental science is crucial in global change research.

1.2 Global science and the information explosion

Unless there is a free sharing of information "it will be an impossible millstone around the neck of tomorrow's organisation" (Peters, 1987). The desire to share spatial and environmental information is stronger than ever within organisations with shared interests in common geographical areas (Nyerges, 1989a). As global science expands, the numbers of people involved in large collaborative projects increase. Locating, storing, retrieving and communicating data is a growing problem. There has been a profusion of data and an increase both in the number and diversity of disciplines contributing to this area, and in the geographical locations in which information is being recorded, held and utilised. There is a perceived need for geographical analysis and spatial data on a global scale (Tomlinson, 1988). A large number of publications cover the wide range of subject areas relevant to palaeoenvironmental studies, continually presenting new data and evolving theories. The volume of data being produced is very large. Satellite data, for example, is currently being generated at almost unmanageable levels (Ehrlich *et al.*, 1994). There is a growing need for data-on-demand to cover large areas, for a variety of purposes. Data must be shared and transferred between practitioners and the results of studies communicated to funding bodies, policy makers and governments. The ability of Information Technology (IT) to help manage this information and increase the speed and accuracy with which it can be processed and communicated, appears to best address these requirements.

In the field of palaeoenvironmental studies the last fifteen years have witnessed major advances in the investigation of palaeoenvironmental change (Crowley & North, 1991). New methods have created multiple sources of new data and, importantly, computer modelling techniques are now being applied to make sense of these large quantities of data (Eddy & Oeschger, 1991). There are significant benefits to be gained by improving the network of collaboration, and the handling of large volumes of data using computers. An efficient computer network system would reduce the time and resources involved, for example, in repetitive data review exercises. Data reviews are usually undertaken with limited resources and varying degrees of success. They rely mostly on literature sources where information can be obscured, misunderstood and inadequately documented. Structured data held on a computer system would allow immediate access to information required by individual groups at the beginning of most projects which could be formatted according to their needs. Not only would time be saved in this respect, but the value of individual project results would be greater through being inititiated from a better knowledge basis.

They would also contribute directly to the pool of knowledge through the information system. Finally, having all the information in digital form facilitates easily producible, clear, high quality presentation of results. Communication between groups within a project is faster and more efficient. Using computers to manage the data as well as the analysis is therefore of enormous benefit.

Information technology combined with the global communication system fostered by the Internet, offer the possibility for an organised, strategic, global data and information system. This potential has been recognised by various international organisations, most notably the European Science Foundation and the US Government National Science Foundation. These organisations have initiated a number of projects which address the issues associated with large scientific databases and inter-institutional data sharing (e.g. US Global Change Research Program, 1993). Research is now being undertaken in the areas of multi-source, multi-purpose digital databases and the way in which earth observations are stored and integrated will determine the degree to which global spatial processes can be understood (Tomlinson, 1988).

1.3 Emergence of GIS

Increasing volumes of information, and the needs of businesses, governments and researchers for spatial data management and analysis capabilities, have resulted in the emergence of the field of Geographical Information Science (Goodchild, 1992). The 1960s and 1970s saw the development of computer mapping and database management. It was realised that there are special problems involved with digital spatial data handling (Tomlinson *et al.*, 1976) and many initial attempts to create systems for spatial data failed (Marble, 1990). However substantial computing and conceptual advances enabled further development during the 1980s, and a change in focus to robust analytical capabilities and the emergence of cartographic modelling (Tomlin, 1990). The 1990s have seen an extension of cartographic modelling to spatial modelling and the move from mapped data to spatial information (Steyaert, 1993). GIS have gained popularity in business and research as essential data management and analysis tools. They are fundamentally different from other types of information systems because they are specifically designed to handle the complexity of spatial relationships, which have many interdependencies (Evans, 1994).

GIS may be described in many ways. There are a number of definitions which depend on the perspective chosen. The most common definition combines a structural and procedural perspective:

> "A system of hardware and software, data and people, organizations, and institutions for collecting, storing, analyzing and disseminating information about areas of the earth", and, more recently, for integrated modelling of environmental processes (Dueker & Kjerne, 1989)

A functional perspective defines GIS in terms of the application-oriented operations it performs (Nyerges, 1991).

> GIS generally comprises several functional components:
> Data Management: input, update, storage and retrieval, browsing,...
> Data Manipulation: georeferencing, classification, aggregation, integration,...
> Analysis: network modelling, spatial and non-spatial statistics, overlay,...
> Display: present results, visualize information for exploratory analysis,...

GIS has also been described as a system for supporting geographically based decisions, or a Spatial Decision Support System (SDSS) (Cowen, 1988). Alternatively, Berry (1993) offers four descriptions which show the many levels at which GIS is perceived and how it has evolved:

i) a tool to create and update maps
ii) a technology for combining and interpreting maps
iii) a revolution in map structure, content and use
iv) spatial statistics and mathematics allowing users to model complex resources and environmental systems

Berry's descriptions (iii) and (iv) reveal how GIS requires users to view data in completely new ways. Geographical Information Systems (GIS) have the power to manage the large, complex, spatially referenced datasets associated with palaeoenvironmental reconstruction. They also enable these datasets to be integrated directly with environmental models to discover the mechanisms of environmental change. Geographical Information Science drives the development of Geographical Information Systems and sits at the interface between computer science, management science and geographical applications (Goodchild, 1992). Throughout the following chapters GIS will be used to denote both science and systems, but where it is important to distinguish between the two the acronym will be appropriately expanded.

1.4 Changes in scientific conduct

The demands driving science, the increasingly global nature of research activities, the technological revolution, and the changes instigated by GIS in the way data is being used, are revolutionising scientific conduct. GIS is a powerful tool with substantial benefits, but its use reveals the weaknesses in data (Goodchild, 1991) and the way data has been handled traditionally. For example, traditional statistical analysis often assumes an even distribution of information (mean annual temperatures for a region, changes in species populations etc.), whereas spatial analysis characterises the geographic distribution of variables (Berry, 1993) and therefore reveals spatial variability and spatial dependency. It also facilitates the move from mapped data to spatial information. This forces users to think more explicitly about data representation. The suitability of a representation depends on the use to which the data is being put. Hard spatial boundaries are suitable for some applications such as river networks and roads. However, probabilistic distributions are more suitable for other information such as soils data.

In addition the success of GIS is entirely dependent on the quality of the data which it holds (the provision of lineage and uncertainty measures, otherwise known as metadata), and the accessibility of this data to users. The present state of data that do exist, is that they "have limited metadata, and error in particular is not properly documented, [they] are incompatible in terms of temporal and spatial resolution, and have unsuitable archiving and retrieval formats" (Task Group 6, 1991). Lousma (1993) remarks that "we have fallen short in matching the vigour of data collection with the rigor of data management and integration". Many of these GIS issues are "old" issues, but GIS forces scientists to confront them explicitly. Research on these areas, to which the GIS community are currently contributing, will be of widespread benefit (Goodchild, 1991).

Stafford *et al.* (1994) envisage that the current expansion of data management within scientific organizations driven by the need for timely and effective transformation of data into information, will lead to the emergence of "scientific information management" as a discipline, with research and management as fundamental components. The move to scale up traditionally detailed studies to regional and global levels underlines the integration and management of large data sets as crucial.

The concepts of scale and variability become key factors as larger regions are investigated (Levin, 1992). This is a particular issue in palaeoenvironmental studies, for which only certain resolutions of phenomena will be identifiable because of the scarcity of data.

Projects establishing global databases will require the investment of large amounts of resources and will imply long-term commitments (Tomlinson, 1988). The problem is now, that the users' needs are not as well known to data producers as they were in the non-digital age (Hayes & Romig, 1977). This means that the information age demands higher standards to accommodate unforeseen requirements. GIS technology has the potential to provide the "glue" of common conceptual ground required to facilitate interdisciplinary Earth System science (Lillesand, 1993). The US Geological Survey is already going some way towards meeting the challenges of a multiscale geographic approach to global change and understanding earth processes within the United States Global Change Research Program (Kelmelis, 1993). It is important that the palaeoenvironmental research community prepare to follow this trend in order to exploit the opportunities fully. Bradley (1985) warns against the danger of limited interdisciplinary understanding and collaboration in the future. Significant advances in the future are likely to occur through multidisciplinary and interdisciplinary approaches to palaeoenvironmental reconstruction and by adopting a broad perspective and drawing on evidence from other regions (Lowe & Walker, 1984). Such approaches are best exemplified by the work of CLIMAP (1976).

1.5 Thesis Aims

The main aim of the thesis is to evaluate the potential of GIS for addressing the information analysis and management requirements of palaeoenvironmental research. More specifically the objectives are to:

- Examine the data, analytical methods and research organisation involved in palaeoenvironmental reconstruction

- Determine where GIS offers scope for enhanced capabilities in palaeoenvironmental data storage, manipulation and analysis of palaeoenvironmental data using two case studies (glacial geomorphology and sea level)

- Demonstrate areas where GIS offers new analytical possibilites unavailable to research using largely manual methods through the glacial geomorphology and sea level case studies.

- Examine the implications for palaeoenvironmental research of moving from manual methods, to fully digital processing, for palaeoenvironmental data in relation to the organisation of research collaboration within and between groups both nationally, and internationally.

- Propose an innovative conceptual approach, and framework, for future developments in palaeoenvironmental research, taking account of both scientific, and organisational, issues involved in the management, integration and analysis of multiple large space-time datasets.

1.6 Thesis Structure

Chapter 2 reviews palaeoenvironmental research methodology to identify where significant information handling and analysis improvements could be made. From this a series of generic scientific and organisational research requirements are established. The issues associated with GIS are then examined in Chapter 3 by considering the technological and conceptual aspects of using GIS by adopting a spatial approach to analysis, and a systems approach to informaiton management. These details define the planning and design criteria with which the GIS requirements can be addressed. Relevant developments in other disciplines are reviewed. These include geophysical databases, remote sensing data systems, and projects which are addressing the issues associated with large databases and scientific data sharing and provision.

The focus then narrows to two case studies in Chapters 4 and 5. These case studies concern reconstruction of the glacial environment in the area of North West Europe since the last glacial maximum using glacial geomorphological (Chapter 4) and sea level (Chapter 5) data. The datasets were selected because they are important palaeoenvironmental measures, which relate to the same palaeoenvironmental phenomena. They also comprise very different data characteristics and exhibit a range of analysis and processing requirements. The use of GIS to support palaeoenvironmental reconstruction was explored through these datasets. The objective was to store data relating to the last glaciation of North West Europe so that it can be used in a flexible way, be readily displayed in a variety of formats and provides a framework within which a comparison with suitable models can be made. In carrying out this task the many benefits of GIS are realised. The system provides quantitative spatial analysis of data in contrast to previously qualitative manipulations. It also offers a degree of speed and flexibility not previously attainable. However, as well as the advantages, it also illustrates a number of issues of using GIS for scientific research, and the limitations of proprietary GIS technology.

In Chapters 4 and 5 a data and methods discussion precedes the details of GIS implementation. These discussions establish the overall aims of reconstruction for the datasets and the complete suite of data and methods deployed to achieve this. They illustrate the complexity of the information associated with the case studies. Because of the time and expense required to establish a GIS, it is important to consider the wider context of information utilisation in the design and planning of an information system for long-term use (de Man, 1988). A system must be able to evolve to meet new requirements. The case study discussions exemplify the relationship between organisational, communicational and information management issues and scientific development. These case studies result in a set of technical and infrastructural requirements for handling palaeoenvironmental information using GIS.

To address these shortfalls in current systems and research practices a Palaeo Environmental Reconstruction and Information System (PERIS) is proposed in Chapter 6, which provides an innovative conceptual framework for both scientific research and information management. The model addresses the current information and scientific issues identified in the preceding chapters. Proposals are discussed for changes in the global palaeoenvironmental data infrastructure which would facilitate the adoption of such a framework. The research strategies required to evolve a truly global palaeoenvironmental research and information system are discussed as proposals for a research agenda.

Chapter 7 summarises the main conclusions and issues arising from the thesis.

Chapter 2 Palaeoenvironmental Research Requirements

2.1 Approach

In this chapter the inadequacies of current palaeoenvironmental research practices are reviewed to define a set of information handling and analysis requirements. The contribution of an information system can be evaluated against these requirements. The general issues associated with palaeoenvironmental research are addressed in this chapter and then revisited in more detail in the case studies (Chapters 4 and 5). They are also used in the development of a new conceptual approach to long-term information management and reconstruction research proposed in Chapter 6.

The objectives of research define how data are used, and by whom (Section 2.2). Current practices are reviewed to determine how reconstruction is achieved and the characteristics of data and methods deployed (Section 2.3). Some of the significant issues associated with current practices are then identified (Section 2.4), and improvements in information management which would help to address these shortfalls are discussed. A set of palaeoenvironmental requirements is presented (Section 2.5).

2.2 Objectives of Palaeoenvironmental Research

The objective of palaeoenvironmental research is to reconstruct and understand earth evolution. Modern spatial association, can be correlated and parameterised using climatic and environmental variables. For example plant distributions may reflect the combined distributions of temperature, precipitation, seed sources and soil type. As climate changes with time, the mosaic of plant distributions must also evolve in response to this. Knowledge of these associations and an understanding of change in time and space are therefore required. The study of palaeoenvironmental change helps understanding of these processes over a long timescale.

Different groups of scientists have different aims in pursuing palaeoenvironmental science. For the geologist the scientific goal is the investigation of the earth's history, for the geographer and the ecologist it is a search for long-term processes to explain things such as landform origins, and habitats. Botanists and archaeologists seek to uncover the history of plants or of man. There is also a utilitarian role in understanding the palaeoenvironment (e.g. Wright, 1973) to determine the original natural state of areas affected by man-induced change, for restoration purposes, or the origin of geotechnical properties in engineering (Weeks, 1969). Environmental changes have implications for the long-term safety of radioactive waste disposal sites (e.g. Boulton & Payne, 1992b). Reconstruction of past environments can also be used as a means of extrapolating future environmental changes. It is important to understand the full range of natural variability in the climate system to recognise any man-induced effects. Despite these varying objectives, there is a common need to reconstruct the sequence of past environments.

Some of the current issues in palaeoenvironmental research were recently discussed at the Dahlem workshop (Eddy & Oeschger, 1993). This series of workshops was founded in 1974 to provide a forum to stimulate co-operation and research. One of the aims during the 1991 meeting was to identify gaps in knowledge, find new ways to approach stubborn issues and define priorities for research. The results and recommendations of these discussions focused on spatio-temporal gaps in the data and the problems in certain methodologies. The main points of discussion are summarised below. Future palaeoenvironmental research should focus on studies in these areas:

- Investigations into the validity of using geological analogues for understanding past, and projecting future, changes
- Increased understanding of the reliability and consistency of palaeodata derived from Continents, Oceans and Ice Sheets
- Better approaches to the harmonisation of different dating chronologies
- Investigations into particular phenomena and mechanisms of change (for example the problem of lead and lag between causal phenomena and the recorded consequences of change)
- Consideration of the role of modelling in simulating and facilitating an understanding of change

2.3 Methods and Data

The evidence of past change comprises chemical, biological, sedimentological and morphological remains. These are proxy indicators from which palaeoenvironmental properties, such as temperature and precipitation, can be inferred, but not directly measured. These proxy data types include ancient pollen spores, beetle assemblages, geochemical signatures from deep oceans and cave deposits such as speleothems and glaciological deposits.

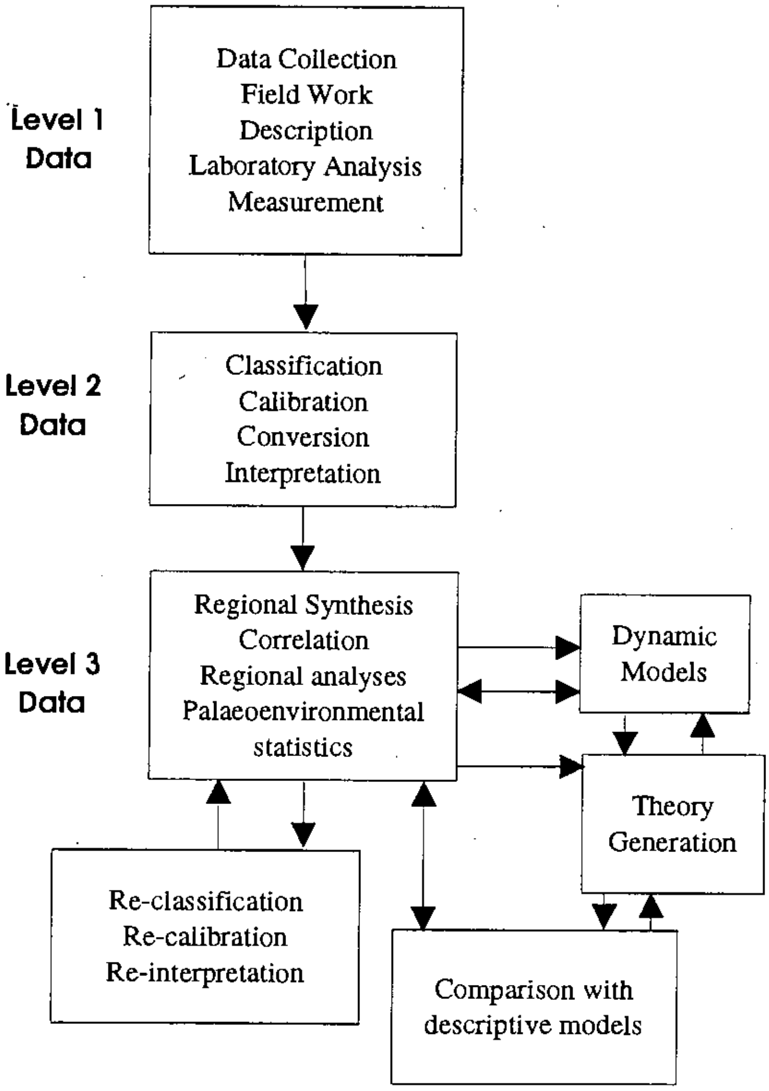
From this evidence palaeoenvironmental phenomena can be reconstructed in space and time. The reconstruction process comprises several stages which involve data collection, the derivation of palaeoenvironmental information from this data, and regional syntheses of this information through modelling and theoretical inferences (Figure 2.1). From the reconstructions, and from temporal and spatial sequences of proxy indicators, mechanisms and processes of change can be inferred. This can be achieved in several ways. Correlation methods allow the comparison of environmental proxies through time to establish spatial and temporal links and associations. For example sea level index points on raised shorelines, discussed in Chapter 5, have been measured and correlated to produce maps of relative sea level change through time (e.g. Walcott, 1972a; Pirazzoli *et al.*, 1982; Taira, 1975). Relationships between different data are then analysed to establish causal mechanisms for these associated changes. These hypotheses can then be tested using data from other areas. Modelling techniques also facilitate hypothesis testing with proposed mechanisms expressed as mathematical relationships. For example, Tushingham and Peltier (1991) developed a model which incorporates mantle viscoelastic structure and the deglaciation history. They tested this model using data not used in the model formulation (Tushingham & Peltier, 1992). All palaeoenvironmental inferences and reconstructions are based on uniformitarian principles, in other words that "the present is the key to the past" (George, 1976).

The most important issue which arises in generating reconstructions is determining the temporal component. Essentially palaeoenvironmental inferences can be divided into three types based on their temporal attributes:

(i) Data to which a dating method can be applied and therefore for which a date is known

(ii) Data for which some dating constraints are available. These can be considered to be relative dates. The samples cannot themselves be dated, but lie temporally close to (above and below) samples which can be dated, or which are correlatable with features of known dates.

Figure 2.1 Illustrating Simplistically the Iterative Nature of Stages in Palaeoenvironmental Reconstruction



(iii) Data for which no dates are known, but which give valuable palaeoenvironmental information.

2.3.1 A Data Hierarchy

In order to manage the range and complexity of information represented by the term "palaeoenvironmental data", some means of identifying different sorts of information is required which distinguishes data according to their origin and their role in the reconstruction process. The divisions (levels) discussed below relate to the stages of data transformation. This subdivision is also used in the following chapters (particularly chapters 4, 5 and 6) in the context of computer-based information systems. The analysis uses these subdivisions to help explore the limitations encountered using current methods of information management (section 2.4).

The methods of palaeoenvironmental reconstruction have been summarised by Bradley (1985). This summary refers to palaeoclimatic proxy records, but can be extended to include morphological stratigraphic evidence, and is used as the basis for the three data levels considered below. The numbered stages describe the processes required to obtain the different data levels.

LEVEL 1 DATA (observations)

1. collection of samples and observations usually involving fieldwork
2. laboratory analyses and measurements (e.g. tree ring width, isotopic ratios)

LEVEL 2 DATA (palaeoenvironmental inferences)

3. Calibration of Level 1 data to achieve palaeoclimate estimates. This may be qualitative (using terms such as 'warmer', 'wetter' etc.) or may involve explicit, reproducible procedures that provide quantitative estimates of palaeoclimatic variables and, often, a record of palaeoclimatic change through time for a particular location.

LEVEL 3 DATA (spatial reconstructions of variables through time)

4. Mapping of Level 2 data to provide a regional synthesis of palaeoclimate at selected time intervals. The synthesis provides a greater insight into former environmental patterns than any individual data set could provide alone (e.g. Nicholson & Flohn, 1980). In a few cases three dimensional arrays of Level 2 data have been transformed into objective derived statistical summaries (such as, for example, principal components eigen vectors showing a reduced number of modes and patterns of drought (Wang & Zhao, 1981)).

These data levels are useful as a generic, although crude, classification system for palaeoenvironmental information. They reflect the degree of interpretation and processing which the data has undergone.

2.3.2 Level 1 and 2 Data

Obtaining Level 1 data requires field and laboratory work on core samples, earth morphology and observations and measurements of regional spatial characteristics (including photographic or satellite image data) or cross-sectional evidence (which may come from excavations or from seismic, gravitational or other geophysically sensed data). This results in a mixture of digital and non-digital data which will be textual (descriptive), diagrammatic, cartographic, photographic and numeric. In spatial terms, Level 1 measurements are usually associated with point locations, or a series of vertical point samples (such as core or sample site locations), but can comprise areal, linear and volumetric spatial measurements in cases such as geomorphological studies. There is a wide variety of Level 1 data types, such as marine and lake cores and terrestrial excavations (Table 2.2), from which can be derived a number of palaeoenvironmental inferences (several observations may be required to derive one palaeoenvironmental variable). The uncertainty in inferences made from these data are relatively small in the spatial dimension although poor base maps and inadequate ground control can introduce large spatial errors in field or remote sensing observations. The temporal errors depend on the resolution of the dating technique used, and are often of the order of several thousand years or more.

Level 2 data inferences vary from quantitative measures of seasonal temperature variations and water depth, to more qualitative inferences such as "warmer and wetter than the present day" (Table 2.3). The links between Level 2 data and Level 1 data can be complicated and more than one Level 1 measurement can contribute to a Level 2 datum inference (for example temperature can be derived from the size of particulate matter in ice cores, the relative abundances of insects, and the growth of speleothems). The type of data will have implications for the suitability of current computing techniques to achieve Level 3 reconstructions. Interpolation routines may be applied to quantitative, numerical estimates with a reasonable spatial coverage. Most current methods of spatial analysis can only handle quantitative measurements and not qualitative data. The conversion of Level 1 data to Level 2 data involves a number of processes from interpretational intuition (for example, a glacial direction from a landform such as a moraine) to the complex use of present day analogues and

Table 2.2 Level 1 Proxy data (compare with Table 2.3)

Source	**Level 1 Data**	**Description**	Symbol
Ice cores	Stable isotope compositions (Oxygen, Deuterium)	point, measurement, depth sequence	∃
	Ice fabric (melt layers/crystal size)	point, event, description, depth sequence	♣
	Gas Bubbles (volume/composition)	point, measurements, depth sequence	Δ
	Particulate matter (size/composition)	point, measurements, depth sequence	Φ
	Nitrate ions	point, measurement, depth sequence	Γ
Marine Sediments	Microfossils (relative abundances/morphology/porosity)	point, classification, measurements, depth sequence	Σ
	Oxygen isotope composition of microfossil tests	point, measurements, depth sequence	Ω
	Sedimentology (composition/bedding/mineral surfaces)	point, measurements, descriptions, depth sequence	Ψ
Terrestrial Geology	Periglacial Features (pingos, ice wedges, polygons...)	point/area, size, description	∅
	Moraines (morphology, composition)	line/area, size, description	Π
	Eskers (morphology, composition)	line/area, size, description	✞
	Drumlins, flutes, striae (directions, size)	line/area, size, description	♈
	Shorelines (height/date)	point/line, height, description	♉
	Lake levels (height, palaeosols)	point/line, height, description	♊
	Speleothems (Deuterium/oxygen isotopes,varve width)	point, measurement, event, width sequence	♋
Terrestrial Biology	Plant macrofossils (assemblage, relative abundance)	point/area, measurements, description, classification	□
	Insects (assemblage, relative abundances)	point, classification, depth sequence	◆
	Tree rings (ring width, density variation, isotope composition)	point, measurement, event, width sequence	*
	Pollen (relative abundances, assemblage)	point, classification, measurements. depth sequence	⊃

The Symbol column is a reference code for the Level 1 data observations to show which observations are used to derive which Level 2 inferences in Table 2.3

Table 2.3 Level 2 Inference Data (showing Level 1 links Table 2.2)

Level 1 Data	Level 2 Data	Data Type	Description
∃ Ω Σ ♋	Global Ice Volumes	quant.	aspatial, discontinuous time sequence
∃ ◆ ♋ ⊃ Σ Φ	Temperature	quant./qual.	spatial, point, time sequence
⊃ ∅ ♣ ☐ *	Seasonal temperature variations	quant./qual.	spatial, point, time sequence, isolated estimates
♣	Accumulation rates	quant./qual.	spatial, point, time sequence, isolated estimates
Π	Glacier mass balance	quant./qual.	spatial, area, time sequence, isolated estimates
Δ	ice surface height	quant.	spatial, point, time sequence
Φ Ψ	atmospheric circulation	quasi-quant.	aspatial, time sequence
Γ	solar activity	quasi-quant.	aspatial, time sequence
♦ ☐ ∅ ⊃ Ω	temperature ranges	quant.	spatial, point, time sequence
Σ	sea surface temperature	quant.	spatial, point, time sequence
Σ	bottom water temperature	quant.	spatial, point, time sequence
Σ	ocean circulation	quant.	spatial, point, time sequence
Ψ	ice rafting - ice sheet size	qual./quant.	aspatial, time sequence
Ψ	trade wind intensity	qual./quant.	spatial, point, time sequence
Ψ Φ ☐ ♦	aridity	qual.	aspatial/spatial, point, time sequence, isolated estimates
∅	permafrost extent	quant.	spatial, area/pt, isolated estimates
* ♦ ⊃ ∅ ♋ ☐	precipitation	quant./qual.	spatial, point, time sequence, isolated estimates
♈ Π	ice extent	quant./qual.	spatial, area/line/pt, isolated estimates
⊃ ☐ ♊	water mass balance variation	quant./qual.	spatial, area, time sequence, isolated estimates
✞	fluvioglacial hydrology	qual./quant.	spatial, point/line, isolated estimates
✞ ♈ Π	deglaciation patterns	qual./quant.	spatial, line, isolated estimates
♈	direction of ice movement	quant.	spatial, line, isolated estimates
(Σ) ♉ ♊ ♋	sea level	quant.	spatial, point, isolated estimates
⊃	soil type	quant.	spatial, point/area, isolated estimates
⊃	vegetation type/distribution/cover	quant.	spatial, point, time sequence, isolates estimates
Σ	arctic frontal position	qual.	spatial, point, isolated estimates
⊃ ☐ *	length of growing season	qual.	spatial, point, time sequence, isolated estimates
* ☐	run-off	quant.	spatial, area, isolated estimates
*	anomalous weather patterns	qual.	spatial, point, time sequence, isolated estimates
Δ	atmospheric composition	quant.	aspatial, time sequence
Σ	salinity	quasi-quant.	spatial, time sequence

transfer functions, to derive palaeoenvironmental parameters (for example, temperature and water salinity, from microfossil assemblages - Imbrie & Kipp, 1971).

Uncertainties in Level 2 data are often difficult to quantify, even for results derived from mathematical equations, such as transfer functions. Errors are multivariate and therefore problematic conceptually. Errors depend partly on Level 1 measurement and interpretational accuracies, but also on the reliability of the relationship between the measured parameter and the inference, which is often difficult to assess. Methods of calculating errors exist for some techniques such as radiocarbon dating (Stuiver & Pearson, 1986). Errors in dates which are achieved through correlation are not usually addressed, although a probabilistic approach may be appropriate. These issues are little considered because of the difficulty of error determination and subsequent incorporation into analysis techniques.

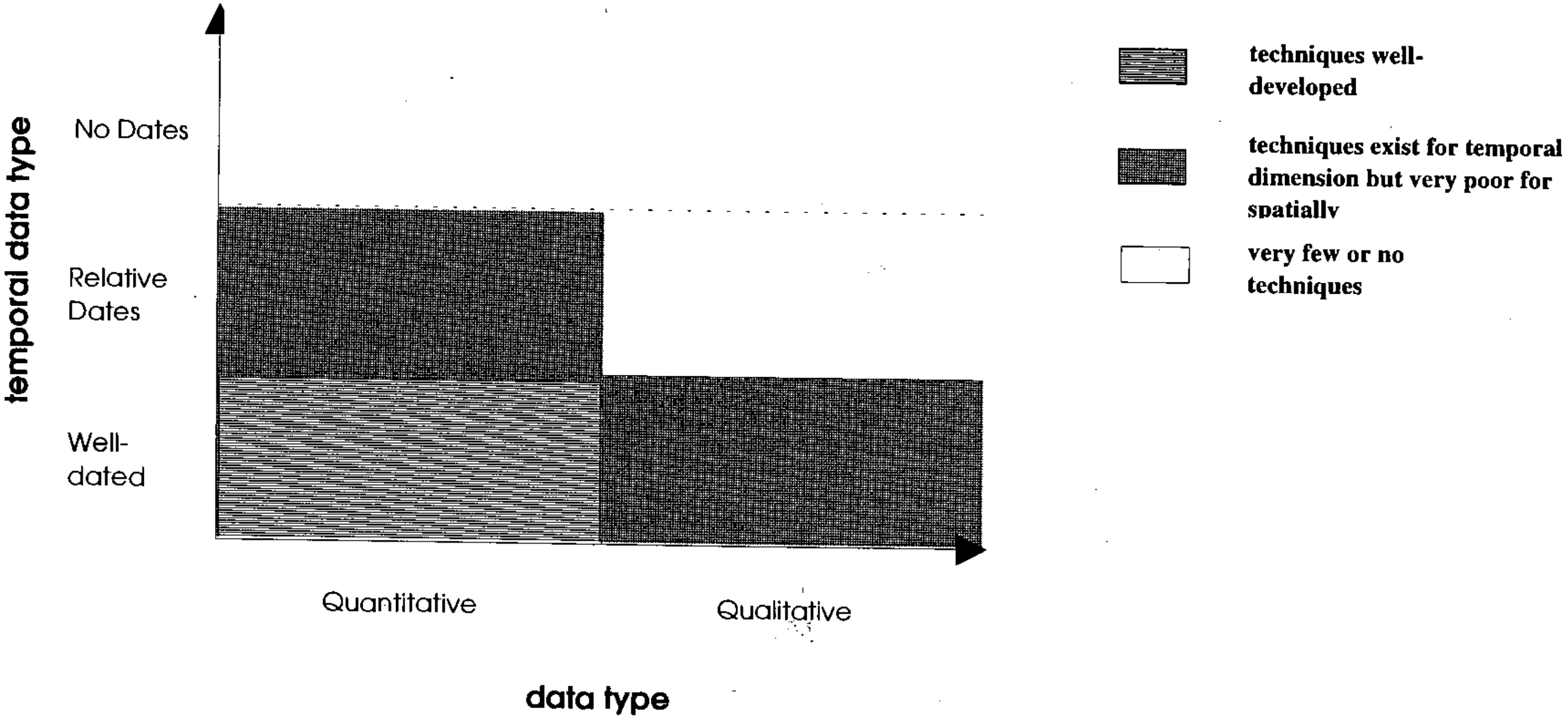
2.3.3 Level 3 Data

Methods of regional synthesis are rarely rigorous. Scientists build up a regional knowledge over years of personal endeavour and utilise work published by others. Information is usually plotted by hand onto a map, and synthesised by eye. As with all scientific theory generation, visualisation plays an important role and is traditionally achieved with the help of maps, tables and specialist diagrams (e.g. pollen diagrams). Level 2 data comes in different forms (Table 2.3) with different levels of resolution and certainty. Some of the data is qualitative (using terms such as "warmer", "wetter" etc.) and not accurately fixed in space and time. It is therefore difficult to integrate using quantitative methods, particularly for data which have limited dating constraints (Figure 2.4). Regional synthesis of even a single variable such as temperature, requires significant mental agility. In a few cases where data are sufficiently dense, computing methods have been employed to interpolate information (for example in sea level studies discussed in Chapter 5).

To achieve a complete spatial synthesis of palaeoenvironmental evolution through time requires the integration of information from different sites and time frames, at a variety of scales. Data is fragmentary and becomes more scarce the older the environment under study. With few constraining data points the number of possible scenarios is fairly broad. Combined with the large error envelopes associated with these data points, the errors become three- and four-dimensional in nature, and the possibilities for palaeoenvironmental reconstructions (both valid and erroneous) are

Figure 2.4

Techniques dealing with different areas of the data spectrum



enormous. In order to help manage this, by narrowing down the number of possible "fits" to the data, different modelling strategies are used:

(1) A non-empirical model describing in a qualitative manner the relationships between entities;

(2) An empirical, quantitative description of the palaeoenvironment;

(3) multivariate and stochastic models which describe a variable or set of variables using statistic and mathematical relationships;

(4) Dynamic models which use mathematical and differential equations to describe relationships between variables using physical principles (these may also utilise empirically derived relationships).

(Jeffers, 1991)

The first two models are predictive only in that they predict what should be found at a certain place for the instance of time which they describe. The third group of models describe the relationship between parameters in order to map their spatiotemporal patterns. They can be predictive in some cases, where they can statistically predict the changes in one variable with another (e.g. time series analysis of stable oxygen isotope ratios down a core, reflecting Milankovitch signals.).

Dynamic models are based on differential equations and difference equations. These equations express levels of state variables in terms of rates of change, which are controlled by decision functions, with deterministic solutions, and positive and negative feedbacks. They involve the solution of a large number of equations and offer a means of concentrating on critical variables and subsystems (Jeffers, 1991) (e.g. ice sheet growth and decay - Boulton and Payne, 1992a). Multivariate and stochastic models are used to derive Level 2 parameters from Level 1 data, and dynamic models are increasingly used to help model the processes of palaeoenvironmental change and make sense of the fragmentary evidence.

2.3.4 Key characteristics of data and methods

The spatial distribution of palaeoenvironmental data is not uniform with the spatial sampling determined by data occurrences. The density of sites on the continent is very low, even for Europe and America, for the last 18,000 years BP (the density decreases rapidly with the age of the environment under consideration). The situation is even worse for less thoroughly investigated areas such as Africa, South America and Asia. The scattering of sites is not random (tending to be clustered within regions easily accessible to man, such as coastal areas) which causes further problems with piecing together the fragmentary evidence. For example two palaeoenvironmental models for Eastern Russia differ markedly (Grosswald, 1980 and Velichko, 1984) because of the paucity of data, and the correspondingly large number of possible interpretations.

Palaeoenvironmental reconstruction is both multisource and multidisciplinary. A single site or core can yield several types of information (Table 2.2), and several of these Level 1 inferences may need to be combined to derive the value of a single palaeoenvironmental variable (Table 2.3). Furthermore a palaeoenvironmental parameter can be inferred from more than one source type. For example temperature estimates can be made by considering the size variation of mountain glaciers through time, studying the texture of ice cores, or through inferences made from pollen spores in bog and lake sediments. Records from these different sites must be combined to cover the complete temporal spectrum, since no single source supplies all the information for one variable throughout (Figure 2.5).

A single site or core frequently requires the skills of a variety of experts working together, to apply specialist techniques and interpret the proxy records (Figure 2.6). Inter-site correlation is required to date sequences, and is also necessary to achieve a regional synthesis for reconstructions. Often inter-site correlation is achieved by comparing sequences with a known standard such as the Specmap oxygen isotope curve (Imbrie *et al.*, 1984). This allows sequences to be dated and a spatial synthesis of events through time developed. Thus access to up-to-date standards and sets of techniques is required for site investigation.

Computing methods are already being employed for measurement of some Level 1 data (surveying equipment, digital image processing etc.) and some transformations of Level 1 to Level 2 data. For example, transfer functions utilise computing techniques to derive temperature and salinity measurements from microfossil assemblages (e.g. Imbrie & Kipp, 1971; Webb & Bryson, 1972). Generating reconstructions from Level 2 data has also involved computer aided interpolation. However reconstruction is currently achieved manually for the most part, because of the fragmentary and complex nature of the data, and because of the difficulty of representing the complexity of experience and circumstantial knowledge used by scientists to achieve these visual syntheses in computing terms.

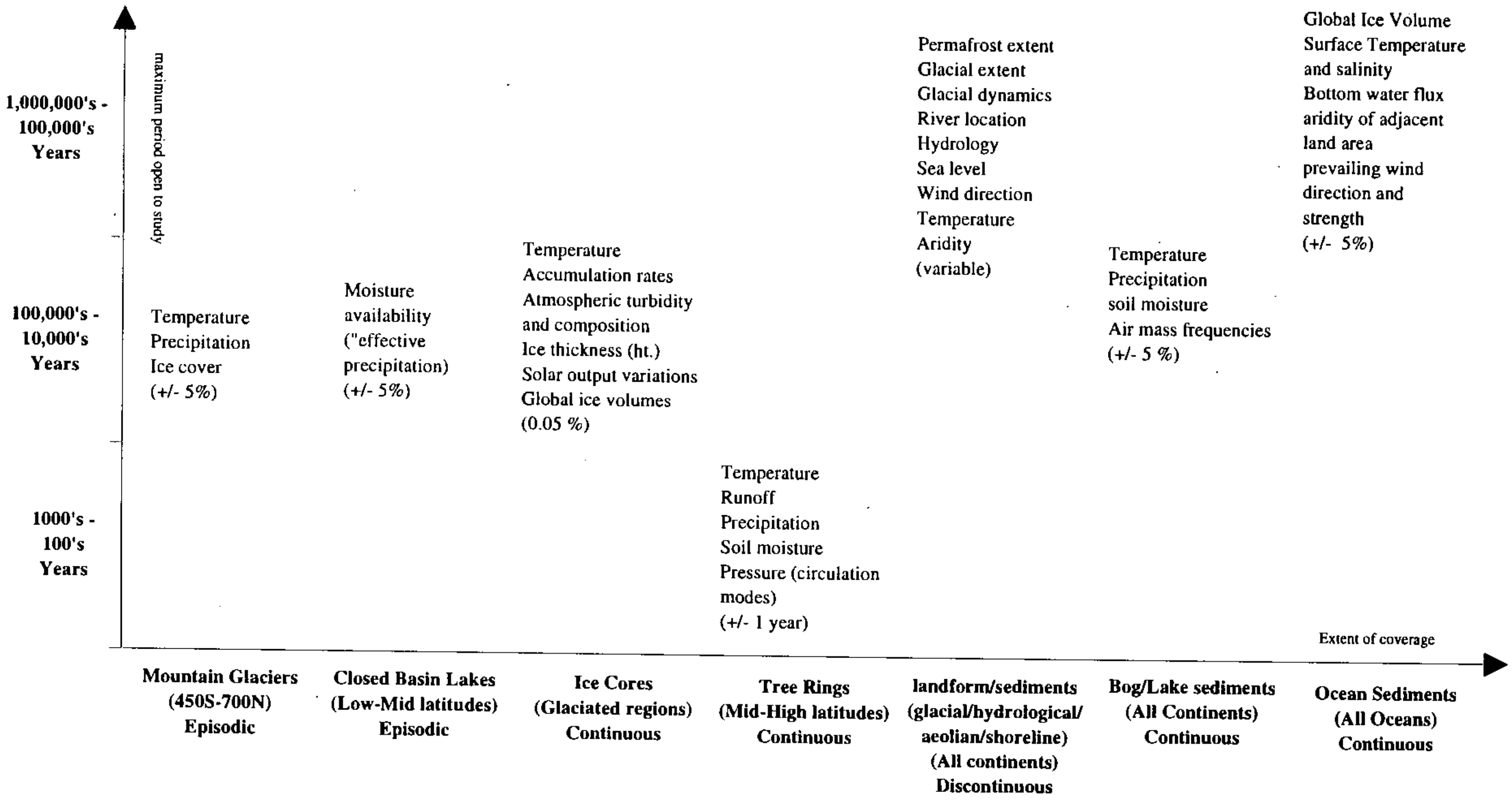
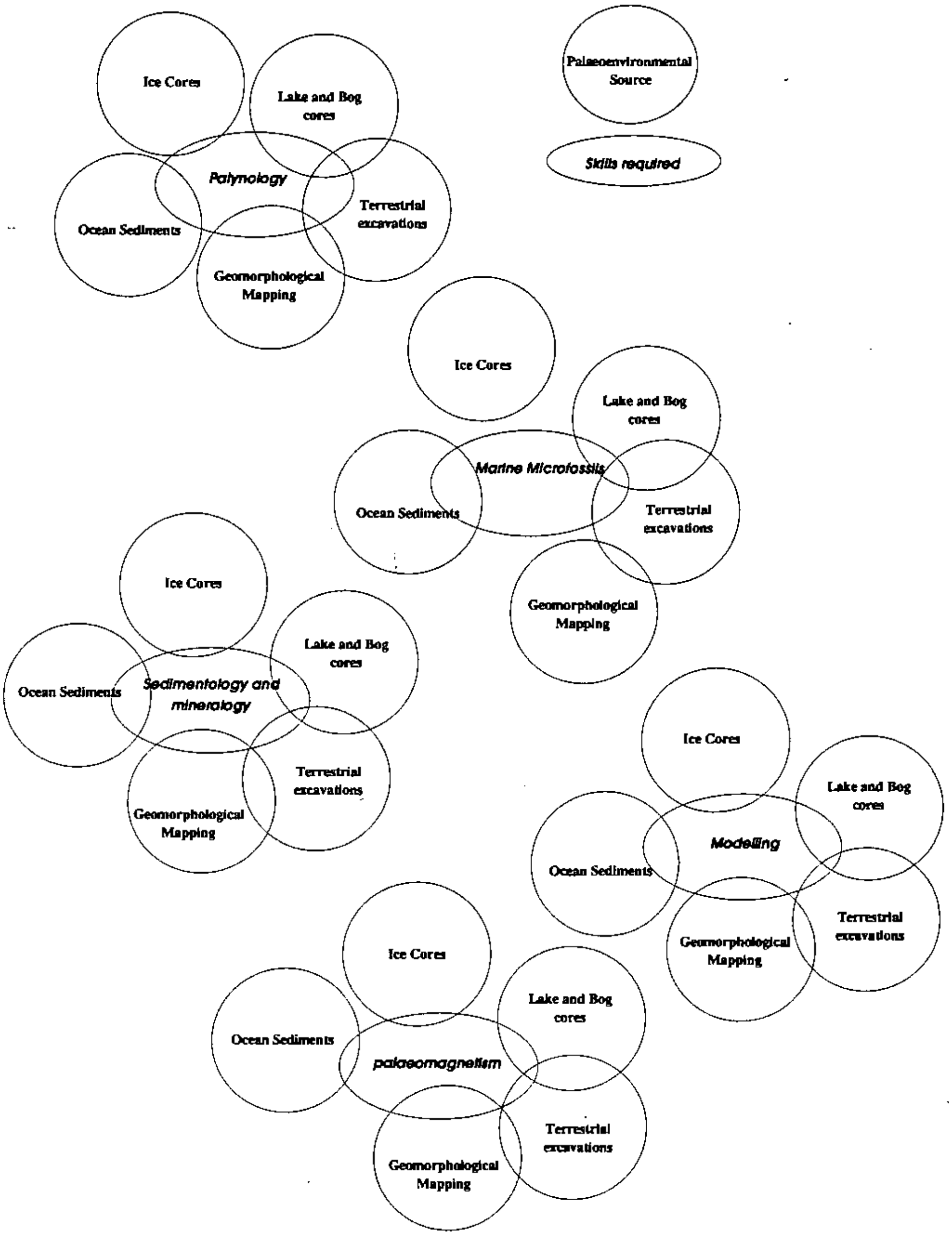


Figure 2.5 Characteristics of major palaeoenvironmental data sources (based partially Bradley (1985))

Figure 2.6
Intersection of palaeoenvironmental source data and skills domains



There are also a number of vital supporting datasets, information pools and methods (e.g. equations and procedures) which must be readily available to those working in this area, whether they are concerned with the generation of Level 1, Level 2 or Level 3 data. These reference data can be classified into dating methods, present day information, functions, methods, and models, and correlation standards (Table 2.7).

2.4 Inadequacies in current practices

The main problems associated with palaeoenvironmental data stem from a lack of rigour in some current practices for handling information, and the fragmentary distribution of research workers and the data they generate (examples are discussed in both of the case study Chapters 4 and 5). These practices are now increasingly inadequate for regional scale analysis. They came about because individual scientists traditionally mapped small areas and used the data as a basis for further interpretation. There is little in the way of regional approaches, spatial comparisons, areal continuity and thematic correlation. There is no existing means of managing this information so that it can be accessed and processed easily, and archived for future use in the light of new theories. This limits the potential for producing credible global palaeoenvironmental reconstructions through time, and is reflected in the scarcity of such synopses. Given the resources required to collect and process data, and the pressures on the palaeoenvironmental research community to contribute to global change research, this is both uneconomic and unwise.

There are several issues associated with current reconstruction practices which are imposing increasing constraints on the ability of scientists to manage, and exploit to the full, the palaeoenvironmental data available. These issues concern the way data is collected, recorded and archived, and are associated with inadequacies in the current scientific information infrastructure. The points discussed below in Sections 2.4.1-3 indicate the limitations imposed at different data levels by traditional practices, how these problems are propagated through the transformation processes between levels, and the potential GIS solutions (Figure 2.8). Many of these issues are clearly demonstrated by the case studies described in chapters 4 and 5. Geographic information science can facilitate solutions which address these shortfalls in method and infrastructure. These are proposed in Chapter 6 through the PERIS conceptual framework.

Table 2.7 Reference Information (not exhaustive)

Present Day Information
Topography/bathymetry/coastlines/islands/lakes/ice extents
Geology and surface drift
Faunal/floral distributions and habitats
Pollen dispersal patterns

Correlation Standards and Reconstruction Theories
Palaeomagnetic Reversals/secular variation
SPECMAP (Oxygen Isotope Stages)
Pollen Stages
Regional Eustasy
Global Ice Extent for different time slices

Functions and Models
Transfer Functions
Time Series Analysis
Climatic variables and interrelationships (atmospheric compostion...)
Static and Dynamic Models (e.g. Ice Flow, Milankovitch Variations...)
Ocean and Atmospheric Circulation

Dating Methods
Tephrachronology
Palaeomagnetism
Lichenometry
Dendrochronology
Amino Acid
Weathering Rates
Radiocarbon
Potassium-argon
Uranium Series
Thermoluminescence
Fission Tracks

Table 2.8 Data Transformations (Traditional Practices, Issues and GIS Improvements)

Level 1 Data	Sites/sources	Level 1 Transformation	Level 1 Data	Level 1-2 Transformation	Level 2 Data	Level 2-3 Transformation	Level 3 Data
Traditional Practices	Field Sites Surveys Cores Satellite Images	Description, Measurement, Surveying, Recording often using tape measure, and field note book	Photographs, descriptions, measurements, chemical and sediment content, hand scribed notation on maps and notebooks	Visual interpretation and correlation, classification, pattern matching, calibration. Correlation using standards such as Specmap curve.	Palaeoenvironmental estimates (temp., precipitation, wind direction, glacial flow direction, ice volumes, sea level change). Temporal sequences of variables	Visual interpretation Manual mapped data transcription Integration of multiple data sources from publications or through collaboration.	Hand drawn maps of palaeoenvironmental phenomena locations at different temporal bands, hand drawn contour maps of temp. isostasy, descriptions of palaeoenvironment and change.
Issues	Poor field maps, time required to browse literature for background and appropriate methods and strategies	Difficulty with location in some terrains Time required to transfer and reformat data, Ommissions in recording data not thought relevant	Location inaccuracy, Incompatible map scales and projections Little structured data management Limited data archiving Illegibility of field notes Result: data loss, quality reduction	Lack of standardised methods, Variation in terminology use, Limited use of quantitative methods, Data discarded if not in line with current thinking Loss of level 1 data after transformation and so difficulty of adjusting data to new theories and standards	Few uncertainty and data quality measures, interpretations and assumptions not properly documented. Loss of data which does not comply with theories	Loss of data thought not to fit theories, or good enough to publish, lack of quantitative spatial analysis techniques to support multisource data integration. Lack of information management strategies to facilitate data sharing. More error introduction. Visual interpretation very demanding.	Few quantitative measures of how well theories fit data. Loss of data which does not fit current thinking, locational and temporal uncertainty is unnecessarily increased by hand-transcription, and so it is difficult to identify data conflicts
GIS improvement (more details in Chapter 3)	Portable field GIS linked to GPS	Direct digital input, accurate location direct access in the field to information as required, data analysis in the field	Accurate, complete data in digital form appropriate for use in Level 2 transformations and archived for future reference and use.	Quantitative techniques Measurable data fitting Speed of experimentation Access to variety of up to date standards and techniques	Archiving of contextual data, interpretations, assumptions, lineage of data processing, and traceability to level 1 data, better quality and quantitative methods	Spatial analysis methods for handling uncertainty, modelling phenomena. Direct integration with mathematical models. Accurate mapping of reconstructions. Reconciliation of information at different scales.	Archiving and management of methods and uncertainty measures, quantitative techniques of rigorous data handling and analysis, spatial data handling facilities.

2.4.1 Data recording and processing practices

Most of the limitations in current practices centre around Level 1 data observations and measurements. These impose restrictions on data manipulation at later stages of reconstruction.

Inaccuracy in recording data and a lack of uniformity in sampling, measurement and descriptive techniques mean that data is often insufficiently detailed for integration or application to many scientific theories. Using aerial photography and satellite imagery with inadequate ground control, or making measurements in areas with poor base maps can introduce substantial spatial errors. Poor georeferencing of site locations is compounded at later stages of data integration by combining maps, using manual methods, which are not only at different scales, but also have different map projections and datum levels. Examples of this problem are discussed in section 4.3 of the glacial geomorphology case study (Chapter 4).

Field work can also involve data loss through omissions in data recording, and through visual methods of data generalisation during data transformation, integration and interpretation stages. Information can also be lost because field notes are illegible. Such field information is often only used by one person and communicated to other researchers in an abstract form.

Inadequacies in recording Level 1 data pose problems when it is transformed to Level 2 information. Inferences cannot be checked between sites by those wishing to make a regional synthesis to ensure that compatible methods and hypotheses are being used. There is no possibility for checking site misinterpretations, because this information is not available. This limits the usefulness of data for other scientists. The ease with which misinterpretations can be made given insufficient evidence can be exemplified using Greenland ice core data. Two ice cores were drilled which displayed very similar records for several hundreds of metres depth (Johnsen *et al.*, 1992; GRIP Project Members, 1993). Below a certain depth, however, there was little agreement between the two records. Glaciologists interpreted this as due to multiple ice folds close to the glacier bed which one of the cores had penetrated, but which had affected the other core much less (Boulton, 1993). Since many scientists view ice sheets as stratigraphic accumulations of snow, had only one core been drilled, this possibility may have been missed and resulted in a very different view of palaeoclimatic variation through time. This underlines the importance of supplementing Level 2 and

3 data with an understanding of the details of the Level 1 data to allow variations in interpretation of different sites by different scientists.

The fragmentary and poorly documented nature of palaeoenvironmental data imposes restrictions on the potential for scientific innovation. There is a propensity amongst researchers to fit new data to old theories because few individuals hold sufficient information to reassess all the data and develop new models. This occurs even when it becomes increasingly obvious that these models are inadequate to explain new data. Such limitations to scientific innovation are exacerbated by the fact that many of the popular models are not demonstrably well substantiated. Charlesworth's model depicting the pattern of glacial events in the UK (Charlesworth, 1957) gives little indication, and no detail, of the information used to derive such a model. Nevertheless, this model has been cited in numerous papers ever since its conception. The limited information available to individuals has meant that most palaeoenvironmental research has involved Levels 1 and 2 data for individual sites only (Bradley, 1985) and there are only a few examples of work which included a spatial dimension to climate studies (CLIMAP Project Members, 1976; Petersen *et al.*, 1979; COHMAP, 1988).

The poor quality of some Level 1 data has limited the rigour with which the data can be treated and the reproducibility of many transformations (such as the transcription of data between maps). The limited application of quantitative techniques has restricted the degree to which the accuracy of data can be evaluated in many cases. Poor locational accuracy in particular makes meaningful integration with other information difficult. It has also hindered the development of methods to help manage the quantity of complex information which must be integrated spatially to obtain reconstructions. For example individuals compile and interpret data by eye using manual transcription, but variations in the interpretational adjustments during such transformations mean that these changes are neither reproducible nor compatible. There are also few quantitative spatial methods that are frequently used, such as areal calculations and spatial correlation algorithms. Consequently there are few measures of how well data fits conceptual models.

The limited availability and use of quantitative methods has also hampered the development of techniques for handling scale and error during palaeoenvironmental data integration and analysis, and limited the application of rigour in respect of these issues. The extent to which data uncertainty might affect palaeoenvironmental reconstructions, and measures of how well data fit theories, are two important aspects rarely considered in palaeoenvironmental research because of the difficulty in handling the information.

There are also few appropriate techniques for global scale analyses. Recent changes in the quantity and geographical extent of the data sets being manipulated, and the global nature of the phenomena being reconstructed, have highlighted this inadequacy. Techniques which have been used on small regions are inappropriate for global scale analyses and integration. Some of the areas under study are too large to ignore the curvature of the earth, and map projections distort space at this scale. Whilst this has previously been the realm of cartographers, increasingly these concepts and skills need to be available to a larger spectrum of the scientific population. A failure to grasp these issues will result in scientific conclusions which are fundamentally flawed. There are cases where such errors have occurred. Areal calculations of basal melting under an ice sheet, for example, have been made using standard base maps (Ian Morrison pers. comm., 1992). Calculations made using inappropriate projections which do not preserve area produce very large errors in basal meltwater estimations.

Finally, the time and expense of map drafting using manual methods is considerable. With each update in ideas or theories, redrafting of maps is required. This limits the frequency with which maps are updated and republished.

2.4.2 Data archiving practices

Most areas of palaeoenvironmental science suffer from inadequate data archiving. First of all data can be lost because they are not published if they do not accord with current thinking. If data are not published they are rarely available in the public domain. Data are also lost between projects because they are distributed between individuals who often leave an organisation at the end of a project. In addition the data may be published as interpretations which are perceived to be of more value than the original data, which is not published in detail. Level 1 data in particular are rarely retained with sufficient detail to allow them to be reassessed in the light of new theories. This loss of valuable information limits the possibility for reinterpretation and increases the propensity for misuse of data which have been archived without their contextual information The problems discussed in section 2.4.1. are thus exacerbated and the capacity of the scientific community to develop new theories and models is limited

For example, during post-cruise work associated with Ocean Drilling Program (ODP) Leg 133 (Northeast Australian margin), Alexander (1996) found significant discrepancies between isotopic records from the Australian margin and the SPECMAP oxygen isotopic chronology of Imbrie *et al.*, (1984). The conclusion drawn was that certain parts of the Australian records, which did not match the reference curve, had been modified by post-depositional processes, and therefore data were discarded. However, there was no other evidence to support this conclusion. If the standard was flawed in some way, or not applicable to these circumstances, then much information was lost by drawing this conclusion. Such standards are being used throughout the world, and this is only one example of a very widespread phenomenon which goes beyond oxygen isotope stratigraphy. Were these data to be properly archived, they could be called up and reassessed in the light of any new theories and findings, or compared with other "reject" data to see if an alternative interpretation may be appropriate.

Lack of comprehensive data archiving means that the connections between Level 1, 2 and 3 data discussed in Section 2.3.2 are lost. Those undertaking regional syntheses of variables may thus unwittingly incorporate Level 2 inferences which were made using out-dated theories. Programs which are addressing the issues of data archiving are merely archiving a subset of information (sea level examples are discussed in Chapter 5). The databases being designed only accommodate a specific subset of data, are not publicly available, and fail to reflect the full richness and complexity of palaeoenvironmental information demonstrated in Section 2.3 above. To date, it would appear that none of these databases have been designed to link with other palaeoenvironmental databases. The lack of comprehensive and available data archives mean that many of the models and palaeoenvironmental synopses used by the scientific community have a limited, traceable documentary basis.

2.4.3 Scientific infrastructural limitations

The scientific infrastructure poses several difficulties for the use and exchange of palaeoenvironmental data and the development of research.

Communication and data sharing is achieved, for the most part, through publication in the literature. This is neither a timely, nor comprehensive mechanism of communication. Much of the data which is measured is never reported because it is, for particular reasons unpublishable (Section 2.3.2). In addition site and method information is frequently not documented in any detail. These limitations in published information have been noted, for example, in relation to the use of publication material for constructing a sea level databank, where the research group was forced to contact individual authors for apropriate material (Shennan, 1989).

Conventional publishing through journals and periodicals can delay the dissemination of new work by up to a year or more. For example, the median time for publication in the Journal of Ecology is approximately 52 months (Porter & Callahan 1994). The journal audience is also limited because of the number of journals which currently exist. Individuals and institutions have limited funds and so purchase only a small subset of available journal titles. New trends in on-line publishing through the World Wide Web (WWW) are, however, currently revolutionising this state of affairs.

This delay in publication of new work, and the patchy communication coverage can cause significant problems. For example, some recent refinements (Shackleton *et al.*, 1990) in the interpretation of the ODP Hole 677 stable oxygen isotope curve have not been incorporated into all subsequent analyses of such data making it difficult to compare results and interpretations. For example, Raymo *et al.* (1990), presumably unaware of these changes because of publication timing, used the old interpretation (Shackleton & Hall, 1989).

There is also a significant lack of standardisation between researchers in both data measurement (sampling techniques, tools, units, formats etc.) and methods of reporting (nomenclature, description etc.). Many standards do exist, but many conflict and there is little incentive for researchers to use them. Long-term, however, it becomes difficult and in some cases impossible, to reconcile such heterogeneous data over large areas. Imposing standards on research data collection is problematic and, in some instances, undesirable. However, integration over large areas is vital for understanding global phenomena, and standardisation facilitates integration.

Finally, the current infrastructural support for the scientific community makes little provision for access to good basic map data, reference data sets, up-to-date standards and methods, or databases. This problem has been recognised, for example, by the Natural Environment Research Council (NERC) in the UK which is currently taking steps to develop a comprehensive information strategy (Richard Healey pers. comm., 1997).

2.5 Discussion of Palaeoenvironmental Requirements

In summary, the cross-disciplinary nature of research means that these datasets cannot be treated in isolation if a coherent picture of the palaeoenvironment is to emerge. Retaining links between site information and measured data is vital, and the Level 1 data associated with field sites requires detailed archiving. Existing databases are partitioning valuable site information so that it becomes disconnected from the original data. It is also vital that links are retained between data and the correlation standards, dating techniques, sampling strategies and reference data with which their measurement and interpretation is associated. These issues are crucial to the progression of palaeoenvironmental science.

Limits are being reached in the capacity of individuals to manage the quantity and complexity of data associated with palaeoenvironmental research using traditional methods. A structure to facilitate better management practices is imperative. The capacity of the current research paradigm to manage and utilise effectively data in the face of increasingly global scale demands, is rapidly becoming inadequate.

One of the biggest issues for the integration of global scientific datasets is that of standardisation. Whilst data standards are a fundamental requirement for the integration of information, they pose several significant problems in the area of research. Not only will past data have to be reinterpreted to conform to standards, but standards change as theories change and standardisation between geographical regions can be problematic. Age names, for example, are often related to identifiable climatic changes. In Quaternary geology one of the main stumbling blocks to spatial integration has been the correlation of events of unknown extent (Kind, 1972; Sissons, 1979; Mangerud, 1979; Boulton, 1979). An event which has been recorded in sequences in Scandinavia does not appear in sequences in North America. It is not known whether this event, known commonly as the Younger Dryas, is a European climatic anomaly, or whether there has been a failure to identify it in North American sequences (Dawson, 1991). Further issues can be exemplified by developing a scenario discussed previously, which considers the case of two marine cores which were measured by different groups (Alexander, 1996). One group measured the oxygen isotope content, and the carbonate content, and used the latter to define where the former was reliable and where it was not. The other group, either through lack of awareness, or because they did not share the belief that carbonate content had any bearing on the reliability of the oxygen isotope signal, did not measure this parameter. How should standards be enforced in this situation? Would all groups be required to measure carbonate content in a core, regardless of whether it related to their primary aim in a particular scientific context? How would these "minimum data elements" (Slagle, 1994) be defined? It may be possible to address the problem in terms of a suite of objectives and scientific issues which can then allow the designed integration of different approaches (Slagle, 1994). Other issues include the ability of research scientists to improve their capacity to perform both empirical and qualitative modelling of data which requires manipulation of larger volumes of data over larger areas in four dimensions.

There are practical and institutional, as well as scientific issues which must be taken into account when trying to improve scientific research and facilitate communication and data sharing. Complications arise because the data originates from different countries with their own methods, datum levels, protocols and languages.

It is clear that there is a pressing need for new ways of managing these rapidly expanding data sets, of visualising the complexities of the information they represent and of developing rigorous methods which yield reproducible and testable results, which have a more measurable certainty. Timely and effective communication between a diverse and rapidly expanding international research community is of paramount importance because of the demonstrably interdisciplinary nature, and political immediacy of the palaeoenvironmental reconstruction problem. For global science the requirements are of information management, co-ordination of effort and communication. In terms of individual scientists the needs are for convenient provision of data, methods and standards, and a means of visualising, integrating and analysing the data using quantitative, rigorous techniques which allow interactive adjustment of parameters and multiple analysis runs.

Generic palaeoenvironmental research requirements which have been identified in this chapter are thus summarised as points below:

1. Comprehensive archiving and management of complex palaeo-data

   Level 1 Data
   - storage of all information (maps, photographs, laboratory measurements)
   - retaining links between data from the same origins and sites

   Level 2 Data
   - recording of methods, techniques and standards related to the data
   - retention of unpublished data

- retention of uncertainty information

Level 3 Data

- preserving links between data levels
- measures of "goodness of fit" of data to models
- support for the existence of many versions of analysis and reconstruction

2. More rigorous and quantitative methods

   Level 1 Methods

   - Improvements in rigour of data measurement and recording methods

   Level 2 Methods

   - Techniques for data correlation and pattern matching
   - support for, and analysis of, specialist methods (e.g. pollen diagrams)

   Level 3 Methods

   - spatial analysis methods suitable for irregular heterogeneous data
   - improved data integration methods (particularly spatial)
   - methods appropriate for large areas on a spherical earth
   - rigorous methods to exploit qualitative and poorly dated material
   - support for dynamic, stochastic, empirical and qualitative modelling
   - methods for assessing data uncertainty through data transformations

3. Improvements in communication throughout the scientific community
   - provision and use of data standards, and methods
   - timely access to all levels of data, and new findings and techniques
   - provision of present day information, particularly good base maps

The development of palaeoenvironmental research must involve innovations which will go some way towards satisfying these basic methodological and operational requirements. The issues associated with using GIS technology to address these requirements are identified in the following Chapter.

Chapter 3 GIS Issues

3.1 Introduction

This Chapter provides an overview of the fundamentals of GIS. The purpose is to assess their capacity to address the issues that palaeoenvironmental research currently faces, at a conceptual level, and to provide information required for an appreciation of the case study chapters. From these fundamentals what GIS has to offer is established, and the issues that must be considered in improving the approach to the management and analysis of palaeoenvironmental data.

The importance of GIS, as a collection of theories and techniques which can contribute to palaeoenvironmental research, is demonstrated through a brief overview of the areas GIS research encompasses (Section 3.2). Key GIS concepts are then introduced and explained. These concepts are discussed in relation to data capture (Section 3.3), data storage (Section 3.4), GIS functionality and spatial analysis (Section 3.5), data integration (Section 3.6), data management (Section 3.7), and finally global information networking (Section 3.8). Section 3.9 provides an overview of the potential of GIS to improve palaeoenvironmental research at a conceptual level, given the palaeoenvironmental requirements identified in the previous chapter. The key points are then reviewed to establish a set of general GIS issues for palaeoenvironmental research, which will be further explored in the case studies (Chapters 4 and 5).

3.2 GIS potential for palaeoenvironmental research

It would appear that the advent of computing techniques has already had a significant impact on palaeoenvironmental studies. Major contributions have been made in the areas of process modelling to simulate palaeoenvironmental change (glacial and general circulation models in particular) (for example Boulton & Payne, 1992a), time series analysis (for example Pestiaux & Berger, 1984), and remote sensing (for example Punkari, 1982), with computing power being exploited to solve equations and manipulate large data sets. However, computers have not been fully exploited to address the requirements identified in the previous chapter, although they appear to hold potential in this area. This is because of the complications involved with using computers to address the problems of information management and research and the difficulties in converting from manual to computing methods.

GIS is not just a technological tool for storing and manipulating spatial data, but represents a growing body of scientific research. This research is concerned with addressing the intellectual questions associated with information systems and the handling of spatial data. The scientific issues range from philosophical to technological discussions. They concern the representation of geographic reality and how perceptions of the real world are structured and expressed. They also involve the methodological development associated with analysing systems and managing data. They include the development of technical solutions such as algorithms and spatial indexing schemes. GIS combines aspects ranging from computer science and geodesy, to cartography and cognitive psychology, to address questions about the use of spatial information.

GIS sits at the interface between geographical applications, computer science and information management. The area embodies a set of issues which can be considered generic, and the research findings can be used to support data management, spatial data handling, and analysis in geographical fields (Goodchild, 1992). The results offer new methods which may lead to new insights. GIS comprises a broad range of investigation topics which have importance for palaeoenvironmental research and will help in addressing the requirements identified in Chapter 2. GIS is relatively new, and these areas of combined methodological and technological development do not fall neatly under particular headings. The following sections have been selected to contain the key components.

3.3 Data Capture

Substantial technological progress has been made in the area of digital data capture in the last decade (Goodchild, 1992). Essentially data capture is of two sorts:

- Primary (field, laboratory or satellite imagery input directly in digital form)
- Secondary (capture from paper documents such as maps)

Primary data capture offers the most significant improvements to the quality and handling of field data. Direct digital data capture is becoming more viable with cheap, portable, pocket-sized computers and GPS (Global Positioning Systems). These can be taken into the field for data acquisition and will make data more usable (Gosz, 1994). Tried and tested systems are reported to have improved data collection efficiency and accuracy (particularly locational accuracy) (Carver *et al.*, 1995). They allow interactive development of sampling strategies through visualisation and feedback, on-the-spot modelling capabilities and field-based verification. This reduces the number of field visits and associated project costs. The disadvantages are currently the logistical problems associated with power sources, transport and protection of the equipment in the field, limited data availability for certain areas and the need for technical backup, education and training.

Secondary data capture (from paper documents such as maps) entails the following stages:

1. Data preparation

   Various important issues must be considered at the data preparation stage which have implications for using digital data at digitising, editing and analysis stages. Clean copies must be available for digitising, particularly where scanning is used. It may be necessary to reclassify or transcribe data to a common base map, particularly if overlapping layers of information are to be digitised. If different information layers share boundaries (for example geological and vegetation maps share the same coastal, lake and river boundaries) but are digitised separately, it is unlikely that these common boundaries will be identical. If they are not identical, then subsequent overlay operations will produce "sliver polygons" which are merely artefacts of the differences between digitising accuracies of the line, or different rendering of the same coastline on different maps. These considerations have major implications for data integration and are important for system design (they are discussed further in the following sections).

2. Digitising

   - Digitising table and puck

     The precision with which data can be captured using a digitising table depends on the precision of the digitising grid of fine wires in the digitising table, the accuracy of the operator, and the inherent accuracy of the material being digitised. Digitiser table accuracies typically vary from 0.075 mm to 0.25 mm.

   - Scanning

     Scanning can be used to input both spatial and tabular data. Scanner accuracy depends on the scanner resolution (typically 2,000-4,000 dpi (dots per inch)). Whilst scanners are much faster than manual digitising methods, they produce large data volumes and for vector (point, line, polygon) and character data they require clean paper copies and specialised line following software. For complicated maps, with overlapping text and symbols, current software is inadequate and so manual separation of data layers is required. Alternatively scanned map images can be digitised on-screen, and some scanning/line tracing software also provides interactive line tracing so that operators can have control of the sequence of digitising and provide the interpretation necessary for feature coding prior to feature capture.

- Keyboard input

  This is a very slow method of data input, usually used for entering attribute data.

3. Data checking and editing

   Probably the most time-consuming aspect of data capture is data checking and structuring (Nagy & Wagle, 1979; OEEPE, 1984). Checking is commonly achieved by the combination of manual editing and software algorithms designed to check for data inconsistencies.

4. Data structuring

   Data are structured for storage in the information system (Section 3.3 provides more information about this). Feature numbers are assigned to lines and polygons so that they can be identified in the database. Links are created which define the spatial relationships such as polygon adjacency, line direction and so on (Burrough, 1986). A particularly troublesome aspect of this structuring process, which is rarely appreciated by new users of GIS, is the necessity to create topology for vector data. This allows the system to identify features as points, lines and polygons via, for example, a link node structure, and to store, manipulate and analyse their spatial relations. Line duplication and unclosed polygons are common problems which require editing. Without topological structuring spatial analysis of, for example, network and vector polygon data is effectively impossible (Burrough, 1986).

Data uncertainty is a function of the reliability of the source data which is usually much more significant than digitising errors (Aspinall & Pearson, 1995), although this is not always recognised. For example, Walsby (1995), has examined the issue of error in digital British Geological Survey maps as a function of digitising error, when the uncertainty in the geological boundaries on the original maps are rarely known to anything like the degree of accuracy implied by the hand-drawn map boundaries.

Inputting large volumes of multisource data into a system requires a very high investment and most of the cost of establishing a system is associated with data conversion (Masser & Blakemore, 1991). Tomlinson (1994) has suggested that this value is approximately 70-80 % of the total system cost. The substantial cost of data capture is often underestimated and results in compromises in accuracy and completeness. The problem is particularly acute for short-term ventures, with the consequence that the data have very limited value, and potential, for re-employment on subsequent projects. This is a significant issue for systems as they evolve since the initial system set up time can be longer than new users expect, and the anticipated adaptation of the system for new projects is not possible.

Research areas focus on the development of more efficient means of data capture to reduce the time and cost. Methods to convert data from conventional media (mainly paper maps, diagrams and tables) to digital forms are required and developments are focusing on areas such as Artificial Intelligence to improve line-tracing algorithms. Automatic conversion of scanned images to topologically correct, structured, georeferenced data could significantly reduce the cost and time involved in data capture. Two GIS companies LASERSCAN and ESRI and the Turing Institute in Glasgow, have developed sophisticated line tracing software which can be set to ignore character symbols (for example where height intervals are noted on contour lines), and maintain a continuous line trace. As more information is generated through direct digital data capture this will ultimately preclude paper-to-digital conversion and reduce the importance of this issue.

3.4 Data storage

The unique issues associated with handling geographical data are demonstrated most clearly by research into the means of representing spatial and, more recently, temporal, information in a database so that it can be accessed by location and time as well as by attribute. The issues associated with storage and transformation of data concern how the data should best be represented conceptually, in a form that is both structured for database efficiency, and useful to the data user. Data is stored in GIS using data models and data structures. Most developments to date have been concerned with spatial representation. Spatio-temporal issues are more complex and are discussed at the end of this section. Data modelling is a definition and formalisation of the semantics of spatial data concepts (Egenhofer & Herring, 1991), and data structures are the programmable implementation of data models in the system (Peuquet, 1984). Both are important areas of research in GIS, and data modelling constitutes one of the major design components of a system. The NCGIA (National Centre for Geographic Information Analysis) Initiative I, "Multiple Roles for GIS in US Global Change Research", identified data models as the key issue for linking the GIS Community and the Global Change Modelling Community (Jelinski *et al.*, 1994).

Whatever decisions are made about data representations and relationships at this stage will be hard-coded into the system and may be impossible to change subsequently (Marble, 1988). Until recently the choice has been between raster (or tesselation) versus vector (point, line and polygon) representation for spatial data, although the debate has now been extended to include object oriented discussions (Goodchild, 1992). Raster data is more appropriate for the representation of continuous data and for modelling activities, but network analysis is almost impossible using raster data. Vector data is good for representing data with discrete boundaries and good for overlay of such data and for network analysis. Recent research has facilitated the transformation between the two so that both representations can be utilised. The pay-off is the risk of error introduction in the transformation operation (known as fuzzy creep).

Entity relationship modelling is a type of data modelling, based on mathematical concepts which is particularly suited for complex attribute data. It ensures the maintenance of data integrity within the database to minimise the problem of data redundancy (duplication of the same information in different parts of the system) which can cause major inefficiencies in the database (Codd, 1982). Complex attribute data are best handled within a DBMS (Database Management System), but it is not sufficient merely to hold map elements in a database because standard database query languages do not support spatial query functions unless specially extended to do so (Healey, 1991). This is because explicit storage of spatial relationships is required to facilitate spatial queries and analyses, and a large degree of processing may be required to answer many spatial queries (such as what is adjacent to a location, or what is within a radius of a particular point). Most standard software systems, such as the one used for the case studies, handle the spatial and attribute data separately and link them through a unique identifier.

Data structures have important implications for the way data are stored and the speed with which they can be accessed and processed. If one were to overlay two complex maps, the amount of processing time saved would be considerable if topological relationships were used to build the new polygons. Another illustrative example concerns the quadtree data structure used for raster data. Successive divisions and sub-divisions of image space into quadrants can be stored in a hierarchical tree structure with nodes representing heterogeneous areas (Samet, 1989). Where there are significantly sized homogeneous areas the quadtree offers more compact storage and more efficient querying than a regular grid. However it can be less efficient for the analysis of certain sorts of adjacency problems because of the need to search up and down the tree structure. Morton indices (Morton, 1966) were introduced to alleviate this problem. They provide a means of subdividing space and assigning addresses for storage in quad tree structures in order to minimise the amount of hierarchical searching. These are merely a few demonstrative example of the many types of spatial data structure implementations. Some structures are more suited to some purposes than others, depending on the nature of the data and the query and processing demands.

Currently research is ongoing to devise data models which accommodate data on a geoid and assess their suitability for global databases. An integrated raster-vector model (Peuquet, 1988b) is thought to be needed and, to this end, a unified body of representational theory is required. Goodchild and Yang (1992) describe a hierarchical data structure for global GIS that avoids the problems of projection distortion. A regular, hierarchical, spherical tesselation would have advantages for handling nested representations of global data to minimise redundancy of information amongst different storage models. Some new work recently published by Dutton (1996) proposes a means of doing this using a notation for location that offers scale-specific positional encoding, at the same time as describing multiple characteristics using spherical quadtrees and a Quaternary Triangular Mesh (QTM).

In the future it ought to be possible for system designers to select suitable data structures depending on data use, so that a GIS should provide the opportunity to make such choices. A unifying theory which could act as a framework for such a system to integrate multiple spatial paradigms has been proposed by Herring (1989) and Herring *et al.* (1990), but remains, for the moment, at the theoretical level.

There is a growing body of research into developing methods concerned with incorporating the temporal dimension into geographic data handling and storage within a GIS. In current operational GISs time is treated as an attribute. As with space, different models are used for different temporal situations (Frank, 1994). most models currently address time as calendar time with respect to measurements on an interval scale (Barrera and Al-Taha, 1990) although work is now developing to incorporate relatively ordered events without time which uses a qualitative as opposed to a quantitative reasoning model for time (Frank, 1994). This more recent work would be applicable to the palaeoenvironmental situation where relative temporal concepts play a major role. With respect to palaeoenvironmental reconstruction, models of time which permit both calendar dates, and relative dates to handle versions of time associated with a particular set of observations are required. Such models should be able to handle variations in spatio-temporal sampling and discontinuities in temporal knowledge. Temporal GIS which are suitable for all but the most specific basic functions which are based on simple temporal concepts do not yet exist, and spatiotemporal models which are appropriate for handling palaeoenvironmental reconstruction need to be developed (e.g. Wachowicz and Broadgate, 1993). Various issues associated with temporal data are demonstrated in the following case study chapters. These examples show the difficulties of treating time as an attribute which does not reflect the dynamism of the time dimension with respect to the concepts of past, present and future. The provision of a history of change which is not possible using the attribute treatment of temporal palaeoenvironmental data, is crucial to understanding patterns of change in the temporal domain, and therefore in facilitating temporal analyses, modelling and prediction.

3.5 GIS functionality and spatial analysis

An active and growing research area is that of spatial analysis and GIS functionality (Fotheringham & Rogerson, 1995). The availability of GIS opens up new vistas for spatial data exploration and the development of new analysis techniques. Research in this area currently has a dual focus: 1) to develop new spatial techniques and 2) to develop appropriate systems architectures so that these techniques can be embedded within GIS and easily applied to the spatial data contained therein.

Functions which operate on spatial data and its attributes within or outwith a GIS can be divided into three main categories.

(i) data manipulation, querying and spatial data integration functions (e.g. raster to vector conversion, reclassification and grouping of data such as buffering, resampling, rectification, querying and data selection and display). These features are commonly found in proprietary GISs and in fact make up the vast majority of commands in these systems. They are essentially automated mapping facilities with management operations.

(ii) exploratory data analysis and modelling functions (e.g. statistical and geostatistical modelling, time series analysis, overlay, correlation, network analysis). Apart from limited methods for interpolation, and some network analysis facilities, only a few of these functions are available within most current GIS packages.

(iii) data visualisation and display functions (plots, graphical displays, three dimensional visualisations, map display, panning and zooming facilities). Many of these methods of displaying and visualising data are available in today's systems, although some, such as three dimensional display, are rather limited.

In many systems it is possible for users to create their own analysis tools using macro languages, or to use programs written in standard programming languages (such as FORTRAN) within the GIS environment.

Methods are currently being developed to utilise multivariate techniques and correlograms on spatial data, allowing the assessment of spatial structure and the quantification of spatial dependence (Cressie & Helterbrand, 1994; Dubin, 1994). Other research is investigating the suitability of GIS architecture to support spatial modelling (Densham, 1994), and the use of expert systems and artificial neural networks to facilitate spatial analysis and modelling within GIS (Fischer, 1994). Important areas of research include developing methods for tracking error propagation to enhance analysis of integrated datasets which are spatially heterogeneous (e.g. Aspinall & Pearson, 1994) and spatial techniques for global modelling and analysis in 3-dimensions (Wahba, 1981; Legates & Willmott, 1986). Advances in parallel processing, and the use of particular processing approaches for particular tasks to optimise processing in an intelligent heterogeneous processing environment is becoming a realistic and promising development (Densham & Armstrong, 1994).

The role of visualisation, both of data and of analytical results, in the development of theories, is an extremely important area where GIS has potential. "*Visualisation is a tool both for interpreting image data fed into a computer, and for generating images from complex multi-dimensional datasets*" (McCormick *et al.*, 1987). Visualisation is important for increased understanding of the problem and, exploration of the data.

It is important for communicating theories and results to third parties. All types of data analysis can be enhanced by visualisation. Humans have extremely sensitive sensory and cognitive systems for visual pattern recognition. Thus representing reality in abstract form enables us to make connections and solve problems which are at the centre of the research process (Tobler, 1961). More sophistication is required to sift through the volumes of multivariate data currently at scientists' disposal. For example Openshaw *et al.*, (1995b) have used neurocomputing methods to apply multivariate classifications to census data in the UK. The efficiency of imagery, maps and graphs and the human visual processing system can be exploited to the maximum effect in order to manage and utilise this enormous amount of information. Future directions of visualisation research are addressing the development of multidimensional (3- and 4-dimensions) data structures and GIS capabilities for temporal analysis and display, and have the potential to revolutionise research design in science (Buttenfield & Mackaness, 1991). It is already possible to use GIS to visualise problems in three and even four dimensions (Gahegan, 1996).

3.6 Data integration

GIS provides the facilities for data integration including algorithms to convert data to different map projections, and rubber sheeting algorithms which allow data to be fitted to a common base map. However, some of the most difficult and complex problems of system design and implementation are associated with data integration and data sharing and therefore have significant implications for planning and establishing a GIS. Transformation of data for integration can also involve the introduction of uncertainty.

Integration requires transforming, or rectifying all data to a standard co-ordinate system. This is important if data are to be integrated into a single data set, so that entities are accurately represented and manipulated in relation to one another. This is particularly crucial if the spatial coincidence of features on different layers is important. There are two methods of data rectification. If the projection system parameters are known with respect to the other data layers, then algorithms can be used to transform co-ordinates from one system to another. However, if the parameters of the co-ordinate system are not known then entities can be transformed using fitting algorithms (known as "rubber sheeting", or "geometric conversion" in Image Processing), as long as common points can be identified on both maps. The projection transformation method is preferable because it is usually simple to achieve and more accurate. The accuracy of the rubber sheeting depends on the number of common points which can be identified and their relative spacing. For small projects this may not be much of an issue if all the data are the same scale and map projection and, related to the same base map. However, there are limits to the size of area, and circumstances for which rubber sheeting can be successfully applied. Major projects have fallen foul of paper map series whose projection stays the same, but for which projection parameters vary from sheet to sheet. Initial work on the CORINE (details in Appendix I) soils map of Europe, for example, ran into these difficulties. It was found that both co-ordinate and thematic information were incompatible across map sheets within countries, and could be irreconcilably different across national boundaries (Mounsey, 1991).

Sliver polygons are data artefacts which can occur when maps which share common spatial boundaries are overlaid. They happen when different themes relating to the same region are digitised separately, and/or require different georeferencing procedures. Considering that map overlay may take place several times in a particular project, eradicating results which are merely artefacts and distinguishing them from the rest of the information for a large area could become a major practical issue. To avoid this problem the data preparation stage may involve transferring all the datasets to a common base map prior to data capture.

Difficulties with edge matching adjacent map sheets can also occur. The uncertainty of information contained in a series of contiguous maps sheets will vary between sheets because of the accuracy of digitising, the accuracy of map drafting and the fact that maps may have been produced by different interpreters and organisations, and may incorporate different classification systems. Approaches to this problem must be considered in the planning stages. Many difficulties experienced on the CORINE project related to the variations in timeliness, spatial coverage, density and measurement method which were masked by inconsistencies in terminology and imprecise definitions (Mounsey, 1991).

Thus the expected evolution of small systems, designed with short term goals, rarely occurs because information is unsuitable for reuse in subsequent projects. Information may not be at the correct resolution, or structured in a way that is unsuitable for the next set of requirements. In order to share data effectively it must be possible to integrate the information with all the sharing systems. If one considers that different groups and institutions may approach the design of a database in different ways then the result will be a suite of very complex data models and incompatible data structures and data dictionaries. The potential for integration at a later date will thus be very limited (Marble, 1988).

This argues for the introduction of data standards. FGDC and the US National Committee for Digital Cartographic Data Standards (Chrisman, 1984a; NIST, 1992) define basic metadata standards with particular emphasis on data quality (see the following section on metadata). However the time required for compliance with standards at the data capture stage is one factor that currently makes the use of standards unattractive to small, tightly budgeted projects. Several researchers are investigating the issues of data standards, and they are becoming an increasingly important issue for large institutions moving towards the use of digital data. This is discussed further in the following section.

3.7 Data Management

Traditional scientific methods of data collection have meant that scientists have usually been aware of the contextual information which accompanies their own data. Incorporating this knowledge into data analyses and interpretations has been routine and possible because of the individual expertise that is tied to data ownership. Paper maps were previously a fixed scale and used mainly by cartographers and surveyors who understood their limitations. Digital data are released from the scale "locking" of paper maps and can now be used at "scales" for which they have the "wrong" information (Goodchild, 1991). Whilst the resolution on a paper map is restricted by the smallest physical mark of cartography, it is not so easy to interpret the resolution of a digital map where the scale of display can be changed at will. However, as data are being more extensively broadcast and processed using computers, the consequence is that the contextual information is frequently not communicated to other parties and has been subsequently lost.

The principal problem with data processing is "knowing what methods can be regarded as valid in processing a particular data set or what can be combined and compared legitimately" (Jeffers, 1991). The key to this question lies in the provision of adequate information about the data such as how they were collected, for what purpose and with what accuracy. The major difficulty is being able to foresee what processing might be required, and therefore what additional information is necessary. Particularly in scientific contexts, it is almost impossible to know to what applications the data will be put in the future.

The umbrella term for this uncertainty and lineage data is metadata. Metadata needs to provide several distinct sorts of information. In response to the problem of metadata inadequacy, a large number of data standards have come into existence (Chrisman, 1994), although many of them are unsuitable for the scope of data types which currently require metadata definitions. Unlike the pre-computer era, users' needs are no longer as well known to the data producers (Hayes & Romig, 1977). One example is the US Geological Survey's metadata standard (Federal Geographic Data Standards Committee, 1992). The Survey have also developed an electronic means of automatically checking that data input conforms to these standards. The FGDC Standard defines metadata as follows (the elements in brackets indicate entities defined as optional, and each category denotes the top of a hierarchy of sub-categories which are not shown):

Metadata = Identification_Information
+ (Data_Quality_Information)
+ (Spatial_Data_Organization_Information)
+ (Spatial_Reference_Information)
+ (Entity_and_Attribute_Information)
+ (Distribution_Information)
+ Metadata_Reference_Information (FGDC, 1992)

Criteria defined by the US National Committee for Digital Cartographic Data Standards (NCDCDS) (Chrisman, 1984; NIST, 1992) provide another example, and include:

1. Quality Information: the spatial variation in quality for spatial data including lineage, positional accuracy, attributes, logical consistency and completeness, including temporal accuracy. Three methods of reporting accuracy are defined:

(i) Deductive Estimate: Any estimate, even a guess based on experience, is permitted. The basis for the deduction must be explained in as quantitative a manner as possible.

(ii) Tests Based on Independent Point Samples: A misclassification (or confusion) matrix for categorical data, tabulated by the categories of the sample and of the tested material. Sampling procedure and sample point locations should be recorded and described.

(iii) Tests Based on Polygon Overlay: A misclassification matrix reported as areas. The relationship between the two maps must be explained as far as possible and the two sources should be independent, with one having a higher accuracy (and therefore probably covering a smaller area) (Chrisman & Lester, 1991).

2. Lineage: Description and date of the source material(s) from which the data were derived (such as the sampling intervals and methods used), methods of derivation, any transformations which the data have undergone, the dates and source material involved in any updates, and the dates on which all these transformations, updates and additions have occurred.

There is now a need to find ways of measuring and describing error and uncertainty in maps. There are several methods which have been developed to address thematic and spatial uncertainty in categorical maps (Thapa & Bossler, 1992; Goodchild & Gopal, 1989), which consider the empirical assumptions of uncertainty within a formal model of error (Goodchild *et al.*, 1992). Such an approach allows information to be represented as sets of "mean objects", thus addressing the problem of uncertainty in boundaries derived from different map origins, as well as uncertainty in class identification and spatial heterogeneity within, for example, mapped polygons (e.g. Aspinall & Pearson, 1995). However these methods are not currently available within proprietary GIS packages for incorporation or analysis (Lanter & Veregin, 1992).

Compiling metadata for digital data input is one stage, but computers can use this information to calculate the effects of transformations and analyses on error propagation. Lineage tracking functions attach metadata to new datasets produced as a result of computer processing. Research is currently looking into developing a framework for version management, to link metadata to source data, model code, storage and retrieval and model testing information. Management of such information is important. Various developments are occurring in this area. GEOLINEUS (Lanter, 1992) is a software package which tracks system transactions to attach lineage information to newly created datasets within the GIS package ARC/INFO. ARC/INFO provides logging facilities, such that system operations are recorded as sequential chronological entries in a flat (no structure, indices or pointers) log file (a log file records system transactions as they occur). This has been utilised by specially written software to reverse-engineer basic lineage information for datasets (Lanter, 1994) (although there are limitations in that the software does not record all the operations such as sub-command parameters and user-developed functions).

Other management issues concern data volumes, particularly for the storage of the results of data processing, analysis and transformation. Having a much lower volume than the processed data, the processing information could be stored with the original data and re-applied to generate the results. This precludes the need to store large quantities of voluminous results and research is being carried out into the use of JAVA applets (applications written using the JAVA internet programming language) which would retain this information and apply it to data for delivery of results over the internet (Raper & Livingstone, 1996).

Further research is beginning in the area of managing the results of interpretation, analysis and modelling activities (Jelinski *et al.*, 1994; Evans, 1994; Chrisman, 1994; Strebel *et al.*, 1994) and can be adopted, together with other efforts, to develop a metadata framework for coverage and attribute data (Lanter, 1991, 1992). This would enhance efficiency, data sharing, co-operation and collaboration on a large scale.

3.8 Information networks

Data access and sharing rely on a medium for exchange, and on efficient communication networks. Electronic communication has enhanced the desire and ability to share information. Merit (1993) found, for example, that the chief use of the Internet was data sharing. The Internet now offers very sophisticated data access. Recent advances in networking, allow systems to operate in a distributed fashion. This means that only the processed information need be stored locally and both data and processing power can be accessed remotely, and the burden of data capture can be shared between sites and users. However, the implementation of standard practices network-wide, will be a crucial factor in ensuring that the distributed data can be integrated. This is an important management and organisational issue.

The speed of networks is increasing, and large-volume, long-distance data exchange is a rapidly diminishing problem (having attracted a lot of research attention and investment in infrastructure). There exist a number of spatial data browsers currently available on the Internet which are based on simple spatial metadata (theme, extent, scale and accuracy), and although these browsers combine user friendly interfaces with powerful search tools (e.g. Vrana, 1992; Thieman, 1992; Menke *et al.,* 1991), data browsers to date omit important data semantics. They provide merely a standard representation of information which cannot be queried more deeply in response to particular enquiries and thus may limit their usefulness to wider applications. Data dictionaries which provide information about terms, definitions, notations, formats and standards associated with particular datasets are critical to the success of data browsers (Marble, 1991). Further research is ongoing in this area because these data dictionary approaches have been developed for business operations and may not be appropriate in the scientific context.

The most realistic approach to the plethora of autonomous databases which have blossomed over the last couple of decades is that of Composite Information (or federated) Systems. These systems allow communication and information sharing across organisations and databases which are based on different data models, interfaces and organisational strategies. Unfortunately these are still very much at a theoretical level (Baker & Broadhead, 1992) and are not yet a tried and tested reality in global data sharing. Some development of test systems (e.g. Templeton *et al.,* 1987) have promising solutions. However maintaining information on, for example, data lineage for derived datasets over networks between autonomous databases is a particular problem which has not been properly addressed to date, even in the context of current Composite Information System theory (Wang & Madnick, 1989; Siegel & Madnick, 1991). Information sharing is a growing research area across disciplines ranging from computer science, organisational management science, GIS and environmental science (Evans, 1994). There is a particular challenge in locating relevant spatial information. Whereas attribute data can be searched via full text indexing, (using, for example Archive (Archie) and Wide Area Information Servers (WAIS)), there is an extra dimension of searching via location as well as theme for spatial data. The browser must be capable of assessing whether the search area and time frame correspond to any available datasets and exchange of spatial information makes it difficult to keep track of spatial relations which must be rebuilt after transfer (Evans, 1994).

Despite the major advances in technological progress, the most significant barriers to global information sharing are organisational. Personal, organisational and institutional factors are thought likely to have a profound influence on the extent to which the application of GIS techniques and the management of geographical information can be realised in practice (Campbell, 1991; DoE, 1987; Medyckyj-

Scott, 1989; Openshaw *et al.* 1990). Research into these organisational and ethical issues (technology transfer, data ownership, copyright and data security) has been slow to be initiated, but is becoming an active area of work as it is realised that these factors are increasingly important.

3.9 Addressing palaeoenvironmental requirements

It is clear that GIS offers a broad spectrum of technology and knowledge which could be used to address the issues currently restricting aspects of palaeoenvironmental research. Broadly speaking, the requirements identified in Chapter 2 comprised:

1. Comprehensive archiving and management of complex palaeo-data

2. More rigorous and quantitative methods

3. Improvements in communication throughout the scientific community

GIS provides special facilities for the storage and handling of spatial data, relationships and attributes. Many organisations are travelling inexorably down the road of digital databases because of the benefits they offer in information handling. Various examples of this move to digital data and methods are reflected in the number of large databases currently being developed, particularly concerning the state of the environment (Appendix I). GIS provides the methods and experience which palaeoenvironmental scientists can use to design and operate databases, which are tailored to their needs. Proper archiving of, and access to information and data which are at present inadequately reported is vital to the development of scientific theory. Metadata issues are akin to the requirements for comprehensive Level 1 data. Palaeoenvironmental research requires its own set of metadata standards, but has the advantage of being able to use other standards as a development base. The lineage criterion of the NCDCDS metadata standard for example is one of the most relevant to palaeoenvironmental data. The lineage element is not emphasised as much in the FGDC Standard (FGDC, 1992).

The cost of digital data capture, the issues concerning the representation of data in GIS, and the problems of data integration show how long-term planning is of paramount importance. If several scientists in an institute were to digitise their data separately, the hoped-for integration using projection and rubber sheeting algorithms would not avoid the problem of sliver polygons and edge-matching. The data would require re-capturing and this doubles the work, whereas forward planning would avoid the problem entirely. In the case of palaeoenvironmental data the volume of information associated with palaeoenvironmental reconstructions (e.g. the results of the processing and the interpretations), may be significantly greater than the volume of the original data. From a scientific viewpoint it is imperative to have a means of tracking the metainformation associated with these datasets.

It is clear that merely archiving data is very different from developing an infrastructure and concepts so that data is stored in such a way that it can be manipulated and analysed. The ability to integrate data effectively and accurately would in itself be a major step forward in looking at data interrelations and variation. Being able to integrate this information, for example, for the last glaciation in NW Europe, would put many more constraints on the possible reconstruction scenarios, and allow more rigorous testing of models and results. It is particularly difficult using conventional methods to visualise this quantity of information for such a large area, but GIS could facilitate integration and visualisation of data and proposed reconstructions together. GIS methods also provide a suite of spatial analysis and correlation methods and scope for developing specific palaeoenvironmental methods. GPS together with field-based GIS would greatly improve the locational accuracy and completeness of level 1 data recordings. The propensity for data integration with, for example, air photographs and satellite imagery would be greatly increased because the improved georeferencing will facilitate multiscale analysis. Improving the quality of level 1 data will improve the reliability of Level 2 inferences and the efficiency of data input and processing. The ability to change map projections, or in the future, to analyse data on a geoidal surface, will be a significant improvement on current manual methods, and provide more flexible use of data. New methods to describe uncertainty in data will facilitate improvements in data analysis and modelling.

The nature of space with respect to information is now changed (Abler *et al.*, 1972). The scientific community is now linked into a global community and the internet is a medium for communication and data exchange. Development in this area has been extremely rapid. A co-ordinated digital access service for environmental scientists is already being proposed as part of the US Global Change Research Program in the Draft implementation Plan for the US Global Change Data and Information System (GCDIS) (CEES, 1993). Other strategies are reviewed in Appendix I, and discussed more fully in Chapter 6 (section 6.8)

The new incentives to share data nationally and internationally, in order to investigate problems of global change, are initiating a change in scientific practices and have led to a desire to exploit the possibilities offered by information technology.

GIS provides both the methods to develop robust systems and the experience to avoid major pitfalls. From this discussion several key issues can be distilled.

1. Project planning is crucial, and includes looking at all aspects of information use, both immediate and expected. All aspects of possible system evolution should be considered including the incorporation of other data sets and the establishment of standards.

2. GIS establishment may be slow, particularly where analogue to digital data conversion is required, and since the research is distributed throughout several countries and organisations approaches will need to be compatible to facilitate data sharing and data management.

3. GIS provides the basis for a framework for palaeoenvironmental data management, integration and use. Management requirements, for example metadata and data modelling require science to scrutinise methods and approaches more closely and rigorously.

Now that the palaeoenvironmental requirements and GIS issues have been considered at a conceptual level, the next two chapters proceed to more extended case studies of two palaeoenvironmental applications that elaborate a number of these points much more fully.

Chapter 4 Case Study 1: Glacial Geomorphology

4.1 Introduction

This chapter concerns the first GIS case study. GIS is used to assemble, and perform quantitative analysis on a glacial geomorphological dataset which covers the entire Fennoscandian Shield. The analysis is much faster than has been achieved using manual methods, and allows a flexibility of experimentation and visualisation which was hitherto impossible. In addition, it has facilitated the integration and storage of detailed information over a large area, at a scale and accuracy not previously achieved.

The geomorphological evidence, and the means of using it to derive palaeoenvironmental reconstructions are described in Section 4.2. The data are discussed in terms of the observational and measurable evidence (Level 1 data) and its transformation to palaeoenvironmental inferences (Level 2 data). Data derived from satellite imagery is discussed in most detail because it is the dataset used in the case study. The spatial reconstruction of glacial phenomena through time (Level 3 data) is then reviewed. The related datasets (such as dating methods and models) required to achieve Level 3 data using Levels 1 and 2 data are then summarised to demonstrate the breadth and depth of information required to support the evolution from observational data to reconstruction. The interrelationships between data, and transformations between levels, are then analysed. The analysis comprises a summary of current practices, and identification of the reconstruction method used to determine a set of information management and analysis requirements.

The development of GIS to handle glacial geomorphological data and to facilitate reconstruction is then examined (Section 4.3). The work focuses on the use of landforms mapped using satellite imagery. This technique gives a regional overview of macro-scale glacial dynamics over the Fennoscandian Shield and is a key dataset for the study of glacial evolution. The steps involved in system development, and the fast, flexible and innovative analysis, and visualisation of the data are described. The system has been designed to accommodate the addition of further data and analysis capabilities, and these future developments are described. These show the increasing benefits of the system beyond the establishment phase. The benefits of using GIS concepts and tools and the issues associated with the current research practices and system capabilities are then reviewed (Section 4.4). The chapter concludes (Section

4.5) with a set of further requirements for the palaeoenvironmental research community and GIS.

Glacial geomorphological data is one of the most important sources of information about the formation, evolution and decay of ice sheets through time. Ice sheet growth and decay are important reflections of climate change and have implications for isostatic subsidence of the earth's crust and the rise and fall of sea level. They also control meltwater influxes which have profound effects on ocean circulation and, consequently, hemispheric heat transfer. These effects can influence atmospheric circulation. Atmospheric perturbations can also be caused by the topography and temperature of large continental glaciers (Heinrich, 1988).

During the last glaciation significant ice sheet growth is thought to have begun around 25,000 years BP in Fennoscandia reaching a maximum at around 20,000 years BP (Lundqvist, 1986b). The ice sheet was estimated to have been over 2.5 km thick (Denton & Hughes, 1981; Oerlemans, 1981). This information has been derived by examining the remains left by these large ice sheets together with related phenomena such as sea level change.

4.2 Glacial Reconstruction

The main objective of glacial geomorphological studies is to understand the evolution of past ice sheets and glacial climates through time and to draw conclusions about the climate system. Mechanisms of ice sheet growth and decay may be derived by analysing their effects on the landscape and by considering their relationship with other phenomena such as sea level change. Information about the size, position, mass distribution and timing of ice sheet growth and decay are required in order to do this.

Glacial processes of erosion, debris entrainment, transport and deposition are governed by the behaviour of ice in different parts of glaciers and the material over which it flows (Collins, 1990). Sedimentological analysis and detailed mapping of ancient landforms, reveal information about the extent and thickness of former ice sheets. The directions of ice movement and ice limits through time can be derived and, in rare circumstances, enough evidence may be available to detect the height of the former ice surface in certain locations. The ice sheet is reconstructed by putting this information together in a single spatial framework. Present day glaciers can be used as analogues for interpreting past remains (e.g. Boulton, 1972). However, the very large continental glaciers of the past may not have behaved in similar ways to present day glaciers which are much smaller and respond to very different climatic environments. Studies of major ice sheets in Antarctica and Greenland have been helpful in understanding present day glacial processes in the spatial domain. However, these processes are not entirely understood because of the difficulty of observing all but their surfaces and edges. Thus glaciologists and geologists have relied on theoretical considerations, particularly through the use of glacial models.

There have been numerous studies to reconstruct the flow dynamics of the former mid-latitude ice sheets from the landforms they left behind, (e.g. Ljungner, 1949; Sugden, 1977; Boulton *et al.,* 1985; Dyke & Prest, 1987), and particularly to look at the changes in ice sheet flow activity through the superimposition of lineation patterns (Punkari, 1985; Boulton & Clark, 1990a). Research has also focused on the role that ice streams play and in the flow dynamics of past ice sheets (Punkari, 1984; Shabtaie & Bentley, 1987; Allen *et al,* 1987; Huybrechts & Oerlemans, 1990). These studies have used combinations of field information and, more recently, remotely sensed data, to reconstruct these flow patterns. Interpreting palaeolandforms has been done with the help of studies of present day glaciers (particularly in the Antarctic, Greenland, Patagonia, Sptizbergen and Iceland), and evidence from other proxy measurements (such as palaeosealevels, palaeotemperatures, palaeovegetation etc.). Currently there are several variants of a deformable bed hypothesis (Menzies, 1989) to explain these depositional landforms. They are thought to occur only under warm based ice sheets where the glacier is not frozen to its bed (Menzies and Rose, 1987). It is thought that high pore pressures reduce subglacial effective pressures and allow unconsolidated sediment to be deformed. Subglacial moulding and streamlining can form as a result of subglacial stress variation (Boulton, 1987). Subglacial sediment may be mobilised by anisotropic conditions caused by localised freezing and dissipation of pressure and water by sediment pores which reduce the effective pressure. Thus the development of flow parallel features depends on the capacity of the sediment to discharge subglacial meltwater and dissipate pore water pressure (Boulton & Jones, 1979; Aario, 1987; Menzies and Rose, 1987). Three subglacial warm-based bedform types have been identified (rigid, deformable and quasi- rigid/deformable) which depend on the meltwater discharge rate, the ice velocity, and temperature, to determine how the sediment will deform. It has also been suggested that basal meltwater can form drumlins and streamlined features, by filling in the subglacial cavities at the sole of the ice sheet formed by catastrophic subglacial floods or subglacial meltwater erosion (Shaw, 1983; Sharpe, 1987). This hypothesis has been used to explain the fact that some drumlins show no signs of deformation in contrast to the previous hypotheses.

Specific landform types are thought to relate to specific parts of the ice sheet (Aario, 1987; Sugden & John, 1976; Prest, 1968). In some models only one stage (the maximum glacial extent) is responsible for most of the landforms. The formation of glacial features is also thought to be dependent on the length of occupancy time of the ice sheet in a particular location. The problem with this research has been that the size of the area thought to have been occupied by the ice sheets is very large, covering several countries. It has therefore been difficult to gain a coherent picture of evidence over such a large area.

The following sections give an overview of the observations and measurements used in glacial geomorphology and the related data required to derive information about ice sheet evolution. The information is classified according to the levels discussed in Chapter 2 (Level 1: proxy measurements; Level 2: palaeoenvironmental parameter derivations from level 1 data; Level 3: spatio-temporal correlation of level 2 data to achieve palaeoenvironmental reconstructions of features)

4.2.1 Levels 1 & 2 Data

Glacial formations are found extensively throughout Scandinavia. The different sizes of observable features depend on the resolution of the sampling techniques. There are generally four broad scales of observation and mapping used to study glacial features. These range from high resolution microscopy (which allows the origin and transport processes of glacial sedimentary components to be inferred, from grain shape and sedimentological analysis), field mapping and surveying, to aerial photography and satellite imagery. The detection and use of the landforms derived using these methods, the theories used to infer ice sheet evolution and the related data required to undertake reconstructions are discussed in the sections below.

4.2.1.1 Field Information

Several types of landforms can be identified at the field level. Terrestrial depositional landforms can be classified with respect to their formation processes, and therefore used to locate different palaeoglacial positions. Table 4.1a lists examples of landforms and indicates their relation to ice flow direction, and the glacier. This classification is based on a scheme generated by INQUA (Goldthwaite & Matsch, 1989) and one originally published by Sugden and John (1976). Similarly classifications have been produced for glaciofluvial (Table 4.1b), glaciolacustrine and glaciomarine sediments. Macroscale feature and microscale grain morphological studies, sedimentological and facies analysis all contribute to elucidate the feature

Table 4.1a Classification of glacial depositional landforms according to position in relation to glacier and ice-flow direction. Glacier surface features before the ice has totally melted are included, but glaciotectonic landforms are excluded, after Hambrey, 1994.

Position in relation to glacier	Relation to ice flow	Landform	Scale
Subglacial; still actively accumulating	Parallel	Lateral moraine	10 m - 100 km
		Medial moraine	10 m - 100 km
	(Transverse)	Shear/thrust moraine	1 m - 1 km
		Rockfall	1 m - 1 km
	Non-orientated	Dirt cone	10 cm - 1 m
		Erratic	ca. 1 m
		Crevasse filling	10 cm - 100 m
Subglacial during deposition	Parallel	Drumlin	10 m - 10 km
		Drumlinoid ridge	50 m - 10 km
		Fluted moraine	10 m - 1 km
		Crag-and-tail ridge	10 m - 10 km
	Transverse	De Geer (washboard) moraine	10 m - 1 km
		Rogen (ribbed) moraine	10 m - 1 km
	Non-orientated	*Ground moraine:*	
		till plain	1 - 100 km
		gentle hill	10 m - 10 km
		hummocky ground moraine	1 - 10 km
		cover moraine	1 - 50 km
Supraglacial during deposition	Parallel	Moraine dump	10 m - 1 km
	Non-orientated	Hummocky (or dead ice/disintegration) moraine	50 m - 100 km
		Erratic	1 - 10 m
Ice marginal during deposition	Transverse	*End moraines:*	
		terminal moraine	10 m - 100 km
		recessional moraine	10 m - 10 km
		Annual (push) moraine	1 - 10 m
		Push moraine	10 m - 5 km
	Non-orientated	Hummocky moraine	10 m - 1 km
		Rockfall	1 m - 1 km
		Slump	1 m - 1 km
		Debris flow	1 m - 1 km

Table 4.1b Classification of glaciofluvial erosional and depositional landforms according to position in relation to the glacier margin. The scale range refers to the maximum linear dimension of the landforms, after Hambrey, 1994

Position	Process	Landform	Scale
Subglacial	Erosion by subglacial water	Tunnel valley	10 - 100 km
		Subglacial gorge	10 m - 50 km
		Nye (bedrock) channel	1 - 500 m
		Channel in unconsolidated sediment	10 m - 100 km
		Glacial meltwater chute	1 - 10 m
		Glacial meltwater pothole	10 cm - 10 m
		Sichelwannen	10 cm - 1 m
	Deposition in subglacial channels, etc.	Esker	10 m - 100 km
		Nye channel fill	1 - 10 m
		Moulin kame	1 - 5 m
		Carbonate film and cornices	0.1 - 5 mm
Ice marginal	Ice-marginal steam erosion	Meltwater (or hillside) channel	100 m - 10 km
	Ice contact deposition from meltwater and/or in lakes	Kame field	100 m - 10 km
		Kame plateau	100 m - 10 km
		Kame terrace	50 m - 5 km
		Kame delta (delta moraine)	50 m - 100 km
		Crevasse fillings	50 cm - 1 m
Proglacial	Meltwater erosion	Scabland topography	50 - 100 km
	Meltwater deposition	Outwash plain (sandur)	100 m - 50 km
		Valley train	100 m - 50 km
		Outwash fan	100 m - 50 km
		Pitted plain	100 m - km
		Outwash delta complex	100 m - 50 km
		Kettle hole/pond	1 - 500 m

types and their origins. Relating the feature types to their formation processes allows the components and nature of parts of past glaciers to be located. Sedimentology can also be used to identify sediment provenances which allow glacial transportation paths to be mapped. Erosional features have also been classified and related to different glacial processes (Sugden & John, 1976). However, it is more difficult to use erosional evidence since it cannot easily be dated or correlated with other glacial features.

Field observations and records are concentrated in areas which are most accessible and therefore there is some imbalance in the spread of information across areas. For example, there may be a lot of information offshore but it is not easily observable. It has been difficult to establish an accurate deglaciation chronology for much of Western Scandinavia because of the difficulty of correlating moraines between different Fjord regions (Marthinussen, 1974; Andersen, 1979). Many of the moraines are submerged and therefore difficult to study and date.

The issues associated with field studies are that detailed measurements and field descriptions are not formalised for integration with other observations, and are retained for the most part by the individual field scientist. Consequently data is not available for use by other scientists. In addition locational accuracy is dependent on the quality of the paper base map, and it is difficult to relate features accurately to other scales of study (for example aerial photography and satellite imagery).

There are many controversies about the origin of features. For example end moraines are an issue of contention. Do they represent only successive phases of glacier retreat, or do some reflect glacial readvance or glacial surging? Furthermore, there is no widely accepted, universal, classification of glacigenic sediments. Some progress has been made towards addressing this issue through INQUA (e.g. Goldthwaite & Matsch, 1989, mentioned earlier), but scientists are under no obligation to abide by proposed standards. This is particularly important because there are often difficulties in distinguishing between different glacigenic sediments in terms of their origin (i.e. whether a sediment is glacial, fluvial, aeolian, marine or lacustrine in origin) and mis-diagnosis cannot be checked without field data.

There are also many controversies about terminology which determine the temporal relations between the various ice sheets (for example the Scandinavian, British, Russian and Barents Sea ice sheets and shelves). These differences in opinion are important because they have considerable bearing on the estimation of ice-water volumes used to calculate the oxygen isotope parameters and to produce different global atmospheric circulation patterns (Dawson, 1992).

4.2.1.2 Remote Sensing

Macroscale features can be identified on aerial photographs and satellite images, with the advantage that large areas can be covered more completely and more homogeneously using these techniques compared to field studies. In addition, interpretation over an area can be carried out by one individual so the problem of combining data gathered from different origins, at different scales, and using different interpretational preferences, is minimised. Many of the features which can be mapped using aerial photographs are visible on satellite images. Images enable the identification of macroscale features too large to identify on a single aerial photograph. They are less time consuming to interpret because fewer images are required to cover a large area. The size of features which are observable depends on the resolution of the technique being used. Air photos, have a resolution of a few metres and LANDSAT MS and TM satellite imagery have pixel sizes of 80 m and 30 m respectively. The linear trends and spatial distributions of features mapped using these techniques are a major source of evidence for reconstructing former glaciers. Various hypotheses were discussed earlier (Section 4.2) about the origin of streamlined bedforms that indicate the breadth of possible glaciation mechanisms used to explain the occurrence of landforms and infer the nature of the processes which formed them against which the observational data is compared and tested. As hypotheses develop it is necessary to revisit data in order to reinterpret it and to make new spatio-temporal analyses of glacial landforms and sediment.

Interpretation of glacigenic landforms from satellite images has been used in many areas and provided new insights into the dynamic behaviour of palaeoglaciers (Punkari, 1980, 1985; Boulton *et al.*, 1985; Boulton & Clark, 1990b; Donglemans, 1995). Interpretation has been visual using enhanced black and white, and colour-composite, images. Auto-classification has been found to be unhelpful in this type of study since the spatial pattern of lineations is most important (Punkari, 1993). Features which can be identified are erosional forms, drumlins, transverse and longitudinal morainic ridges, hummocky and marginal moraines and glaciofluvial formations. The size of discernible features depends on the resolution of the imagery. The morphology of landforms is distinguished by changes in vegetation and moisture conditions. Changes are picked out by the visual and near infrared spectral bands.

This method of differentiating surficial deposits is called geobotanic interpretation (Punkari, 1982; 1985). Very small drumlins are not visible on satellite images (those which are less than or close to the resolution of the imagery), but the spatial coherence of drumlin forms over a large area is much more discernible using satellite imagery, than using any other technique.

The steps used in the interpretation of these features, to explore glacial evolution are detailed in Dongelmans (1995) and are described briefly below:

1. Groups of lineations are identified that form a coherent (often lobate) spatial pattern
2. Features are checked using geological maps to eliminate those of bedrock, as opposed to glacial, origin.
3. The age relations are double checked on different images to establish relative ages using lineation cross-cutting and superimposition (determination of age relations is described in the dating Section 4.2.1.4 below)
4. These patterns and relative ages are compared with known glacial phases.

Inferences made from palaeo-glacial features depend on the accuracy of the models and theories upon which inferences are based. Possibly one of the biggest problems with the interpretation of glacial lineation data is the diachronous nature of the landforms. This makes the assignment of different features to different snapshots in time extremely difficult. Studies of the Ra moraines in Southern Norway, for example, have shown that these features are not the same age throughout their length (Mangerud, 1980).

However linking field measurements to features on satellite images can be more problematic since most of the imagery used is not georeferenced and corrected and therefore it can be difficult to identify locations in relation to ground measurements unless some prominent proximal feature is available for orientation purposes. Interpretations are usually transcribed by hand on to base maps, and this process can introduce major locational errors. This is particularly the case for images which are not properly corrected and georeferenced. These errors are compounded because other information is also transferred to a common reference system using the same techniques. The time consuming nature of inter-map transcription means that generalisation often takes place at the same time in order to reduce the amount of information which must be transferred. This can cause significant information loss.

It is also very important to know the contextual information when interpreting landforms. Morphological features such as the Salpausselkä moraines in Southern Finland could be interpreted geomorphologically from remote sensing as end moraines. However, the sedimentological evidence suggested that they are sediment accumulations in fracture zones parallel to, but possibly some distance from, the ice front (Virkkala, 1963; Hyvarinen, 1973). Other work, however, argues that they are marginal, but may be interlobate in their lateral parts (Punkari, 1985). Further complications arise because the glacial remains may incorporate sediments and landforms produced during former glaciations (Mangerud, 1991a). These interpretational issues are major obstacles to discovering the true nature of the last NW European ice sheet and underline the importance of being able to make frequent reassessments of the available information.

Despite the availability of methods to date landforms, Hambrey (1994) notes that the study of glacial and related landforms has proved to be an unreliable method of establishing glacial chronology. Further complications arise because of the contention between use of the different chronostratigraphic terminologies of the different countries (Dawson, 1992).

4.2.1.3 Dating

For macroscale features, a chronology can only be established in two ways. Where lineations cross-cut, or are superimposed on others, relative dating between associated patterns is possible. Alternatively, features can be related to dated ground observations. This is harder to achieve because it is difficult to relate image features accurately to locations on the ground.

There are several methods used to date field evidence. These approaches are discussed in more detail in the following chapter with respect to sea level data. Most of the methods involve dating of non-glacial remains found incorporated within, or between successive glacial deposits. These are usually organic layers formed during glacial retreat, which constrain the glacial depositional phases (Punkari & Forsstrom, 1995; Liivrand, 1991). Dating accuracy depends on the correct recognition of the circumstances of any dated material, and the resolution of the dating technique. For example, if organic beds are incorrectly thought to be *in situ*, then the sediment beneath is interpreted as being older than the organic horizon. Re-worked material is not always recognised as such. Most of these methods are also used to date other palaeo-features than those associated with glaciations, and the techniques are fairly standard. These dates also have implications for other palaeoenvironmental parameters, such as temperature and vegetation coverage. Therefore, as with sea level interpretations (Chapter 5), the methodological techniques and standards associated with the dating methods are important sources of information which are required irrespective of the particular palaeoenvironmental phenomenon which is being investigated. The contextual information associated with a particular date (such as the material dated, the landform and sediment context, and the position in which the material was found) will help to discriminate reliable dates from those which are less certain. The list below gives an indication of the variety of techniques used to date glacial sediments and therefore the complexity of correlating, not just between sedimentary sequences and landforms, but between the techniques used to date them, which vary in their reliability and resolution.

Radiometric Techniques
    -Radiocarbon Dating (Klein *et al.*, 1982; Otlet *et al.*, 1986).
    -Uranium-Thorium Methods (Ford *et al.*, 1972, 1981, Kaufman, 1986).
Amino Acid Racemization or "Aminostratigraphy" (Abelson, 1954; Wehmiller *et al.*, 1988;)
Obsidian Hydration Dating (Pierce *et al.*, 1976; Trembour & Friedman, 1984).
Lichenometry (Griffey & Matthews, 1978; Innes, 1985; Erikstad & Sollid, 1986)
Tephrochronology (Wilcox, 1965; Westgate & Gold, 1974; Knox, 1993)
Palaeomagnetism (Tarling, 1971; Thompson *et al.*, 1975; Easterbrook, 1988)
Thermoluminescence (Dreimanis *et al.*, 1978; Singhivi & Mejdahl, 1985; Berger, 1988)
Dendrochronology (Damon *et al.*, 1972; Baillie & Pilcher, 1973)
Varve Chronology (de Geer, 1940; Schlüchter, 1979; Lundqvist, 1980)

4.2.2 Level 3 data

Methods of obtaining level 3 data involve correlating features spatially to determine the temporal variations in patterns left by the feature-forming processes. Features are mapped and correlated according to similarities in sediment and stratigraphy, and through the use of dating methods. The identification of spatial patterns is used to correlate landforms derived using satellite images. These patterns reflect variations in the direction and intensity of glacial flow. Inferences made from these features determine the size and position of the ice sheet and surrounding topography. They have implications for changes in the quantities and directions of meltwater discharge, and the isostatic effects on the lithosphere.

Recognising spatial patterns and identifying features relative to their formation mechanisms are crucial aspects of reconstructing the location and evolution of glaciers through time. The scale of information is important because small features such as glacial striae show a higher degree of directional variation. Smaller features are more easily formed than macroscale features, and reflect the local scale topography (Kleman, 1990). Particular features have their long axes parallel to ice flow directions (e.g. striae, drumlins, flutes). Superimposition of one direction on top of another is not always evident, but allows relative dating of the flow directions and therefore the relative dating of lobe patterns (Lagerbäck & Robertsson, 1988; Rose 1987). Coherent lineation patterns comprise contemporaneous sets of lineations. Such patterns of macroscale landforms can be identified to map ice streams at a regional scale. Before satellite images were available these very broad scale patterns were hard to see. They extend over areas equivalent to a single air photograph and it is difficult to identify features that are the same size as, or bigger than the scene being viewed (Lillesand & Kiefer, 1987). However integrating these features over a large area using several images which overlap in order to identify lineation patterns is problematic using manual transcription methods.

The spatial interpretations of glacial lineation features are based on several theories. Many theories are contested and a variety of views exist. Some suggest that flow was radial from the centres of glaciation, known as ice domes (topographically high point centres) and ice divides (linear centres), leaving radially aligned features (Gluckert, 1974; Kurimo, 1980; Punkari, 1985). It has been suggested that erosion under the ice divide was very weak (Lundqvist, 1986a). As glaciation proceeded it is thought that the flow became progressively more lobe like from being a sheet-like flow, although this is difficult to prove (Punkari pers. comm., 1996). The centres of these ice streams had the highest velocity ice, and erosional streamlined bedforms appear to be more widespread upstream, towards the apex of the lobes, with depositional forms probably being formed 2-300 km from the ice margins (Punkari, 1985). In addition, areas between ice lobes are postulated to have left few formations and consisted of passive or stagnating ice. It is thought that these areas underwent much less erosion, and therefore are the most likely areas where older landforms will have been preserved (Punkari, 1980). These interlobate areas are thought to have been dominated by compressive flow, which incorporated subglacial debris into englacial or supraglacial positions, and are thought to be preferred centres of fluvio-glacial activity (reflected in the large numbers of eskers preferentially found in such areas). These theories can be used to interpret the landform patterns but the landform patterns can equally influence the currency of theories. Calibrated ice marginal positions are used to delineate the edges of the lobes and ice streams, based mainly on the pattern of the lineations relative to the marginal positions (determined using correlated and dated moraines). Much of the interpretation often starts by using the patterns and dates of end moraines to help identify which lineations are associated with the ice lobes whose extents are marked out by these end moraines.

The means of correlating level 2 data to produce level 3 interpretations is very much dependent on the theoretical concepts and beliefs adopted by the individual in terms of ice sheet evolution and the mechanisms of formation of glacial geomorphological features. Interpretations are dependent on the quantity of quality information which the interpreter uses. For example if the dates or locations of end moraines are wrong, the interpretation will be flawed. Interpreting ice flow directions, identifying ice streams, ice lobes and hence ice sheet dynamics, through time, from hundreds of lineations interpreted from satellite images, can be a challenge. It must be remembered that most of these features are probably time transgressive. They may also include information from previous glaciations. In addition many lineations may represent manifestations of bed rock linear features not closely related to glacier directions. A high degree of experimentation with landforms for interpretation, is required to test theories and obtain the suite of glacial models which best describe the glacial states through time. This degree of flexibility is limited at present by the time required to manipulate the data using paper maps.

4.2.3 Related Information

A large quantity of related information is required with geomorphological data to generate glacial reconstructions. The glacial record is correlated with, and timed using, many palaeoenvironmental indicators (and *vice versa*). Major changes in ice frontal position are reflected in the deep ocean sediments through variations in sedimentation rates, and sediment composition. They also correspond to changes reflected in the migration of beetles and vegetation, and growth variations of cave deposits. Sea level fluctuations, species of pollen spores and mountain glacier fluctuations in the tropics also reflect to a greater or lesser degree the changes which caused ice sheet growth and decay. Correlating this evidence with the glacial landform record aids the temporal correlation and determination of ice frontal positions and ice dynamics. It is also vital to know where non-glacial features are located, at what times, and with what palaeotemperature inferences, in order to help constrain reconstructions. These related datasets can be divided into two main categories: 1) methods and guidelines; and 2) related data sets used in the derivation of glacial geomorphological reconstructions. Examples of these are outlined below:

1) Methods and guidelines

- Dating techniques

  Methodological standards and guidelines associated with dating techniques are required. The relationships between methods are needed so that measurements made using different techniques can be compared, and dates derived using older techniques updated.

- Formation Theories

  Theories on the formation of glacial features and means of identifying these features for comparison with measurements. This would include studies of present day analogues.

- Standards

  Glacial sediment classification schemes allow identification and documentation of field evidence. The most universally acceptable are those for classifying sediment fractions, grain size and morphological descriptors.

2) Related data sets used in the derivation of glacial geomorphological reconstructions

- Topographic maps

  These are required for many reasons, but particularly because both topography and geology exert control on glacial evolution and meltwater drainage. Topography also interacts with isostasy and sea level measures which are required to calculate palaeotopography.

- Geological maps

  These are important for determining the types of basement over which ice flowed, to look at ice sheet basal conditions, provenances (particularly those of erratics) and to distinguish bedrock lineations from those of purely glacial origin.

- Dynamic Models

  Glacial Models These models are useful for helping to understand the importance of different parameters on glacial evolution and dynamics. Geomorphological data can be used to test them.

  GCMs (general circulation models) It is helpful to involve simulations of the response of the atmosphere to inferred distributions of sea surface temperature, the extent and altitude of former ice sheets, the former distribution of lakes (requires ice extents as an input) (Kutzbach & Wright, 1985; Berger, 1979) and to look at, for example, the orographic effects of the Norwegian mountain range.

  Crustal isostatic models These models are discussed in more detail in the sea level chapter (5). They facilitate the integration of glacial and sea level reconstructions.

- Pollen records

  Ice sheet advance and retreat deposits can be correlated with pollen records. For example the Grand Pile pollen sequence provides a continuous record of climatic change from the Eemian (the last interglacial) to the Holocene (current interglacial) (Woillard & Mook, 1982).

- Cave deposits

  Some information about the timing of melting can be derived from speleothem growth which can be dated using radiometric techniques (speleothem deposits grow in response to an increase in ground water provided by glacial melting). These growth phases can be correlated with glacial deposits and varves in fluvioglacial sediments.

- Deep ocean records

  These can also provide a climate-related chronological framework. They include sediment accumulation rates, oxygen isotope compositions etc. (e.g. the SPECMAP curve of Imbrie *et al.*, 1984) from ocean cores against which glacial phases can be correlated.

There are several issues associated with this "related data". It is difficult to manage the complexity of sites and correlations using different information given the number of different relations and the quantity of data. Comparison is poor between models and data because model output must be compared with numerous small, usually generalised, maps of field data.

4.2.4 Reconstruction Requirements

In summary, to carry out a glacial geomorphological study the following sets of information are required:

I **Background Information (Level 2 and 3 data and Related Data)**

-Review of current glacial theories and state of knowledge about the area (Level 3 Data)

-Specific information about particular areas
(state of current Level 2 Data)

-Current theories and state of knowledge about glacial processes
(Related Data)

II **Focus Data (Level 1 and Related Data)**

-Glacial data (usually new)
(Level 1 Data, but could be Level 2)

-Geological, hydrological, topographical, base and drift information
(Related Data)

III **Methodological Information Linked to Level 1 Data (Related Data)**

-What measurements may be made and how

-Accuracy guides of methods and measurements including assumptions made

-Process, static and dynamic models

IV **Data handling and analysis methods relating to Level 2 and 3 Data**

-Visualisation

-Generalisation of detailed information over an area to produce a regional picture

-Selection of particular data elements for processing

-Analysis of directional information (if glacial dynamics are being investigated)

-Correlation either stratigraphically, spatially or both

Conventional methods of research generally focus on II and IV, with I and III being traditionally literature review activities. Section 4.3 discusses the exploration of a proprietary GIS in facilitating stages II and IV in particular, and discusses the issues associated with I and III.

The numbered points below summarise the issues associated with current practices of palaeoenvironmental reconstruction identified in the above sub-sections:

1. The size of the features to be reconstructed are much larger than the size of field studies

2. The area thought to have been occupied by the Fennosciandian ice sheet covers four different countries with different datum levels, languages and methodologies)

3. The spatial resolutions of measurable features vary from micro to macro scales, and therefore reconciliation between scales is difficult.

4. Temporal correlations are difficult because of the lack of dates and the fact that many features may be time transgressive.

5. Interpretation of the features to be integrated over a large area varies considerably.

6. Features can be located disparately as well as inaccurately, which complicates analysis of relative feature locations, and integration of different features and data types.

7. Paper maps offer limited flexibility for feature visualisation, selection, detailed data integration over a large area, rigorous analysis and theory testing.

Many of the current transformation processes involve methods which are neither rigorous nor quantitative (Table 4.2 Data Issues and suggested GIS solutions). The benefits of GIS in addressing these issues and requirements are investigated in the following section.

Table 4.2 Satellite Imagery and Aerial Photography based investigation of Palaeoeglacial Environments

	Level 1 Data	Level 1-2 transformation	Level 2 Data	Level 2-3 transformation	Level 3 Data
Current practices	Satellite images Air photos	Digital image processing Visual interpretation	Hand drawn lines representing linear features of different ages	Visual generalisation Visual separation into age phases	Generalised lines (ice direction, ice frontal positions, ice divides)
	Field Data	**Detailed ground truth** **Field mapped data** **Aerial photographs**		**Transcription of other field mapped features** **Sedimentological field evidence**	
		Geological and topographic maps *Vegetation cover data*		*Geological and topographic maps* *Standard oxygen isotope and pollen curves*	
				Sea level data	
Data issues	Digital data (pixels) Hard copies of images (georeferenced and not georeferenced)	Information loss from visual interpretation Time-consuming to revisit and alter interpretations Significant feature location inaccuracies	Variablility in the certainty of boundary location Multiresolution features	Information loss complexity of lineations Differences of realting all possible ground evidence to image integers Time required to transcribe different data sets to common basemap	No measure to relate final interpretations to original data Limited visualisation
		Misinterpretation through inaccuracies in geology map overlay		Limited flexibility for testing scenarios because of time required to integrate data	
GIS improvements	Raster representations	On-screen digitising and editing digital image back-drop Detailed surface topography derived from stereo pairs of air photos	Vector lines and polygons Fuzzy boundaries Digital elevation models (DEM)	Quantitative analyses of features Rigorous generalisations Surface visualisation and morphological analysis	Quantified, measurable, results to support hypotheses
		Accurate ground truth location Retrieving detailed sedimentological and field data by location Full integration of field evidence with macroscale studies	Improved locational accuracy (GPS for field observations / accurately georeferenced images)	Improved visualisation	High degree of possible experimentation System manages data, scientist free to concentrate on research
		Accurate map overlay			

Data required to achieve transformation:

Other scales of Levels 1, 2 and 3 glacial geomorphology data

Related data

Other level 2 & 3 data

4.3 A GIS based study

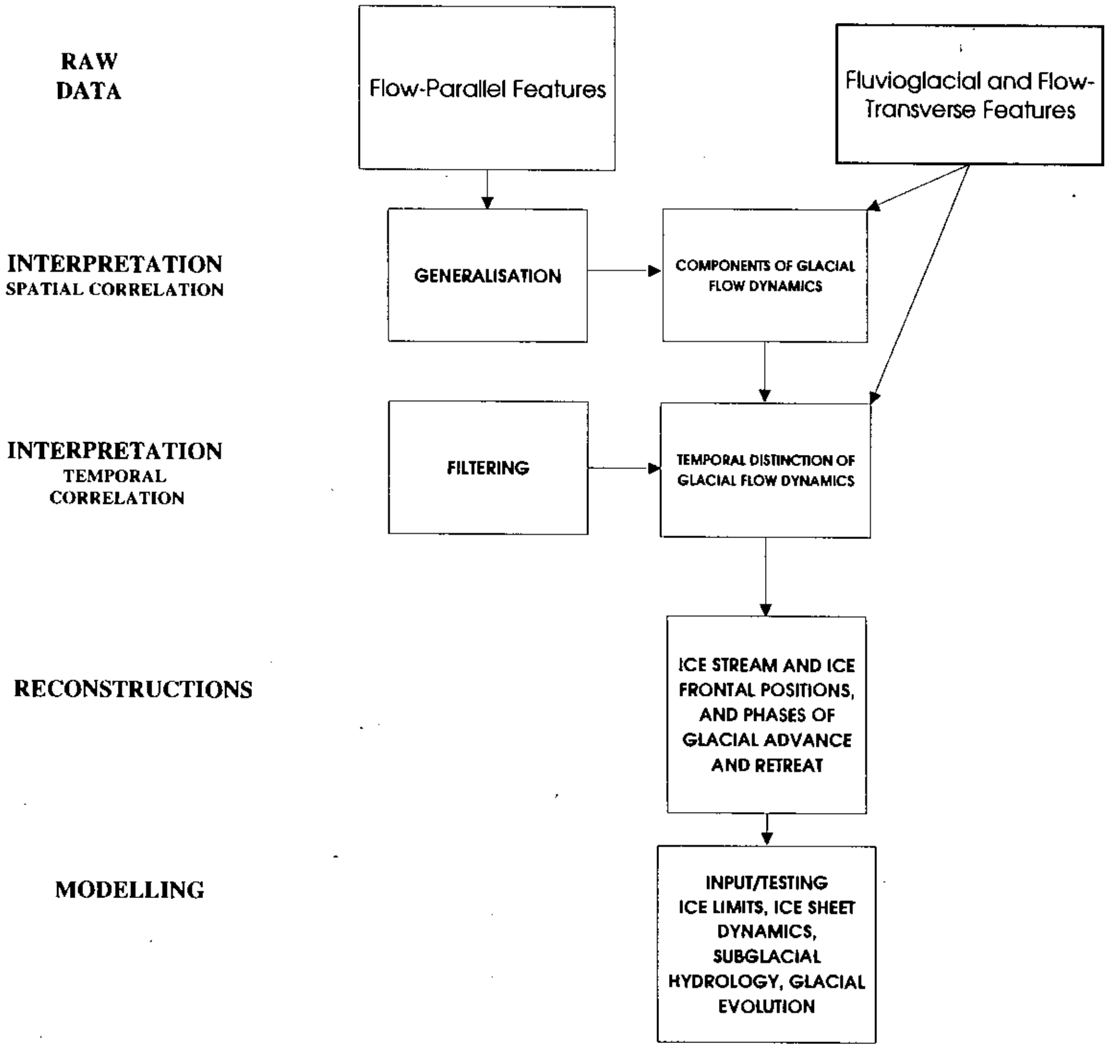
The aim of this study is to utilise methods and techniques offered by GIS to improve palaeoenvironmental research using glacial geomorphological information. In essence the objective was to explore the potential role of GIS as a methodology and set of tools to improve palaeoenvironmental reconstruction and to address the issues identified above. The GIS manipulates and analyses raw data to facilitate their transformation through spatial and temporal correlation to support reconstructions which can be integrated with glacial, hydrological and crustal deflection models (Figure 4.3).

The GIS ARC/INFO is used in this study and was selected because it was available and incorporated all the functionality commonly offered by most systems. The system chosen was a mainframe/workstation-based product. Because of the size of data sets related to North West Europe and the processing envisaged, a PC-based GIS would have been inadequate in terms of disk space, processing power and functionality.

4.3.1 Background to Case Study

The case study focuses on the application of GIS to support glacial reconstruction using data derived from satellite imagery and national drift maps. The focus is therefore on macroscale landforms. The dataset provides a subset of information which covers the entire Fennoscandian region. This information helps draw conclusions about the large scale glacial dynamics and geomorphological relationships for most of the former ice sheet. It was selected because it provides a complete dataset which is manageable in terms of data collection, time, and cost. The spatial complexities of this data means that it is more difficult to integrate than the sea level data, which exist as discrete geographic co-ordinates. Consistency of data has been maintained by using satellite image interpretations generated by only two researchers working in close collaboration. This ensures compatibility of interpretation and therefore comparability of results over this large area. The datasets are discussed below. The first (Section 4.3.1.1) relates to the satellite image derivations and the second (Section 4.3.1.2) to interpretations from national maps. The characteristics of the datasets are discussed in order to describe the rationale behind the database design described in a subsequent section.

Figure 4.3 Manipulation and Analysis Requirements of Glacial Geomorphological Data



4.3.1.1 Satellite Imagery Data

The satellite data exist at two principal scales, although for one small, northern section higher resolution imagery has been used where that was all that was available. The imagery consists of thirty-two LANDSAT MSS (79 m resolution) and four LANDSAT TM (30 m resolution) images. These higher resolution TM data are approximately 1:400,000 scale, and the georeferenced mosaics of LANDSAT MSS data at a scale of approximately 1:1,000,000. In all cases the image scale quoted is based on the photographic versions of the images, which were used for the interpretations. The data consists of interpretations by Pieter Dongelmans and Mikko Punkari, made from hardcopies of satellite images. The methods of interpretation have been described in section 4.2. The coverage for the respective scales of imagery, and the locations of the images are shown in Figures 4.4a (MSS and TM single images) and 4.4b (MSS Mosaics). As it is important to differentiate correctly between flow parallel or flow transverse landforms, the interpretations were checked by the interpreters using field survey and conventional aerial photographic information. Essentially there is a difference in resolution and scale between these image sets which has resulted in a difference in the degree to which the results have been generalised. Linear features which were marked individually on the single images were too small to be marked individually on the mosaicked images and are therefore represented by a single line for a suite of features.

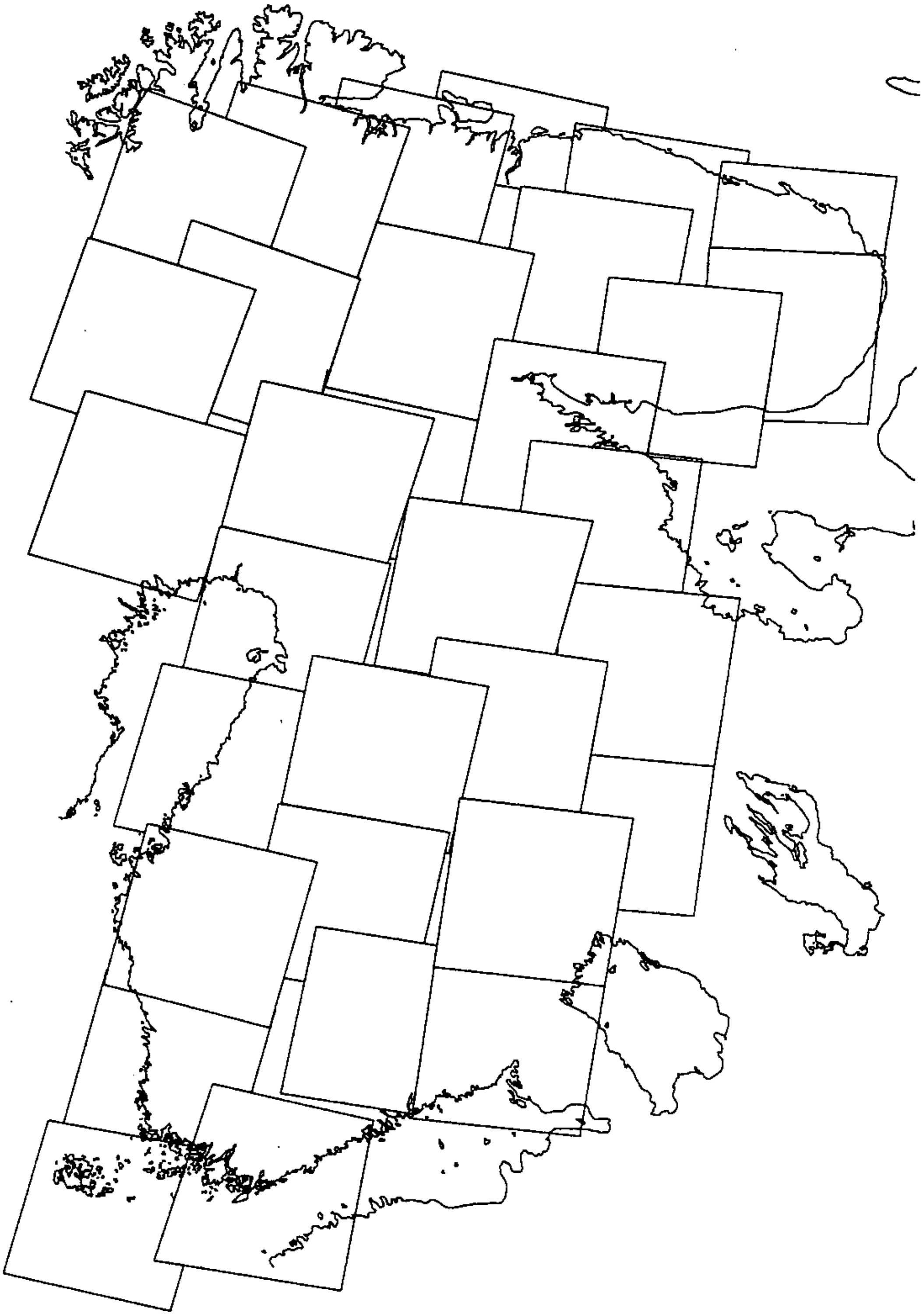
4.3.1.2 National Map Data

Interpretations of eskers and end moraines have been made from national sand and gravel maps, of Norway, Sweden, Finland and Russia (Geological Surveys of Finland, 1979; Sweden, 1958; Norway and Krasnov, 1971) and integrated into a single dataset. The source maps are in different projections at 1:1,000,000 scales. In the interests of completeness the North Kallott Project maps (North Kallott Project Members, 1987) have also been integrated. This map replaces information from the Swedish map in the North Kallott area because it was felt to be better data. It also supplements data for Northern Norway which the national map does not cover. The interpretations from the drift maps were also made by Mikko Punkari and Pieter Dongelmans.

4.3.1.3 Glacial Data Model

The use of macro scale features and end moraines for reconstructing glacial flow dynamics is shown in Figure 4.3. The flow parallel features consist of drumlins, flutes and other macro scale landforms, but are not differentiated as such.

Figure 4.4a Satellite Image Integration (TM)



— Image coverage extents indicating pattern of overlap between images

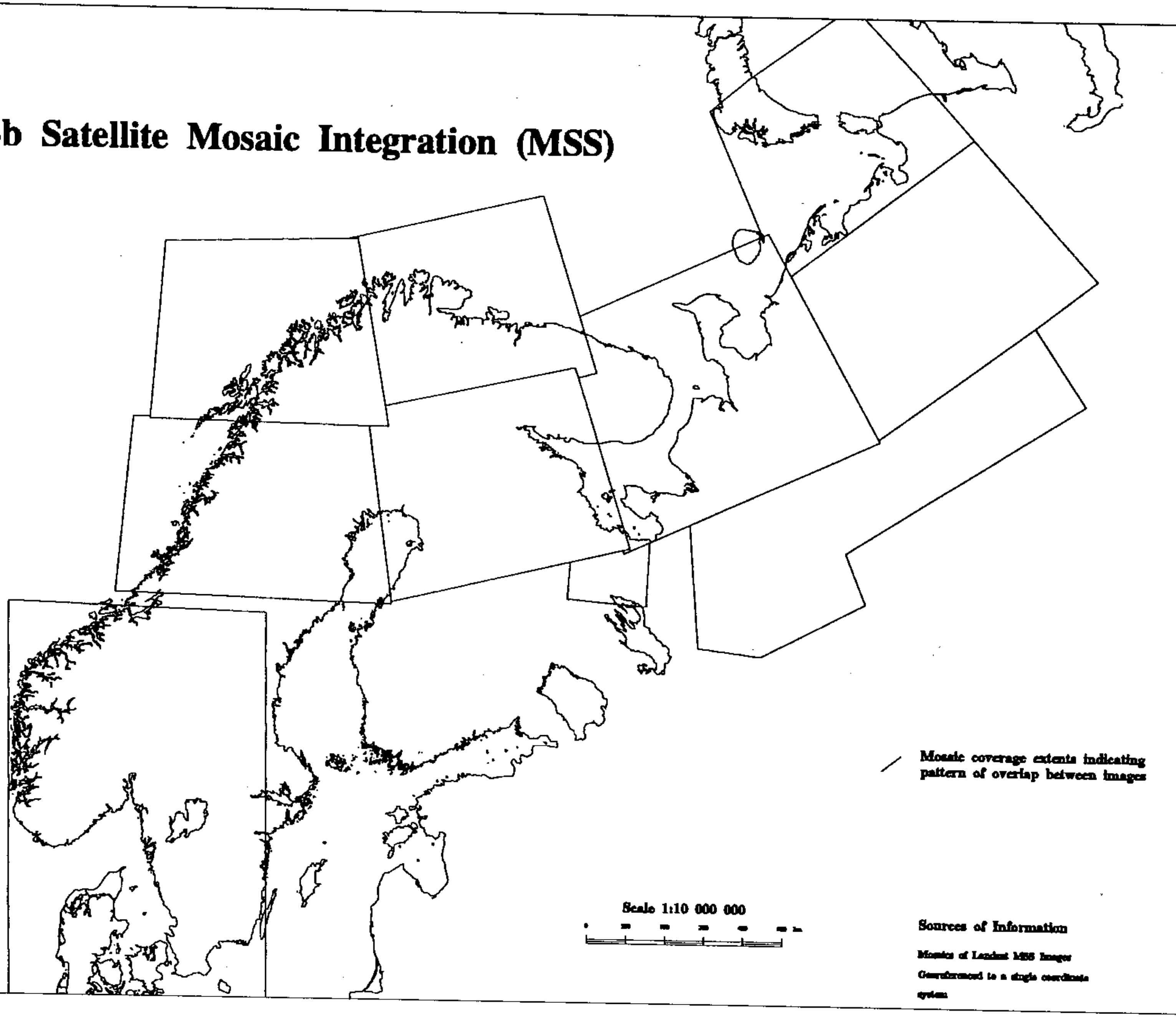
Sources of Information

Landsat TM Images Georeferenced to a single digital coordinate

Scale 1:10 000 000

0 50 100 150 200 250 km

Figure 4.4b Satellite Mosaic Integration (MSS)



Sources of Information

Mosaics of Landsat MSS Images
Georeferenced to a single coordinate system

Interpreted glacigenic landform features are stored as digitised lines. Lineation features reside in one data layer, fluvioglacial interpretations in another and morainic features in a further layer. There are two layers of lineation features, one for each scale of imagery. The names of the data layers were used to identify the features stored therein.

Oriented lineations, which require directional analysis, are stored as straight lines with two co-ordinates only. This enabled their direction to be clearly and unambiguously generated and analysed. The relative angles of mapped lineations, at a Northern European scale, are very much dependent on the map projection employed for the mapping. The single images have not been corrected and therefore their projection is unknown. Since they cover relatively small areas the distortion due to the earth's curvature is minimal. However, once integrated to form a large areal coverage, this issue becomes more important. Data at different scales (for example single images versus mosaicked scale data) may yield different sorts of information about the ice sheet and were treated separately.

There is no provision for linking metadata to coverage layers in the system. To accommodate this information, metadata files, which detail the origins of the images, the interpretations, and the georeferencing, are stored in the same directories as the coverage information.

Finally a base map was required, to provide a framework for the information. The WDBII (World Database II) digital data set has been used. This dataset was originally digitised at 1:3,000000 and is therefore of a comparable scale to the macroscale data. The Lambert Conformable Conical projection was chosen as the reference system because it preserved area in the case of sea level, and is most appropriate for the Northern hemisphere (Maling, 1973). It is also the projection system used for the glacial model, with which it is hoped the data and analysis results can be compared in the future.

4.3.2 Data Capture and Transformation

The interpretations from the maps and images were digitised from acetate sheets on which the interpretations were marked. Other features such as the latitude and longitude graticules, coastlines and lake outlines were digitised in order to check the success of georeferencing later (by matching these digitised coastlines with those of the base map). The data, once digitised was transferred to the operating system and then imported into the GIS. The data was edited, checked and topologically structured within the GIS. The data was then georeferenced so that the relative positions of features could be accurately established with respect to a common co-ordinate system.

4.3.2.1 Satellite Imagery

To georeference the data a GIS makes use of TIC points. These are points which are interpreted as having special meaning in geographical space and are used by the projection and rubber sheeting algorithms in the GIS as being fixed points which are georeferenced. This means that in the situation where a set of digital spatial features is not georeferenced (i.e. the co-ordinates with respect to real world entities are unknown) TIC points can be placed on the map at locations which are known in geographical space. For example, a distinctive bend in a river on the unknown map, can be identified on a map where the co-ordinates are known so that a particular point on the river becomes a known point in real world co-ordinates. If several of these points can be identified on the known map, they can be used by a rubber sheeting algorithm to interpolate co-ordinates for the parts of the map between these known points so that the whole map can be transformed to a known co-ordinate system.

The satellite images were then integrated, via mosaicking, into a single coverage. There are large areas of overlap between many of the images (see Figure 4.4a). Areas of overlap were dealt with by selecting only one image to represent the overlap area. The five mosaic images had already been corrected and georeferencing was much easier. Best estimates were made of the projection system to which they had been georeferenced, and a satisfactory fit was obtained using the Transverse Mercator projection. Similarly the mosaics were also mosaicked (see Figure 4.4b) and overlaps treated in the same way as for the single images (only one image chosen to represent the area of overlap). The final lineation coverages at the two different scales are shown in Maps 4.5a and 4.5b.

4.3.2.2 National Maps

The maps are all Gauss Krueger projections and although not all the projection details are available, some experimentation with projection parameters allowed these maps to be georeferenced with reasonable accuracy (within the accuracy of the base map). Mosaicking the maps to produce a single coverage was straightforward, with the only area of overlap occurring where the North Kallott map overlaps the Swedish and the Finnish maps (no Norwegian map data had been interpreted for that area). The North

Kallott map is thought to be more accurate than the Swedish map (being more recent and having been created with the co-operation of the geological survey in Sweden). The North Kallott map is identical to the interpretations from the Finnish map, so in order to combine the maps the top of the Swedish and Finnish maps were deleted in the area of overlap and replaced using the North Kallott map. The resulting map is shown in Map 4.6.

4.3.2.3 Uncertainty Issues

The extent to which rubber sheeting can be used to improve the quality of georeferencing for each area is limited by the base map, which is less accurate than most of the TIC point co-ordinate readings (taken from Operational Navigation Chart Sheets which are at a scale of 1:1,000,000). There is a notable discrepancy in the representation of features. The base shore and lake lines are more generalised than those digitised from the satellite images. The digital data used for the base map was digitised at scales of 1:3,000,000 and 1:4,000,000. This would imply an accuracy of approximately 1-2 km depending on the reliability of the original base maps and the care with which they were digitised. (It is generally assumed that digitising accuracy is approximately 0.3 mm (Burrough, 1986)). The accuracy of the National Map data interpretations was thought to be better than the base map and probably almost as good as the original maps. Some errors were produced through digitising. Other errors may have been caused because the parameters used in the projection algorithms may not have been identical to those originally used to create the maps.

4.3.3 Data Integration and Analysis

Unravelling the glacial dynamics from the geomorphological evidence requires some combination of generalising and filtering. Conventionally this has been done visually with the addition of hand-drawn generalised lines representing interpreted glacial phases. These lines and their relative ages were interpreted according to the density of features in particular directions for various sub-areas, with an appreciation of the general context.

To facilitate spatial and temporal correlation of the data via generalisation and filtering techniques, a number of programs were developed to manipulate the lineation data which calculate rose diagram and lineation density maps for user-specified areas. The size of the rose diagram area and units are user-controlled, allowing experimentation with generalisation at different scales. Filtering the data was achieved by variously selecting the maximum and secondary directions and displaying them separately. These rose diagrams are easier to interpret than the unprocessed lineation coverage, and combinations of them can be used to interpret relative ages of flow directions and the pattern of flow evolution.

The lineation density maps give further information about the concentrations of evidence remaining and can be correlated with the surface drift, geological basement and hydrological properties using spatial analysis techniques (although this correlation is a future development). It is important to remember that the pattern sets and features identified are time-transgressive and therefore potentially much more complex than might at first appear. Filtering principal and secondary directions can help to distinguish deglacial remains from evidence which pre-dates the deglacial phase, in areas where the deglacial evidence is otherwise very strong. However in areas for which the deglacial evidence is less pronounced, the filtered diagrams should be interpreted with care, as non-deglacial lineations may represent the strongest evidence and these directions will be removed during filtering. This is particularly important for areas which lie near the data coverage limit, where the data density is low because analysis windows overlap areas where there is no data. It may be possible with the addition of more sophisticated functionality, to use interpretations of deglacial ice extent to filter out directions perpendicular to these ice frontal or submarginal positions and obtain non-deglacial components. This could be done progressively using younger and younger ice marginal positions to filter bands of areas within a certain distance of these boundaries. If assumptions about the formation of glacial features is correct, most of the remaining directions should pre-date deglaciation.

The system analyses and manipulation (present and planned) are summarised in Figure 4.7. The input data are shown in the left hand column (Image and Mosaic scale lineations, eskers, moraines and topography) and the outputs (rose diagrams, lineation densities and integrated map overlays) are shown in the right hand column. The centre column and the arrows indicate which layers and analyses contribute to which output.

Map 4.8 a-e show the different rose diagrams (described in more detail below) calculated for a sample area. Each rose diagram represents an area which is 30 km square. The programs used to calculate and plot the rose diagrams are listed in Appendix II. These programs allow a user to select an area for analysis and to define the size of the rose diagrams and the cell size for the lineation density calculations.

Figure 4.7 System data and results storage, and manipulation

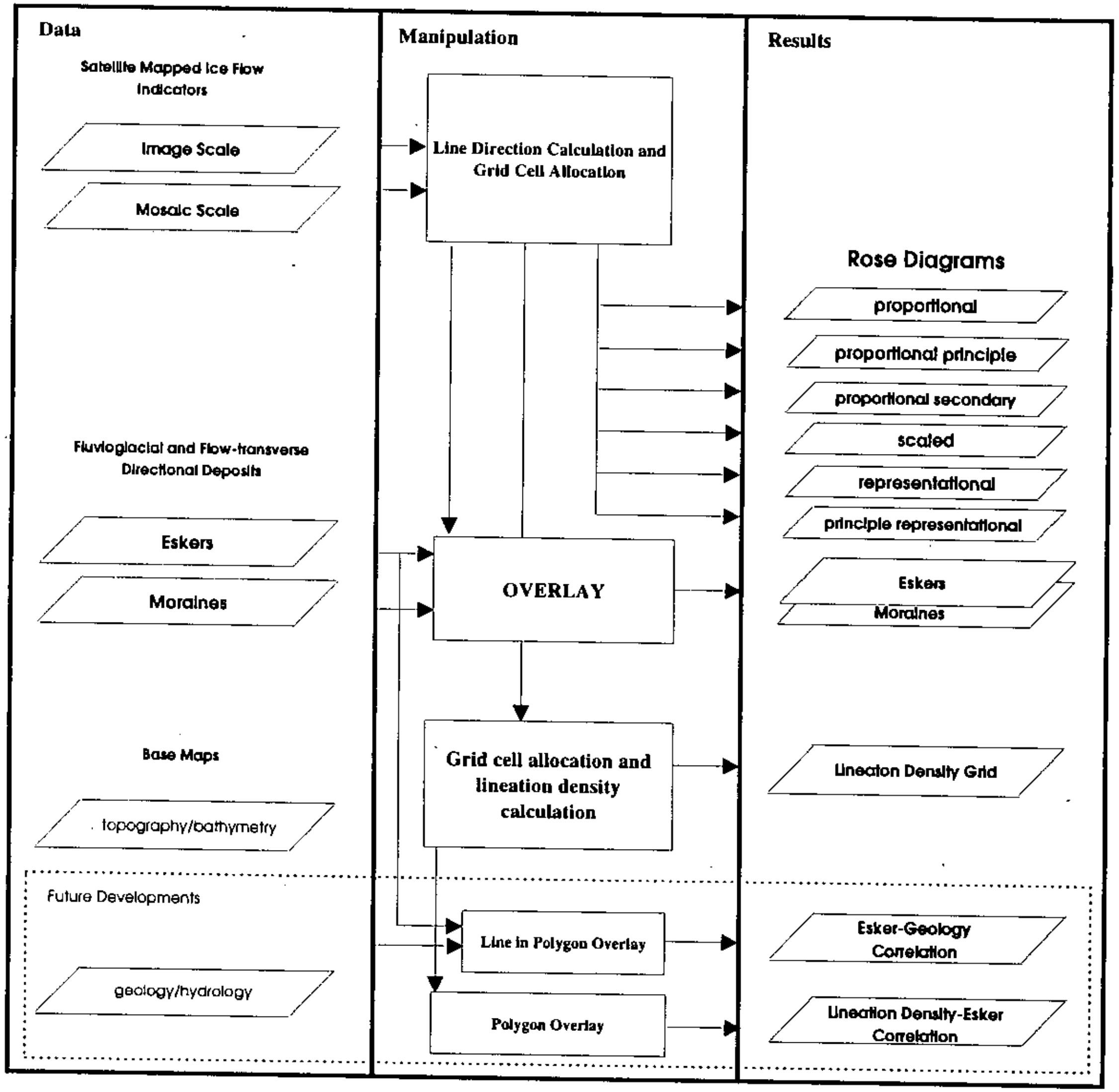
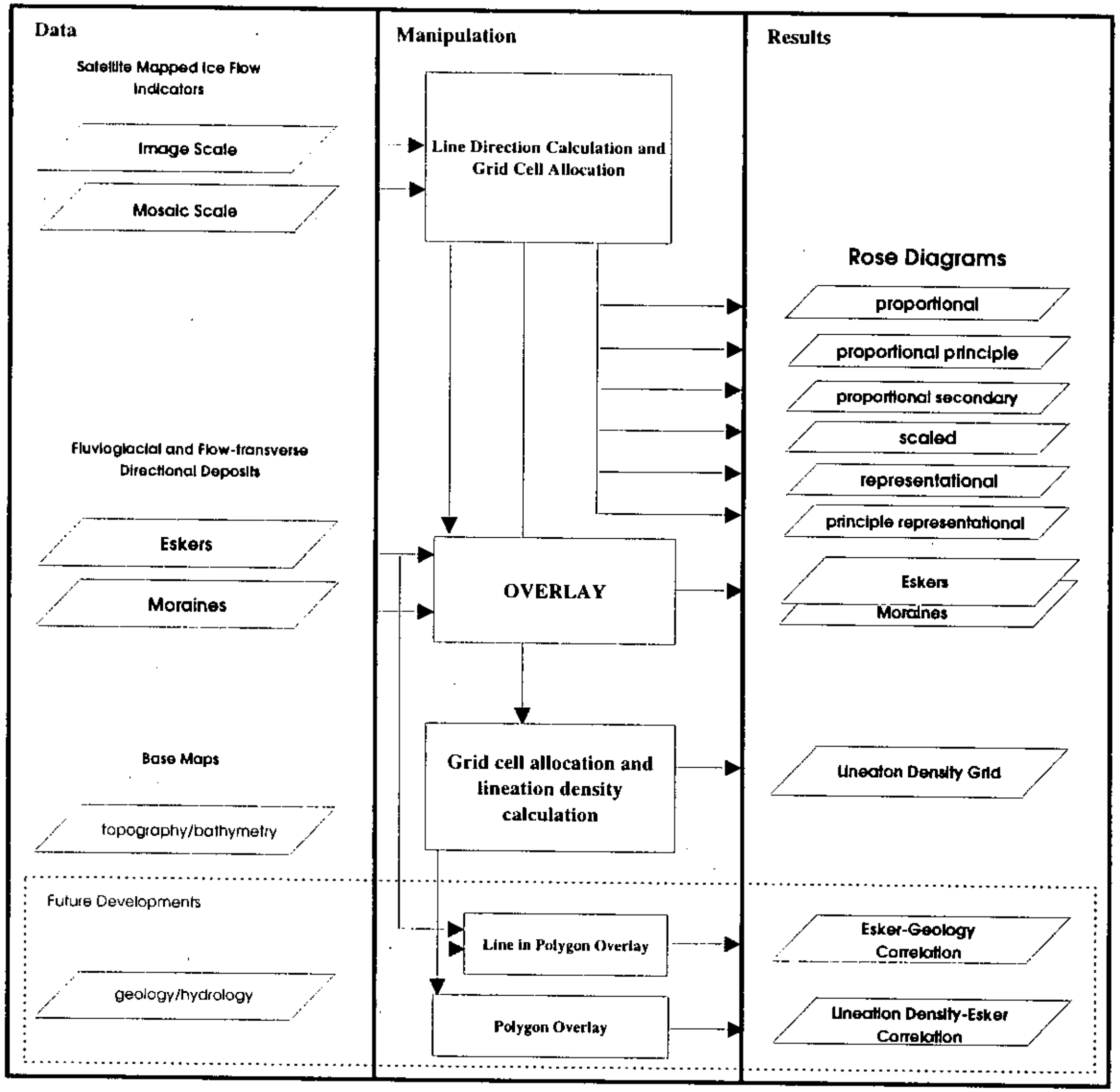


Figure 4.7 System data and results storage, and manipulation



The rose diagrams are created by first calculating the location of the centre point of each lineation to ascertain which rose diagram it should relate to, and then calculating the direction of each lineation. This direction is then assigned to a 5 degree band. There are 36 of these directional bands (viz. Band 1 represents 0-4.999 degrees, band 2 represents 5-9.999 degrees etc.). Thus grouped, the number of lineations in each band is calculated for each rose diagram area and this information is plotted using lines, the lengths of which reflect the number of lineations in a given band. The size of the rose diagram area is user controlled. Because of the complex nature of glacial lineation evidence, several different types of rose diagrams were developed which bring out different aspects of the lineation directions and coverage. The six types of diagrams are described below.

R1 Proportional Rose Diagrams

These are standard rose diagrams. Each directional line in the rose diagram is directly proportional to the number of lineations in that directional band. (Map 4.8a)

R2 Principal Proportional Rose Diagrams

These diagrams show the principal directions only, from R1 diagrams with the other directions removed. These are useful for overlaying with R1 diagrams to help identify the principal directions. (Map 4.8b)

R3 Secondary Proportional Rose Diagrams

These diagrams show the secondary components only of R1 diagrams. The principal directions (R2) and directions five degrees on either side of the principal direction are filtered out. This removes the directions which are most likely to be associated with the same glacial phase. There is an option to plot these diagrams with a larger basic unit so that very weak directions are still visible on the rose diagram. (Map 4.8c)

R4 Scaled Rose Diagrams

Each directional length of the rose diagram is scaled into four ranges relative to the number of lineations in the principal direction. Thus the directions in the top quartile (large number of lineations in each direction) are plotted at one length, those in the next quartile at a shorter length, and so on. This ensures that the minima are not under-represented (using the proportional diagrams the lengths are often too small to distinguish) and that the maximum lengths do not obliterate neighbouring rose diagrams. This is a useful generalised representation of the data present where all components can be identified but with some indication as to the relative importance of each. (Map 4.8d)

R5 Representational Rose Diagrams

Each direction is plotted at the same length regardless of the number of lineations in that particular direction, (unless, the number of lineations in that direction is zero, in which case no representation occurs and the direction is not plotted on the rose diagram). These diagrams give an idea of the spread of directions present. (Map 4.8e).

R6 Principal Representational Rose Diagrams

Only the principal directions are plotted but each principal direction is plotted at the same length. These diagrams are useful overlays for R5 to give an indication of where the principal direction lies amongst those directions being represented by linear glacial elements. (Map 4.8f)

Figure 4.7 shows the data storage, manipulation, analysis and results storage within the system. There are many more possibilities for feature correlation via line and polygon overlay, using the geological, drift, hydrological and topographic maps which are noted in this diagram. Figure 4.9 summarises the system from a user's perspective. The user can select an area or sub-area for which analysis is required and can control grid cell size, rose diagram unit length and can select which particular rose diagrams are to be calculated. It is also possible to select the area and grid cell size for the lineation density plots. The user interface also enables the user to automatically calculate, display, and create hardcopies of diagrams and browse through data, and results already generated and is explained in more detail in Appendix II.

4.3.4 Palaeoenvironmental Reconstructions

It is important that each of these diagrams is not interpreted in isolation. Each is useful to distinguish different elements of the pattern of glacial lineations but spurious conclusions may result in the interpretation of a single diagram out of context.

The results of analyses for 50 km square areas of rose diagrams are shown in Maps 4.10 a-d for the single image mosaic Finnish area and Maps 4.11 a-d for the larger mosaic area covering Fennoscandia (R1 and R2 figures are plotted together as are R5

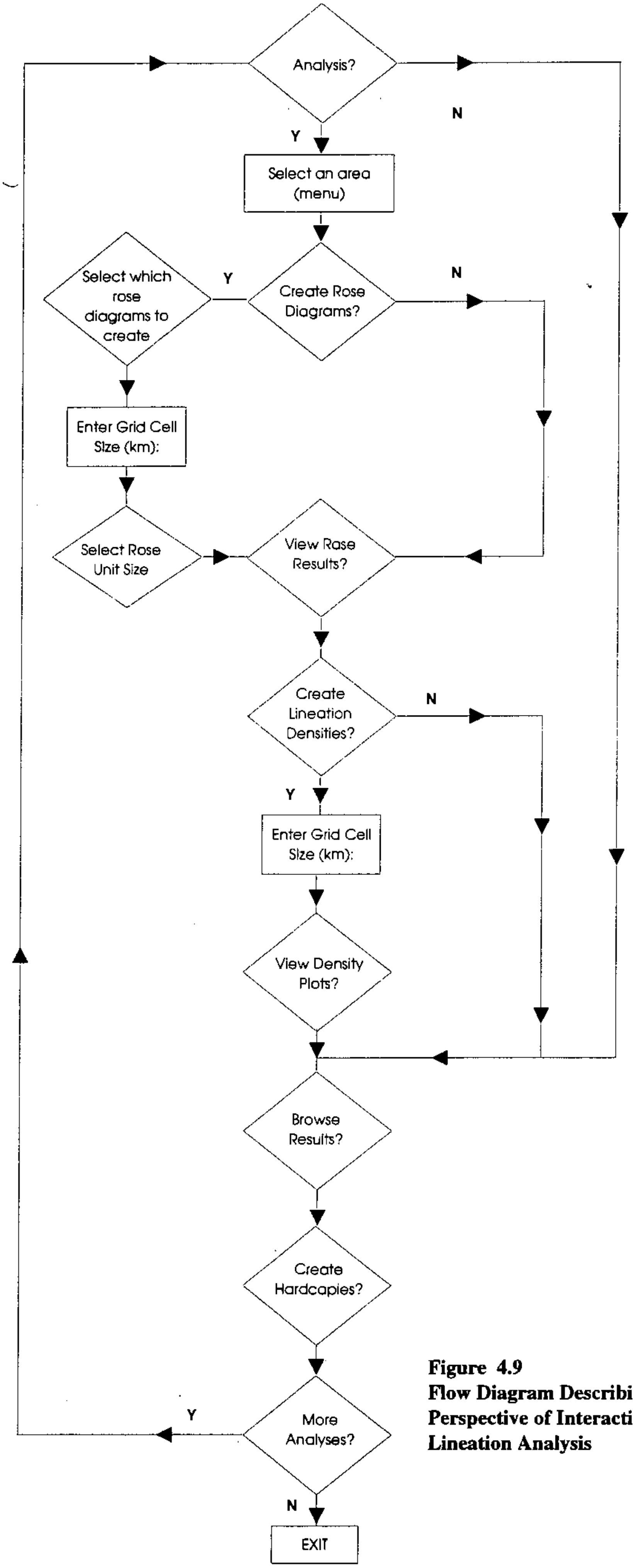


Figure 4.9
Flow Diagram Describing User Perspective of Interactive Glacial Lineation Analysis

and R6 diagrams). Lineation densities for both areas are shown in Maps 4.12a and 4.12b for densities covering cells of 10 km square. Running the analysis for different areal sizes results in different degrees of generalisation and reveals patterns of information at different scales. Selecting and analysing sub-areas where data is particularly complex allows more detailed investigation.

Close inspection of these diagrams reveals a wealth of information about ice sheet dynamics derived directly from the satellite mapped information. R1 rose diagrams (Map 4.10a) clearly reveal several fan shaped ice streams which were thought to be operational during the deglacial phase (c.f. Figures 4.13 a, b and c, from Dongelmans 1995, also identified by Punkari, 1984). On the mid Eastern side of Finland, for example (Map 4.10a) the rose diagrams clearly reveal a very strong ice stream which has its apex to the North East of the Baltic, with the lobe like pattern developing into Western Russia. A similar trend is revealed on the secondary rose diagrams, but there appears to be a shift further south as if the ice stream had migrated north slightly through time. These diagrams show a significant lack of any other directional information in these areas which leads to the conclusions that either these later ice streams have completely obscured older features, or that ice continually flowed in this direction throughout the glacial period.

Looking at the representative rose diagrams (which shows all the directions present equally represented Map 4.10d) for this same mid-Eastern Finnish area would appear to confirm that in some places only a very small range of directions is present. However, these diagrams also reveal that in other places within this ice stream area many more directions exist which do not appear on the other rose diagrams because there are too few of them to be represented. These may represent much earlier glacial directions which have not been removed by the intensity of the later ice streaming. These ice streams are also evident on the density map as areas of high lineation density where the power of ice streaming was sufficient to leave significant erosional and depositional evidence.

In other areas these ice streams and lobate patterns are also clearly identifiable but are overriding other significant concordant directions. In Southern Sweden for example the proportional roses (Map 4.11a) show a distinctive lobate pattern heading south-southeast and then curving round towards the West. The secondary directions (Map 4.11c) reveal at least one other significant direction. These areas reveal significant changes in ice sheet flow directions which could be the result of shifting ice domes or

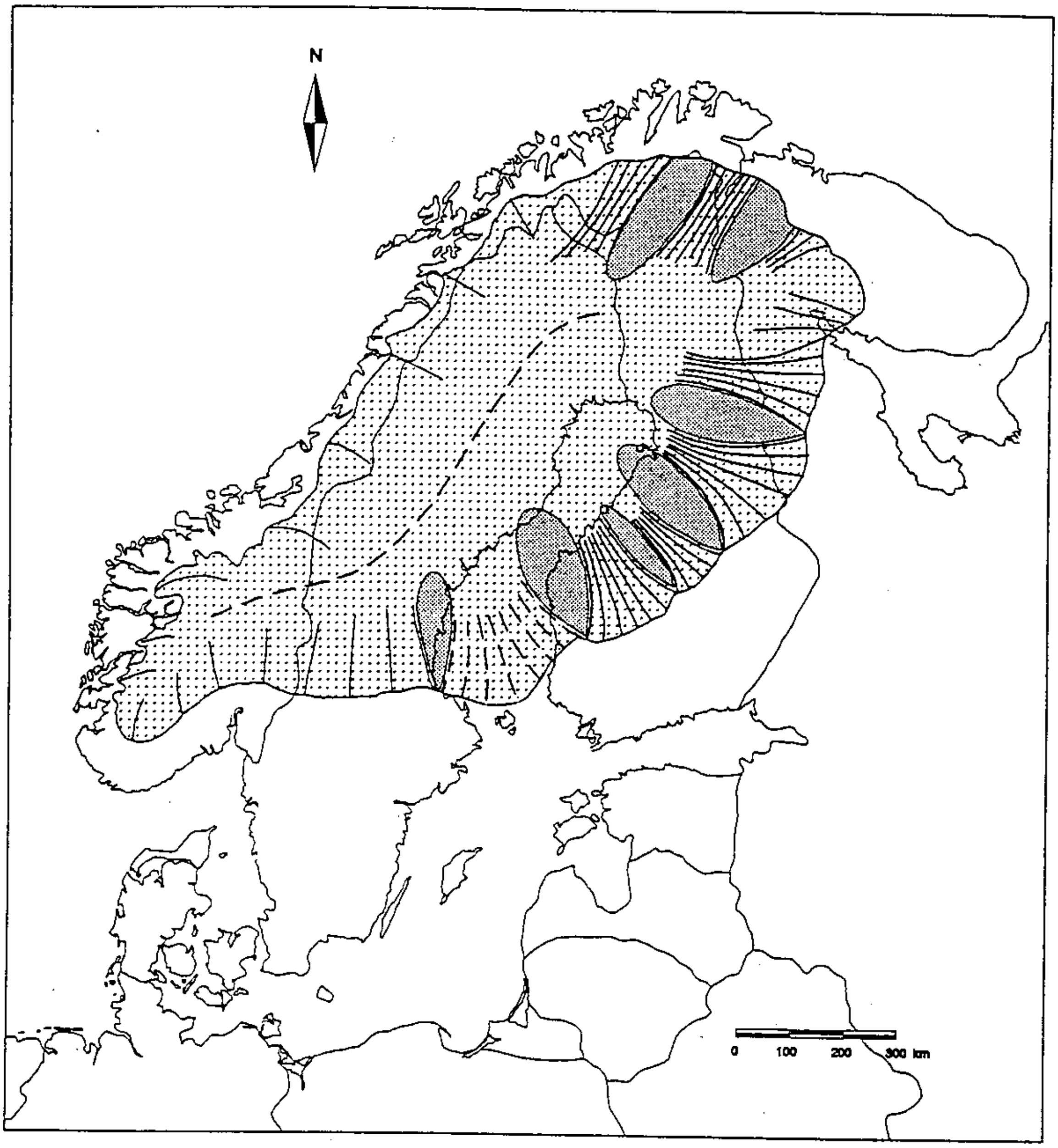


Figure 4.13a. Reconstruction of ice flow dynamics at 9.5 ka B.P. (after Dongelmans, 1995)

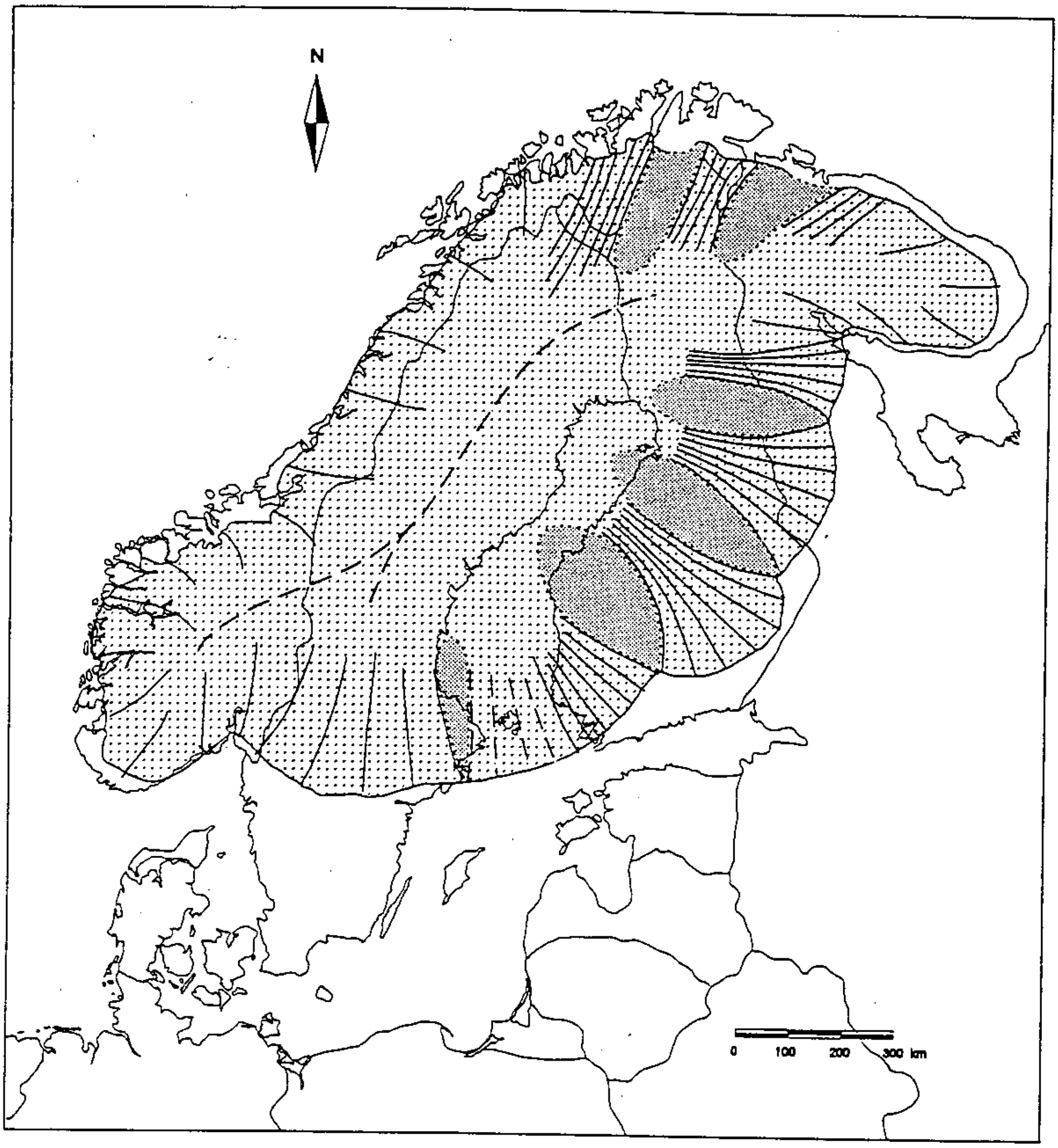


Figure 4.13b. Reconstruction of ice flow dynamics at 10 ka B.P. (after Dongelmans, 1995)

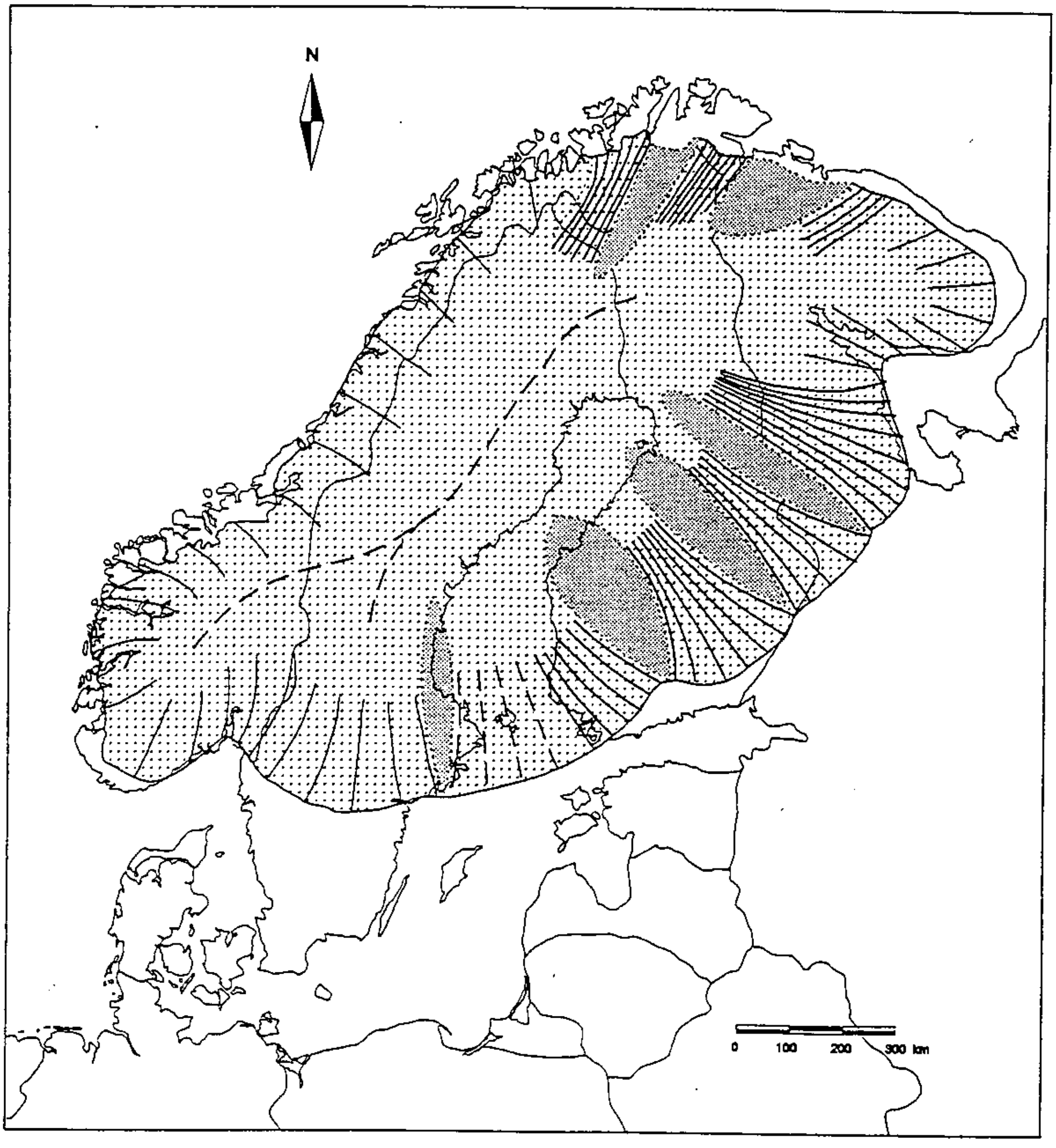


Figure 4.13c. Reconstruction of ice flow dynamics at 11 ka B.P. (after Dongelmans, 1995)

ice divides and controls exerted on the ice sheet at lobe edges by topographic, lake level and sea level variations.

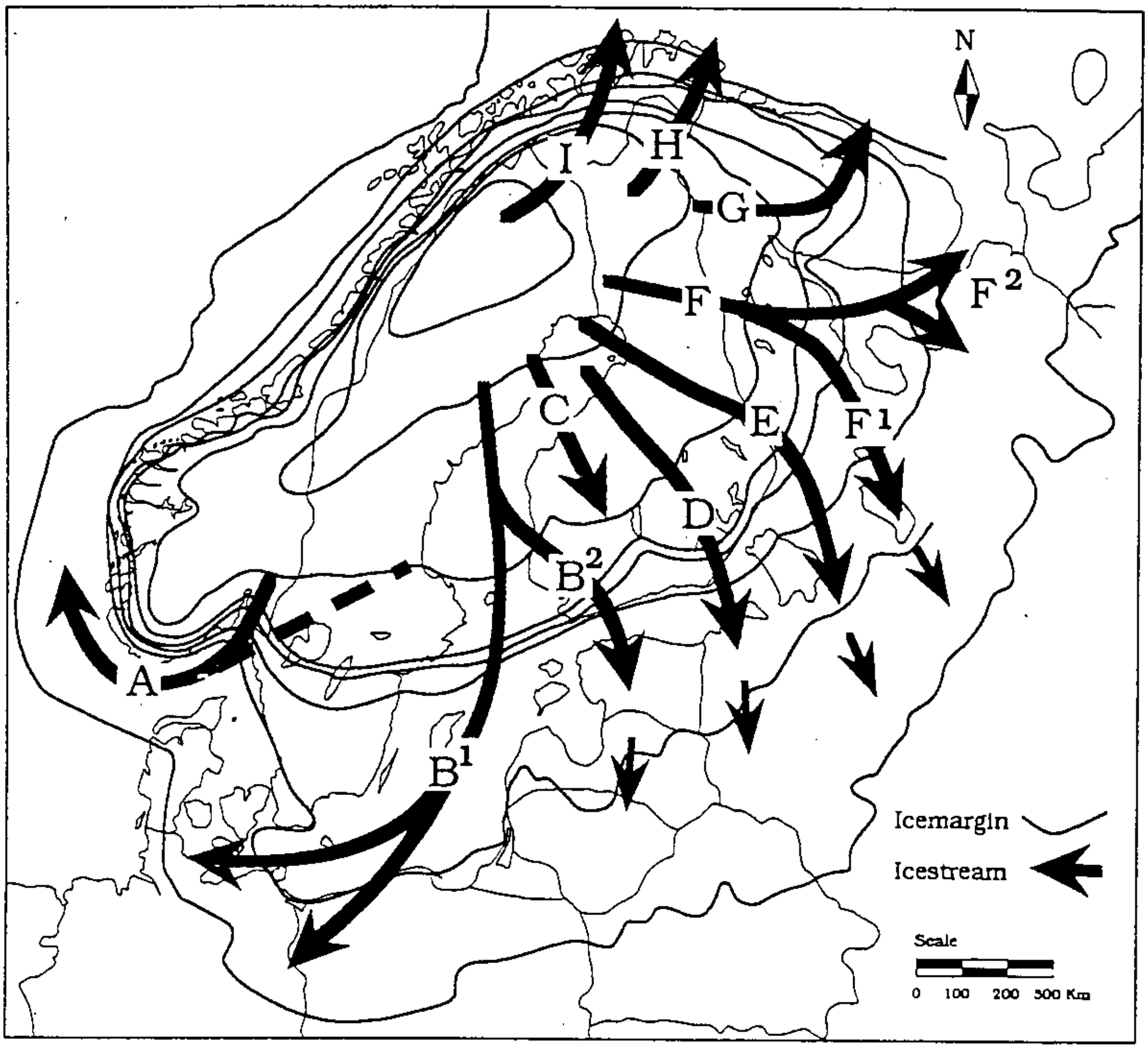
The density map (Map 4.12b) also reveals other areas where there are very low densities of features. In some locations these low density areas often coincide with zones of high directional variation revealed by the representative rose diagrams (Map 4.11d). For example in the North Central Finland near the Russian border. These areas were probably the sites of interlobate zones between ice streams where ice movement and the power of the glacier to erode and deposit was limited (c.f. Figure 4.14, Punkari 1993, where the area is located between ice stream F and G).

Zones of confluence are identifiable where the rose diagram evidence appears complex with many or even all directions being represented, often to equal degrees (for example in parts of Russia, Maps 4.11a and 4.11d, c.f. Punkari 1993 Figure 4.14). Deglaciation patterns and ice extents are more clearly shown where large numbers of concordant directions appear to be truncated. For example North of the Baltic in the vicinity of the Swedish Finnish border, where a pattern of lineations coming from the north is halted at the apex of the very strong ice stream in mid-northern Finland (Map 4.11a). Such very long, intensely lineated, ice stream areas are thought to be deglacial.

Some temporal correlations between lineations can be achieved by looking for sets of concordant directions and by assessing the relative strength of the directional signature using the R1 diagrams (Maps 4.10a and 4.11a). Older signatures are generally weaker, with evidence being obscured by subsequent ice movement.

The significant lack of lineation coverage in certain places can be explained by the location of mountainous areas where glacier movement was constrained by topography. These areas are less useful for studying ice sheet dynamics and the evolution of large ice caps. In the interpretation of these diagrams it is important to take into account topographical and geological basement considerations. Whilst glacial erosion will significantly enhance geological features when movement is parallel to the structural geology, it can also erode and enhance these features, even when ice flow is not parallel.

A very low density of information exists in a band which stretches from the middle part of Northern Finland near the Swedish border to the North Western Russia (Map



A	Norwegian Channel Ice Stream	E	North Karelian Ice Stream
B^1	Baltic Ice Stream	F	White Sea Ice Stream
B^2	Finnish Gulf Ice Stream	G	Kola Ice Stream
C	Näsijärvi-Jväskylä Ice Stream	H	Tuloma Ice Stream
D	Finnish Lake district Ice Stream	I	Finnmark Ice Stream

Figure 4.14. Centre lines of ice streams during the deglaciation of the Late Weichselian Scandinavian Ice Sheet (Modified after Punkari, 1993).

4.12a). The proportional R1/R4 (Maps 4.10a and e) appear to suggest that there is very little evidence in this area. However the secondary R3 diagrams (Map 4.10b) and the representational R4 (Map 4.10d) show that the spread of directions in some of these areas is very marked, with almost all directions being represented in an area in the North East of Finland. The existence of these directions could mean several things. They could represent older directions, indicating that the ice divide may have existed near there and shifted over time producing this criss-cross pattern. The pattern may also be due to misinterpretations where bedrock lineations have been interpreted as glacial forms. Examining field evidence in the area would be an important step in resolving the meaning of these patterns.

Comparing the rose diagram map and the original lineation map, with the moraine, esker and topographic maps (these can be accurately overlaid within the GIS) gives further support to interpreting these patterns, particularly those relating to ice streams. Overlaying different rose diagram maps, and combinations of topographic and moraine maps is very quick and straightforward in the GIS. Switching layers on and off and the ability to zoom in on particular areas of interest can be achieved repeatedly in a matter of moments vastly enhancing the potential for assessing different interpretations.

The programs allow a large degree of flexibility in manipulation of the data. For example it is useful to look at the rose diagrams and lineation densities at different scales depending on the item of interest. High densities of lineations appear to coincide with the axes of the lobes, but a small grid cell size will not incorporate enough data for this to be clear. Too large a grid cell size will generalise the information so that it is too highly aggregated. Therefore, the size of the feature being studied (for example an ice stream, or interlobate area) will determine the most appropriate grid cell size. Features of interest are not always clear prior to analysis, and so programs can be run repeatedly for different grid cell sizes to see which appears to be the most appropriate. They are also data independent, and can perform the same analysis on lineations of any length in any geographic area.

The results of the lineation density and rose diagram analyses can be compared with interpretations derived by Dongelmans (1995) using the same data (Figures 4.13 a, b and c). These interpretations took some time to derive because of the complexity and volume of detailed information. The patterns he interprets can be recognised instantly on the rose diagram and lineation density maps. Importantly these maps give a rigorous and quantitative picture of the data. Previously it was hard to justify a particular interpretation given the complexity of evidence. No quantitative measures of such detailed data have previously been available over such a large area.

The GIS work clearly demonstrates several points:

I That the spatial patterns of data are crucial to gaining insights into ice sheet evolution

II That quantitative, spatial analysis of the detailed information together with improvements in georeferencing of lineations can significantly reduce the amount of information loss compared to manual methods of analysis, and therefore improve the quality of information on which interpretations are based.

III Viewing all the data in a structured format such as that provided by the rose diagram and lineation density plots allows an interpreter to quickly locate areas which require further investigation or where field level information is essential.

IV That it is important to be able to make connections between ground observations and these macroscale features during analysis. This would involve being able to accurately locate one with respect to the other, and be able to query the field information spatially. For example, a significant improvement would be the ability to click on a certain area where macroscale interpretation is particularly interesting or problematic and being able to receive information from a database about the field information available for that location.

4.3.5 Further Work

Establishment time for a GIS can be longer than new users expect (Masser & Blakemore, 1991). However, with good planning and design, the system will be able to adapt rapidly to incorporate more developments according to the needs of the user. Some of the many developments which the current system can support are discussed in the following paragraphs. All of the functionality discussed in the previous section has been developed so that it can be used on any lineation data from any country regardless of the reference system used.

There are many controversies that this detailed mapped and georeferenced data set could help to resolve through a series of simple overlays and correlations of even these macroscale data layers. For example, overlaying the esker inferences with a geological map would allow a quantitative relationship between bedrock type and the occurrence of eskers to be calculated. Some areas, however, must be handled more elegantly. For example, comparing lineation densities can be very useful in determining lobate and interlobate areas. However, some means of adjusting these densities is required for areas where sea and lake areas occupy a grid cell thereby possibly concealing lineations. Further analysis could involve the development of programs which progressively backstrip lineations to remove lineations which are perpendicular to ice frontal positions and are thought to have formed in the active area 100 km behind the ice front (Punkari, 1980; Boulton, 1996) using interpreted deglacial patterns. If this theory is correct this might reveal the lineations associated with ice movements prior to deglaciation. Older landforms which were parallel to the younger deglacial directions would also be removed, but this approach should still allow many older directions to be revealed.

Further flexibility could be obtained by storing the satellite images on the computer. If these images were mosaicked and georeferenced they could be used to digitise interpretations on-screen. This would reduce the time required for data input and allow interpretations to be changed, and their effect on any analyses results to be traced. It would also empower other researchers to make their own interpretations for an area through computer networks and compare these directly with other data they are using. This method is being used by researchers in Sheffield University (Knight & Clark, 1995) but involves using an image processing package for the image processing and digitising. These results would then be imported into the GIS in a separate step.

One of the most valuable developments which could be achieved within the system would be the integration of much more detailed aerial photographic and field information. If this information could be linked directly to identifiable features on the images, the ability to discriminate between the different features would be much improved. Conclusions drawn from this macroscale information would be better founded. Some work is currently being undertaken towards this goal (Abert, 1995) by producing digital elevation models using stereo aerial photography. These models reveal landform relationships previously undetected using field mapping techniques. This method can achieve a resolution of 1 m although the computing resources required for such calculations over large areas are substantial.

A large number of palaeoclimate studies now make use of glacial models to help make sense of the complexities of former ice sheet remains and to investigate the importance of certain parameters on ice sheet evolution. It is an advantage to have the sedimentary information, remotely sensed data, and the results of any analyses on a computer where they can be integrated directly with model results to allow the optimum interpretation of past results and an even greater degree of flexibility in matching different model runs with different analyses and lineation interpretations.

4.4 Discussion

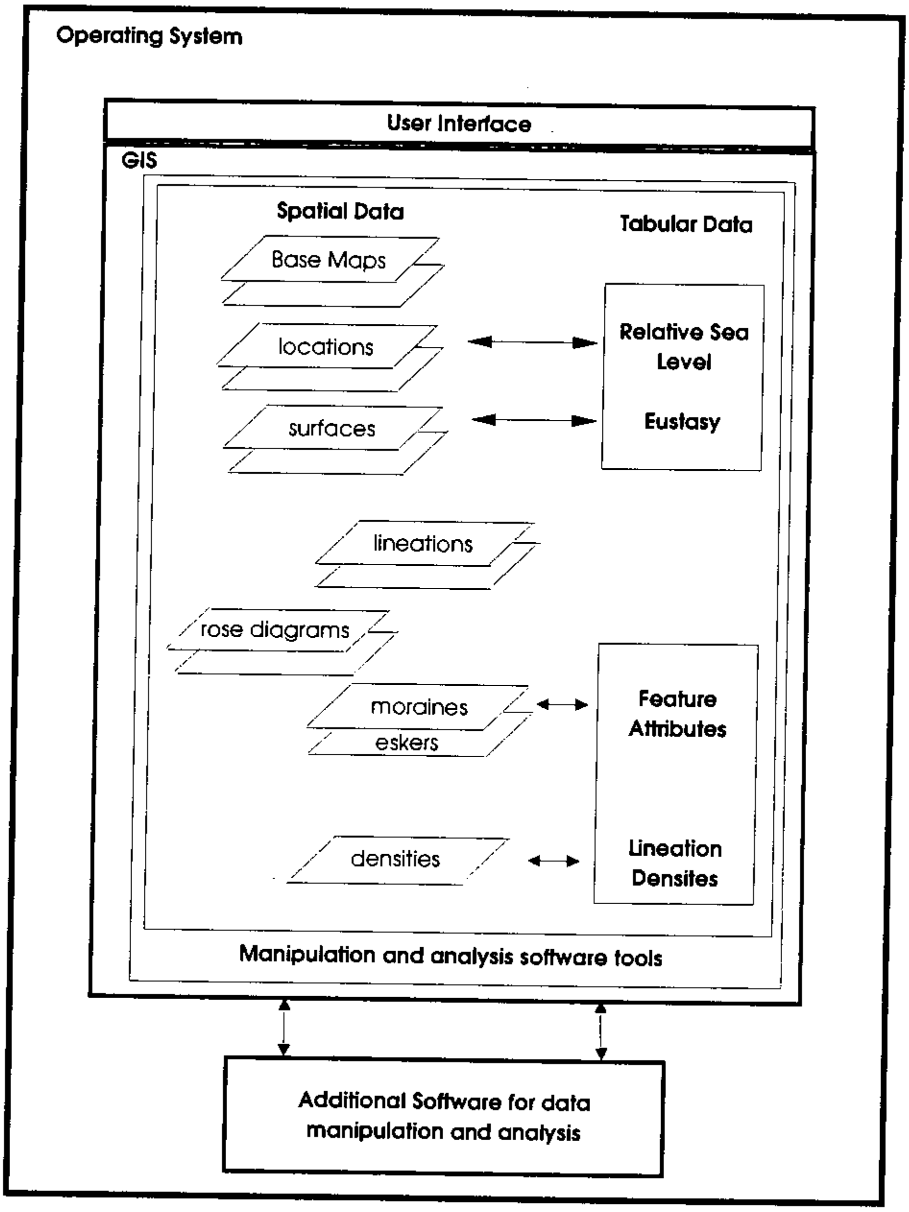
The system (summarised in Figure 4.15) makes a significant contribution to macroscale palaeoenvironmental studies, not only because it enables fast and rigorous analyses via iterative and experimental techniques, but also because it provides a dynamic and flexible framework for the storage and management of macroscale glacial data. Computerising techniques in this way can also facilitate the rapid advancement of glacial theories supported by data for which the source and reliability is known. It is also the first time such an accurate and detailed dataset has been available within the same spatial framework for such a large area. However, there are also issues associated with these advancements which concern the way data has been obtained to date, and the capabilities of current systems to handle this kind of data. The three subsections below discuss the advantages and these two categories of issues.

4.4.1 GIS Contribution

The advantages of having glacial lineations on a computer, for storage, display and analysis are substantial. The task of integrating maps of features of different scales and projections can be done much more accurately and with no loss of detail. The result is complete spatial coverage for the entire Fennoscandian Shield.

Previously manual methods involved the transfer of numerous versions of maps at different scales onto a common basemap. This was mostly achieved by hand. Doing this only once using computing algorithms minimises the possibility of information being affected by artefacts of these inaccuracies. This is particularly important on the scale of NW Europe where the earth's curvature is significant. For example linear elements may have apparently different directions depending on which map projection was used. Data may be repeated at map overlaps. Consequently there may be appeart to be more data in a particular area than there is in reality. When overlaying maps to compare the juxtaposition of features it is particularly important that the position of these features is known with some accuracy. If not, relationships may be apparent that do not exist, or existing relationships may not be identified. This issue is difficult to address using manual methods and is often not recognised.

Figure 4.15 System Summary



For example in many cases it is impossible to obtain the projection parameters for a map. Maps for large areas which are produced by the palaeoenvironmental scientific community are often made up of several different base maps. The projection on these map composites changes across borders. The distortion differences have been "amended" by hand-drawing parts of coastlines, lakes and so on, where the adjacent maps do not match. Notable examples include the 'Map of deglaciations for NW Europe' compiled by Andersen (1980), and maps which appear in papers by Punkari (1980, 1989, 1992, 1993). The problem is much more widespread than these few examples might indicate. Knowledge of map projection parameters is essential for spatial information which is to be used on a GIS.

In addition to this the time required to analyse such large data sets, on a variety of scales, is significantly reduced. Trying to reconstruct the pattern of glacial dynamics requires investigations on all scales. Generalisation of micro- and mesoscale data to the macroscale will require analysis of the higher resolution data initially, and may entail further detailed investigations in areas of particular controversy. It would be very interesting to compare rose diagrams of these more detailed data with the macroscale evidence.

This study has shown that the process of integration, generalisation, analysis and visualisation of lineation patterns has been significantly improved by the use of computing techniques. These quantitative methods can be applied to very large data sets using electronic processors to handle the large volumes of information associated with this task. The method of integration ensures that information is not over-looked and allows more freedom of experimentation without the time and accuracy compromises associated with manual georeferencing and data processing. The results clearly demonstrate how the system can facilitate reconstruction through the identification of ice streams and glacial extent, and how rigorous analyses of the lineations can reveal a great deal about the mobility of the ice sheet and ice sheet dynamics. Spatial correlation with other information such as geology, hydrology and surface deposits reveal relationships which may help in the development of theories about ice sheet dynamics and as input and testing for numerical models. The true association of landforms can be clearly seen without the risk of misplaced landforms being juxtaposed, resulting in misinterpretations. Furthermore, once the system is set up, the generation of clear, accurate, glacial lineation and analysis maps is quick and easy.

4.4.2 Data and Analysis Issues

There are several data related issues which vary in importance depending on the scale of study. Ultimately it would be desirable to store all the information using electronic media to obtain the ease of comparison, analysis and re-use demonstrated above. These issues are discussed below by considering first those which were encountered during the implementation of the proprietary GIS work, and then extending the implications of these issues for other information which would be added in the future.

Firstly, the time required for data capture, georeferencing and integration was substantial. The main issues concern the compatibility and comparability of data from different sources. The compatibility of data was less important because the satellite images and maps were interpreted by only two individuals. However, when comparing the areas of overlap between images, there is some difference in the visibility of lineations depending on variation in sun angle and season. Improvements in georeferencing would help such discrepancies. Currently the spatial correlation of features would only be reliable given error boundaries within which the lineations and map features could be compared.

The most important inaccuracies however concern the way in which the images were georeferenced. The success of the georeferencing depended ultimately on the availability of features which could be identified on both the image and the map. Fortunately Finland is well-endowed with distinctly shaped lakes, otherwise the georeferencing would have been almost impossible given the available information. To improve the accuracy further would require the original images and the relevant satellite flight parameters. Alternatively corrected and georeferenced images could be used for the interpretation.

More fundamentally, the maps lacked detailed georeferencing information. In Finland the projection parameters used for the maps are standard, but in Sweden these parameters were more difficult to establish and some experimentation was required to obtain parameters which produced the best fit to the base map. The base map was not very detailed and so the accuracy with which these features were transformed is uncertain. However they are, for the most part, within the accuracy of the basemap. If more detailed studies were made which would require the linking of field or aerial photographic information with these macroscale features, the lack of accurate georeferencing would become a serious issue.

The inclusion of more detailed field information would require an extensive data modelling exercise to produce a database which could accommodate this information. A central issue for the extension of this system to incorporate detailed data would focus on multiscale feature representation. At the scale under study, features can be treated as lines, which is the most appropriate representation for carrying out directional analyses such as rose diagram calculations. At a more detailed scale, however, these features require an area representation which would be much more problematic for directional analyses, but more suitable for other geomorphological analyses at that scale. Thus, features could appear twice in a system at different scales thereby causing data redundancy, or a more appropriate multiscale representation must be developed. Representation, however, is not the only issue associated with incorporating more detailed field data. Some means of permitting multiple, different, interpretations of features to coexist in the database will be required to accommodate all users views and interpretations. Harmonising the terminology relating to features between countries and dating chronologies will be a pre-requisite for integration. The ability to reinterpret information, and partition data according to different interpretations is required. The database would have to contain a hard core of generic information, to which attachments could be made for an individual to label particular observations with interpretations. Detailed and complete documentation of field data sources are not generally available, and are not recorded in such a way as to facilitate reinterpretation or regional integration.

Again, the analysis of this information, at a scale where the curvature of the earth becomes an issue, argues for the incorporation of approaches which accommodate the data on a geoidal earth.

4.4.3 System Issues

There were several system issues encountered whilst developing the system. The GIS Macro Language was much less suitable for developing programs which can speedily process large arrays of data than FORTRAN. The rose diagram and lineation density calculations were carried out by FORTRAN programs called from within the GIS. The data was exported from the GIS for processing and then re-imported. It would be much more satisfactory to handle all the processing within the GIS. Although the GIS offers a high degree of sophisticated functionality, it lacks many spatial analysis tools. This has been noted by other researchers (for example, Openshaw, 1991b). Whilst the GIS would permit the overlay of eskers with bedrock geology to see how many eskers lie within a particular polygon, it does not provide functions which will statistically evaluate the nature of the relationship between bedrock geology and esker occurrence.

Furthermore, to facilitate the flexibility of interaction required by the user, it was necessary to move between GIS modules fairly frequently. This slowed the speed of interaction. Finally software upgrades and operating system changes were a significant issue. Maintaining the glacial programs between upgrades was time-consuming. This is a major consideration given that upgrades occur at a rate of at least one every two to three years.

The lack of lineage management facilities within current GIS is also a significant problem. Files which explained the origins of the data and the way in which they were coded and georeferenced were retained on the system, but there was no means of attaching these to the data within the GIS. There were a large number of possibilities for processing the data using different geographic extents and different cell size parameters for various datasets. For example the user can select any area within the region for analysis and analyse this data for any grid cell size and generate a number of rose diagrams and lineation densities for this area. The organisation and disk space required to retain this information to enable the user to make comparisons between the different results was considerable, much more, indeed, than that required by the original data. The GIS not only provides limited facilities for storing and handling metadata (for example origins, methods used for data encoding and error and accuracy data), but has no means of structuring results according to their lineage information.

The log files produced by the system do not record processing which occurs outwith the system. Naming conventions and the hierarchical directory structure were employed to try to help users identify which results were produced using which parameters, but further development of the system would require a complete overhaul of this arrangement. A more satisfactory means of handling lineage information, and for communicating metadata to the user, is required for such systems.

A means of recording and representing uncertainty in the GIS is required. Currently one has to estimate the effect of rubber sheeting and projection transformations on data, and there is no simple means of attaching this information to individual features, or visualising it. Space is discretely represented in a GIS (points, lines, polygons or raster cells), but in reality it is usually continuous or has indefinite, fuzzy boundaries

(Burrough, 1996). Whilst discrete representation was acceptable on paper maps, and dotted lines could indicate some degree of uncertainty, the requirement for topological completeness, and the ability to perform powerful analyses on data using computers means that the effect of, and sensitivity to, uncertainty, has increased, and will be rapidly propagated and magnified through multiple operations (particularly when combining several data sets of variable certainty). Such magnification must be noted to ensure that invalid results are not treated as reliable.

In the future, systems should be developed so that quality information can also be used in analysis. For example, considering the error in the directional features may alter the apparent coherence of ice stream patterns and open up new interpretational possibilities. The use of confusion matrices for geological maps may reveal different correlation structures between the coincidence of features with bedrock or drift. The consequences of combining different data sources and changing scales invites a loss of sensitivity to a data set's idiosyncrasies, particularly its accuracy (Goodchild & Gopal, 1989). The user must be certain that results produced as a consequence of these combinations are valid.

Finally, the time required to develop the system was substantial. Indeed others have hinted at the significant investment required (e.g. DoE, 1987; Tomlinson, 1987). The time required to develop sufficient expertise and system skills was also significant. The system used is complex, comprising over 900 main commands, and 4000 including sub-commands. In addition to this, knowledge of the ARC Macro Language (AML) and FORTRAN programming language was required to create programmes which supplemented the GIS functionality. The GIS provides facilities to create a user interface, and although the interface developed is crude, it is robust and a large time investment was required for its development. Hybrid systems such as this, which are created using several packages and programming languages are complicated to develop and difficult to maintain.

4.5 Conclusions

This example clearly demonstrates the need for improved communications throughout the scientific community to standardise and improve the measurement and documentation of observations, to facilitate data re-use and integration. It also identifies the inadequacy of current GIS for this type of palaeoenvironmental research and indicates the need for a concerted effort by the scientific community to develop a set of methods and approaches to address these shortfalls and allow exploitation of the data using GIS concepts and computer power to improve the understanding of the data which are currently held, and to verify results quantitatively and improve the ability to extend current knowledge of past events.

Glacial reconstruction is a major challenge because of the complexity of glacial data and the difficulties of managing scale and quality differences between information sources spread over a large area. Researchers have resorted to macroscale techniques such as satellite imagery in order to achieve that which is not currently achievable using field information: the integration of comparable data over an area the size and scale of the ice sheet. However, in order to interpret this information effectively, knowledge is required of many other datasets, in particular the ground truthing information, which can confirm the accuracy of inferences made from satellite images. Again, the interrelated nature of this information argues strongly for the adoption of an integrated approach at a scientific organisational level, to develop a single framework, within which this information can be exchanged and integrated expediently and accurately. The case study indicates that GIS has great potential in this area, but the demonstrable shortcomings of current systems implies that a new systems approach is required.

In summary, this case study resulted in the following demonstrable GIS benefits and issues:

Demonstrable benefits:

- spatial framework for geomorphological data
- compact storage of detailed information
- fast and flexible analysis and visualisation of data over a large area
- clear, accurate, fast map production
- quantitative, rigorous analysis of glacial lineation patterns

Palaeoenvironmental issues:

- lack of georeferencing information on maps and satellite images
- lack of standardisation and detail for future incorporation of field data
- lack of methods for analysis on a spherical earth

GIS issues:

- time required to gain system expertise

- time required to establish system, particularly for data capture, georeferencing and user interface development
- lack of metadata facilities for managing lineage of system output and error propagation (particularly for georeferencing and rubber sheeting algorithms)
- GIS macro language slow and cumbersome for manipulation and analysis of large scientific data sets

Chapter 5 Case Study 1: Sea Level

5.1 Introduction

In this chapter, details are presented which show how GIS has been used to facilitate palaeosea level reconstruction, by significantly improving the management, analysis and visualisation of sea level data for Scandinavia. Like the previous glacial geomorphological case study, the GIS has been developed to allow much faster and more flexible analyses and data experimentation, than has previously been achievable using manual methods. A comprehensive framework is also developed to store complex palaeosea level data so that it can be retrieved and updated easily.

The means of deriving and analysing Levels 1 and 2 data to generate Level 3 spatial height associations are examined in Section 5.2, from which emerge a set of reconstruction requirements. The application of GIS to meet these requirements is then described (Section 5.3). A data storage framework, analysis tools and a user interface are developed to facilitate palaeoenvironmental reconstruction using sea level data. Further system developments which would improve the existing facilities are also discussed. The advantages of using GIS techniques to enhance sea level reconstruction, and the limitations imposed by current palaeoenvironmental practices and system issues are considered (Section 5.4). The concluding section (Section 4.5) summarises the implications for the study of palaeoenvironmental research and GIS development.

Relative sea level data sets are vital for reconstructing palaeoenvironments. Knowledge and understanding of sea level changes also have fundamental implications for the impact of future climate change on man. Major sea level changes in the past few thousand years have been caused by climatic events associated with ice sheet advance and retreat. These caused global sea level falls of 100-130m during the last glacial (Weichselian) maximum (20,000 Years Before Present) (Mörner, 1979). Sea level data also yield information about isostatic crustal rebound. Net crustal depression and rates of uplift and mantle movements through time can be calculated. The study of isostasy in areas affected by glaciation, is important in terms of hydrological regimes since isostatic rebound will cause changes in coastline locations and land slopes. Relative sea level data can also be used to reconstruct past coastlines, sea levels, and palaeotopography, and have important implications for the study of ice sheet evolution and the behaviour of ice sheets by determining conditions at the ice sheet margin. The interplay between the rate of ice melting, changing palaeotopograhy, sea level and ice marginal retreat are thought to have produced large fresh water ice marginal lakes, for example, in the Baltic area (Eronen, 1983). Uplifted features and coastal zones have been studied for over 100 years in Scandinavia and the North Sea basin (De Geer 1888; Liden 1913; Mörner, 1991a). Therefore the potential database available for study is larger than for any other area of a similar size in the world (Shennan, 1987a).

5.2 Sea Level Reconstruction

The main aim of palaeosea level studies is the reconstruction of relative sea levels through time which can be used to reconstruct palaeosea level surfaces and to understand the causes of sea level change. From these reconstructions and theories the mechanisms thought to cause sea level change can then be determined. Such knowledge helps in the understanding of other phenomena, for which the magnitude and location of sea level has direct relevance. Extrapolation of causal phenomena can facilitate the prediction of future change, such as the retreat of ice sheets (Eronen, 1983), or the effects on hydrological regimes (Jardine, 1980).

The theoretical basis for sea level studies has evolved over a number of years. Essentially, relative sea level change is thought to be determined by components of the following phenomena:

1. Glacio-eustasy (the formation or melting of ice sheets causing major redistribution of the global water budget)
2. Geoidal eustasy (changes in the geoid causing perturbations in sea level surface due to variations in gravitational attraction)
3. Isostasy and local tectonism (crustal depression, rebound, tectonics and associated mantle movements in areas which have undergone loading and unloading by the advance and retreat of large ice masses, known as glacio-isostasy, or by the addition and subtraction of large volumes of water to ocean basins and continental shelves, known as hydro-isostasy)
4. Tectono-eustasy (tectonic and crustal displacement associated with internal earth movements, these cause changes in the land surface with respect to sea level, and changes in the volume of ocean basins over a long time period through spreading at mid-ocean ridges and subduction of tectonic plates at ocean margins)

(after Mörner, 1987b)

Components 1 and 3 are the major factors controlling sea level change during the last glaciation in North West Europe. The history of sea level change through time is complex. Global low sea level stands occurred at glacial maxima with large volumes of water locked into the ice sheets, and high stands during warmer interglacials when melting released water back into the oceans. Sea level changes associated with the last glacial maximum (18,000 years B.P.) were of the order of a hundred metres (e.g. Mörner, 1971). Locally, in the areas affected by glaciation, these changes were complicated by the negative response of the crust to loading by the ice sheet. Maximum crustal depression occurred beneath the centres of glaciation with crustal deflection decreasing outwardly from the centre as the ice weight diminished to the edge of the ice sheet. Further complexities were caused by geoidal[1] perturbations, tectonic movements, gravitational attraction of the ice mass and the isostatic responses to changing water loads on the continental shelves (Walcott 1972b; Chappell, 1974; Farrell & Clark, 1976). These variations are thought to contribute differences of as much as 30% in estimates of transgression rates between certain areas.

Relative sea level, is a term used to describe the resultant effect of these components on sea level at a particular time and place on the earth's surface relative to present day mean sea level. Sea level may change because the land moves relative to the sea, or because the sea moves relative to the land. Thus a relative drop in sea level, may not imply a drop in global, or eustatic, sea level, but may mean a movement of land relative to the sea. Measures of relative sea level through time can allow the magnitude of these components to be estimated, and can be used to reconstruct palaeosealevels, palaeocoastlines and palaeotopography. These measures also give some indication as to the mechanism of isostatic adjustments and facilitate geophysical investigations of crustal rigidity and mantle viscosity. They are also used to estimate the size distribution of the ice masses through time. There are several approaches which are used to reconstruct palaeosealevels and investigate the role and magnitude of the component factors:

1. Measuring the change in (relative) sea level through time from inferences made using palaeoenvironmental evidence (discussed more fully below)
2. Modelling the earth's crustal flexure and response to isostatic loading (for example Clark, 1980; Lambeck, 1993a, 1993b). This may be done in conjunction with ice

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[1] The geoid is the equipotential gravitational surface surrounding the earth, to which the ocean surfaces equate

sheet investigations where the ice sheet growth and decay are also modelled (for example, Tushingham & Peltier, 1992).

3. Comparing adjacent relative sea level measures to establish similarities and differences due to isostatic and eustatic components, and local tectonics (for example Mörner, 1971).

4. Measuring sea level change through time, in stable areas which are not affected by isostatic and tectonic movements (or where the effects are relatively minor). This gives some idea of changes due to glacio-eustasy alone (for example Fairbanks, 1989).

These approaches are based on a paradigm of sea level change, which can be illustrated using North West Europe as an example. The onset of glaciation caused a drop in sea level on a global scale, which caused a relative sea level fall in North West Europe. The formation of an ice sheet over North West Europe would have caused depression of the crust in the vicinity of the ice sheet, but this depression depends on displacement of a slowly flowing viscous mantle under the affected area. Thus, relative sea level appeared to rise as the crust was depressed. With an amelioration in the climate, the glaciers receded and global sea level began to rise as meltwater contributed substantially to the ocean volumes. The response of the crust to the removal of the glacier was much slower than the rate of melting, but gradually, sea level began to fall relative to the land surface in many parts of North West Europe, as the earth's crust recovered from removal of the ice load and rose to regain isostatic equilibrium. This recovery still continues today (Emery & Aubrey 1985). Gravity measurements reveal geoidal anomalies caused by gravitational attraction (e.g. Kakkuri, 1987). These are much less than expected because of the 'missing' mantle which has been displaced away from the deglaciated area. Measurements indicate that recovery (isostatic rebound) is not complete. Crustal depression is thought to be greatest under the centre of the ice mass and decreases towards the edges of the ice sheet (Walcott, 1972a; Mörner 1979). Beyond the ice margin some researchers have hypothesised the presence of a forebulge caused by crustal rigidity and/or mantle outflow (Oerlemans & Van der Veen, 1984)

The sections below summarise relative sea level information in terms of levels 1, 2 and 3 data identified in chapter 2 (Level 1. proxy measurements, Level 2. derivations and Level 3. regional correlations as previously defined).

5.2.1 Levels 1 & 2 Data

In the context of relative sea level studies, level 1 and level 2 data are closely associated and thus will be discussed together, since measurements of the height of relict shoreline features directly yield information about the height of the palaeo-sea or tide levels. The summary below, is intended to give an overview of the wide variety of methods and evidence used in the measurement of former sea levels, and the breadth of information that must be integrated to achieve a spatially continuous picture of sea level change through time, and to derive information about the other palaeofeatures with which sea level is associated.

Geomorphological evidence

The heights of ancient shorelines can be determined through accurate geomorphological mapping with respect to a national datum. Shorelines can often be morphologically correlated by mapping a continuous form over a distance. Maps and measures can be derived from three different origins:

- field surveying (it has been noted that implements less precise than a surveyor's level used with a tripod and staff do not provide sufficiently good results (Gray, 1975))
- stereo aerial photographs (1:10,000 - 1:25,000 scale on at least 1:10,000 maps) (Sissons & Smith 1965; Andrews, 1970; Rose & Synge, 1978).
- echo-sounding, seismic profiling and diving (Eden *et al.*, 1969) for submerged features

Lithostratigraphic evidence

Lithostratigraphic sequences consist of alternating layers of deposits through time. Intercalated marine and terrestrial sediments, or benthic and littoral sediments (Rose, 1990) in particular, provide evidence of changing sea level through time. The identification of a continuous sequence is of vital importance. If hiatuses exist, then timing will be very uncertain. Therefore low energy environments are best and high energy ones such as headland regions or tidal mouths are suspect (Tooley, 1978). The types of sediment found in the sequence may also have implications for other palaeofeatures (such as glacial remains, ice rafted debris, pollen spores which might indicate temperature ranges, vegetation cover etc.) and as such will be key in linking different events through space and time.

Such stratigraphic sequences can be established in the following ways:

- coring through overlying sediments. The form of the sequence in space must be determined by a series of cores. Insufficient or badly spaced cores or boreholes can yield incorrect interpretations. A good knowledge of local stratigraphy can help to limit this problem.
- stratigraphic sequences can also be revealed through dissection of the land surface by rivers and streams or by subsequent coastal processes.

Biostratigraphic evidence

Biostratigraphic remains also indicate the height of sea level for a particular date, and give other related information about the palaeoenvironment. Standard analytical procedures should be adhered to, where possible, when making measurements and using the information (Rose, 1990)

Former sea level can be derived from fossil remains. By analogy with the present day, different fossil flora and fauna indicate specific ecological niches or environments (i.e., marine, freshwater, brackish or terrestrial). Marine fossils enable the position of sea level, relative to the land (sea level transgression or regression), and/or the relative palaeo-water-depth to be determined. Dates nay be determined using pollen spectra (frequency of pollen of open-habitat taxa) (e.g. Tooley, 1978; West, 1972; Jelgersma, 1961), or through correlation of sites using biozones (recognised time-stratigraphic ranges of faunal and floral taxa, some formally established, some not formal)

There are two classes of dating methods in sea level reconstructions (these methods have been laid out more fully, with suitable references, in the previous chapter (Section 4.2.1.3):

- Direct dating methods which give an 'absolute' date by measuring relative quantities of naturally occurring radioactive decay elements, for example, Uranium-Thorium (Ur/Th) dating, or Carbon ^{14}C dating.

- Floating time scales, which give a recognised pattern of events which can be correlated and linked to the radiometric time scales. These include: amino-acid diagenesis, glacial varves, palaeomagnetism (linked to radiometric scales using techniques such as tephra chronology whereby correlation is achieved using chemical and mineralogical signatures and may be dated using a volcanic event), pumice (also dated using volcanic events), ice rafted debris (which has a relation to climatic events) etc.

The spatial distribution of this data is uneven with concentrations near coastal areas where raised beaches have been located and measurements made with a few older sites further inland and a smattering of results from borehole drilling, seismics and echo-sounding by ships. Temporal distribution is also uneven. Generally the data volumes decrease rapidly going back in time, but beyond 14,000 BP in North West Europe much of the evidence has been erased or at least buried and disfigured by the Weichselian ice sheet. Thus the information has an uneven spatio-temporal distribution.

Uncertainty issues associated with sea level reconstruction include methodological problems, such as dating techniques and the identification of appropriate horizons (Sutherland, 1987). Height errors can arise from several sources which relate to the correct identification of the feature, identification of the feature with respect to palaeosealevel, and (somewhat less significantly) the error in measuring the height. Temporal errors can be manifested as height errors where the rate of sea level change over time is severe. Continuous morphological forms may not be isochronous which is a problem when using only morphological methods to identify coastal features and correlate them. The resolution of data is determined by the rate of change of sea level since small temporal errors can be manifest as large height errors, but relates also to the time required for significant beach development.

Accuracy depends on the correct identification of high and low water marks and estimates of their relation to mean sea level (which relies on present day tidal information). Shoreline features are identified through geomorphology or stratigraphic sediments. The determination of mean sea level depends on correct identification of the feature and its relationship to mean sea level. Local conditions such as tidal range and fetch may vary (Rose, 1990). In some remote areas accuracy may be reduced because of difficulties in measuring heights and locations with respect to a distant benchmark or national datum. Often measurements are made with respect to the present day mean spring tide levels and converted using tide tables.

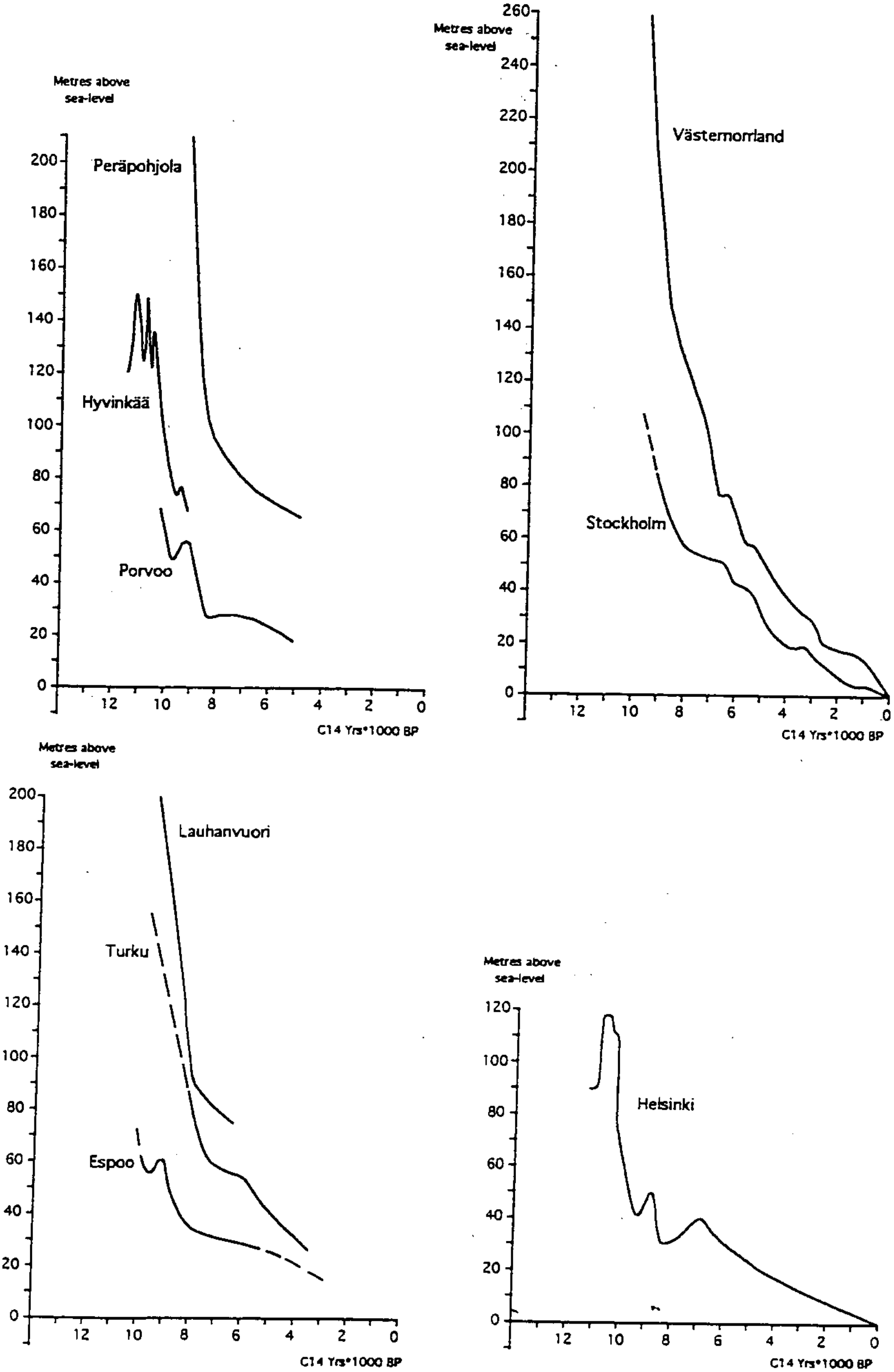
The level of resolution decreases going back in time, and high frequency changes are insignificant compared to the large scale trends (Shennan & Tooley, 1987). Dating errors can be large even if radiocarbon dating (generally considered one of the best methods) is applied. The problems with radiocarbon dating relate to the origin of the material being dated and problems of sample contamination and post-depositional degradation and diagenesis. For example, if a piece of drift wood from a marine contact is used it may not be clear how the age of the wood from the original tree relate to that of the marine layer. Differences in measurements of up to 2000 years have been found depending on the fauna or flora which is dated (Donner *et al.*, 1977). Isotopic fractionation, is a particular problem for radiocarbon dating (Shotton, 1972) and contamination can originate from dissolved carbonates in percolating ground water and/or younger root penetration from overlying vegetation (Sutherland, 1987). There is also some uncertainty about the global variation of carbon isotopes through time. Amman and Lotte (1989) for example, found evidence of two distinct carbon plateaux between 10,000 and 13,000 years BP (Before Present) probably caused by a decrease in atmospheric ^{14}C during these periods. This is manifest as clusters of dates for material of around that age, so that resolution at this time is very poor using this method. Other methods have similar problems and are mostly considered much less reliable than radiometric methods. However, the lack of suitable samples means that many points are not dated using radiometric means, but instead one of the other techniques is used.

5.2.2 Level 3 Data

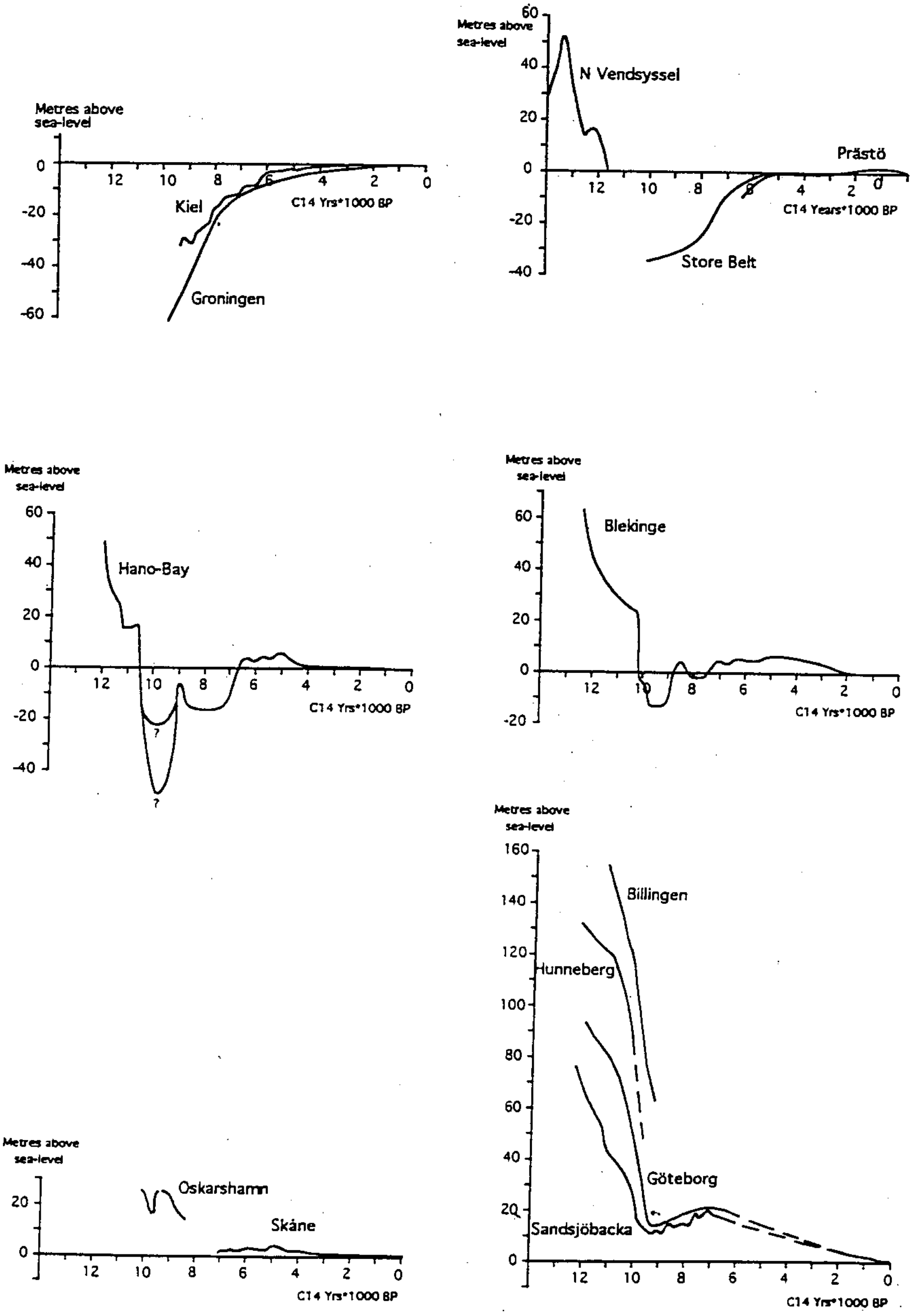
Level 3 data are obtained from level 2 data by correlating and comparing heights and dates according to several criteria which may be geomorphological, stratigraphical (bio- or litho-) and dating-related. Combinations of these parameters are usually used to produce regional syntheses depending on the measurable entities at different sites. To achieve local and regional correlations several methods are commonly used:

1. Sea level curves (examples from North West Europe are illustrated in Figures 5.1a to e, used in the computing study discussed later in this chapter). Sea level curves represent sea level change in an area and are generated by putting together all the evidence for a small area to create a continuous description of sea level through time. These are then integrated spatially to produce four dimensional reconstructions. This is achieved by choosing particular time slices through each sea level curve and then producing a continuous height surface by mapping and comparing heights for each sea level curve location. Derivations such as sea level curves help in that they provide a continuous description of sea level through time. However, it has been noted that significant discrepancies can arise where sea level curves have been derived using different indicators, even for proximal sites (Tooley, 1978, Kidson, 1982).

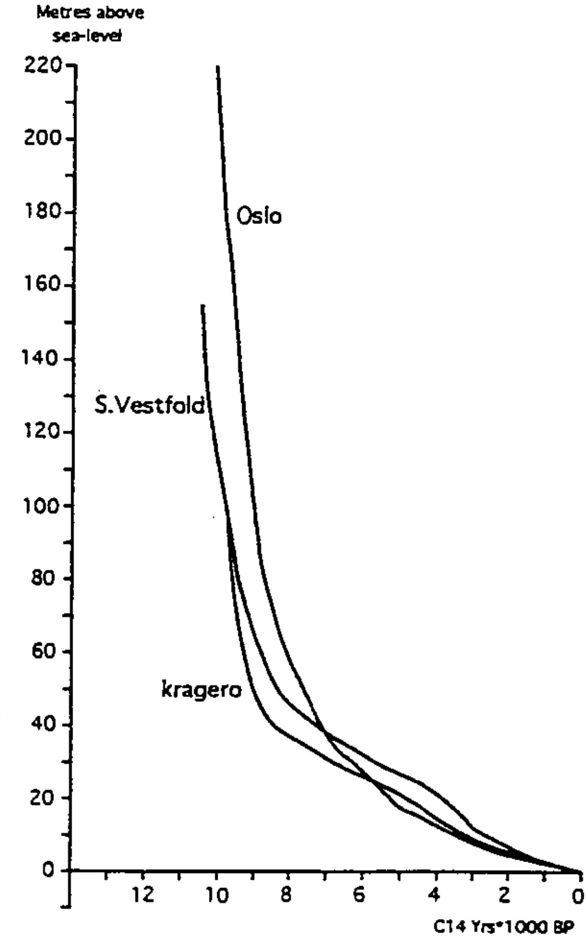
Figures 5.1a. Sea Level Curves (Donner & Jungner, 1977; Hyvarinen, 1980; Miller & Robertsson, 1979; Miller, 1982; Salomaa, 1982; Hyvarinen, 1980, 1982; Gluckert, 1976; Donner & Eronen, 1981)

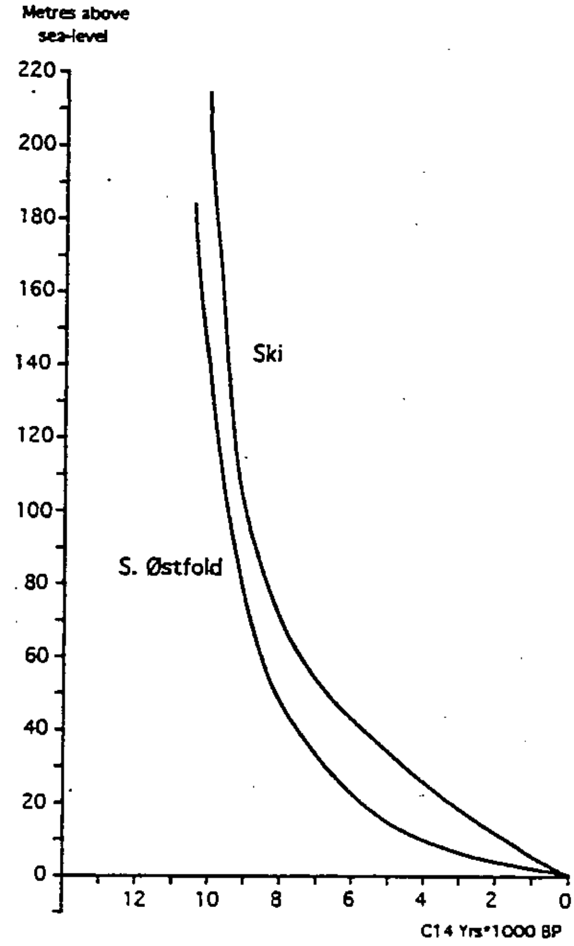


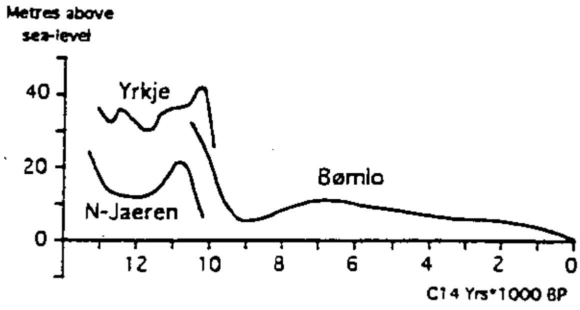
Figures 5.1b. Sea Level Curves (Jelgersma, 1980; Petersen, 1984; Mikkelsen, 1949; Bjork & Dennegard; Bjork, 1979; Svensson, 1985; Bjork & Digerfeldt, 1986, 1982; Passe, 1987)

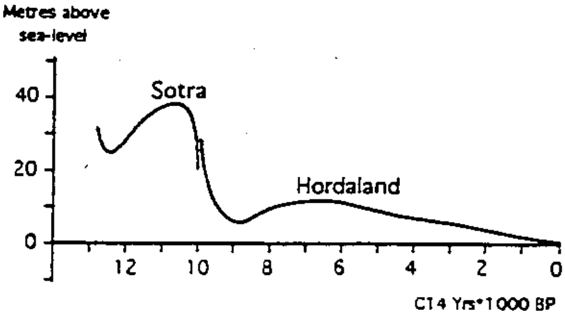


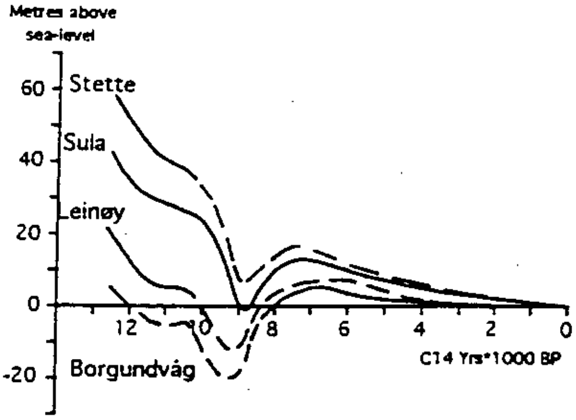
1982; Thomsen, 1981; Haftsen, 1983; Krzywindski, 1984, 1978; Kaland, 1984; Svendsen & Mangerud, 1987; Lie *et al.*, 1983; Svendsen, 1985)



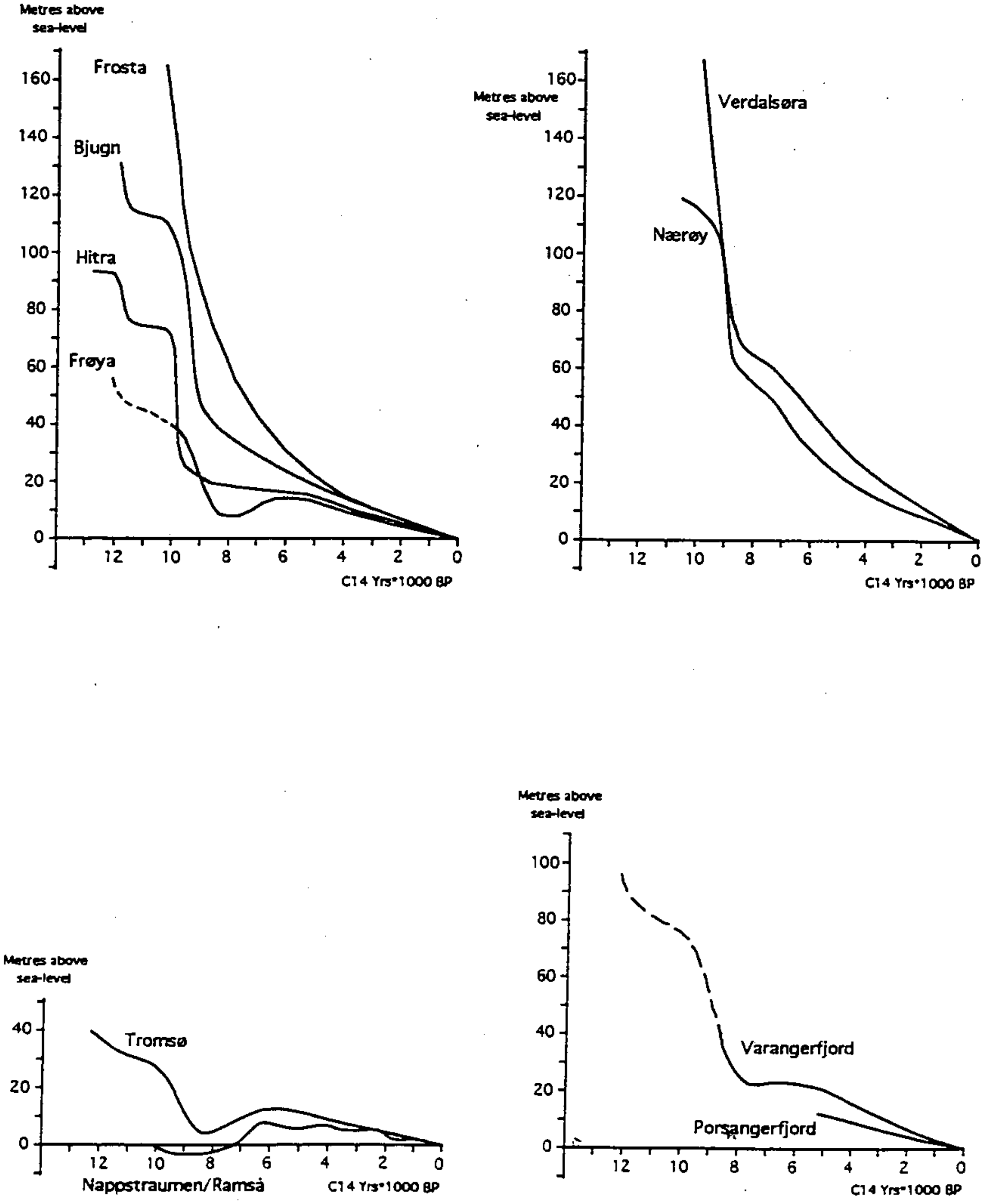




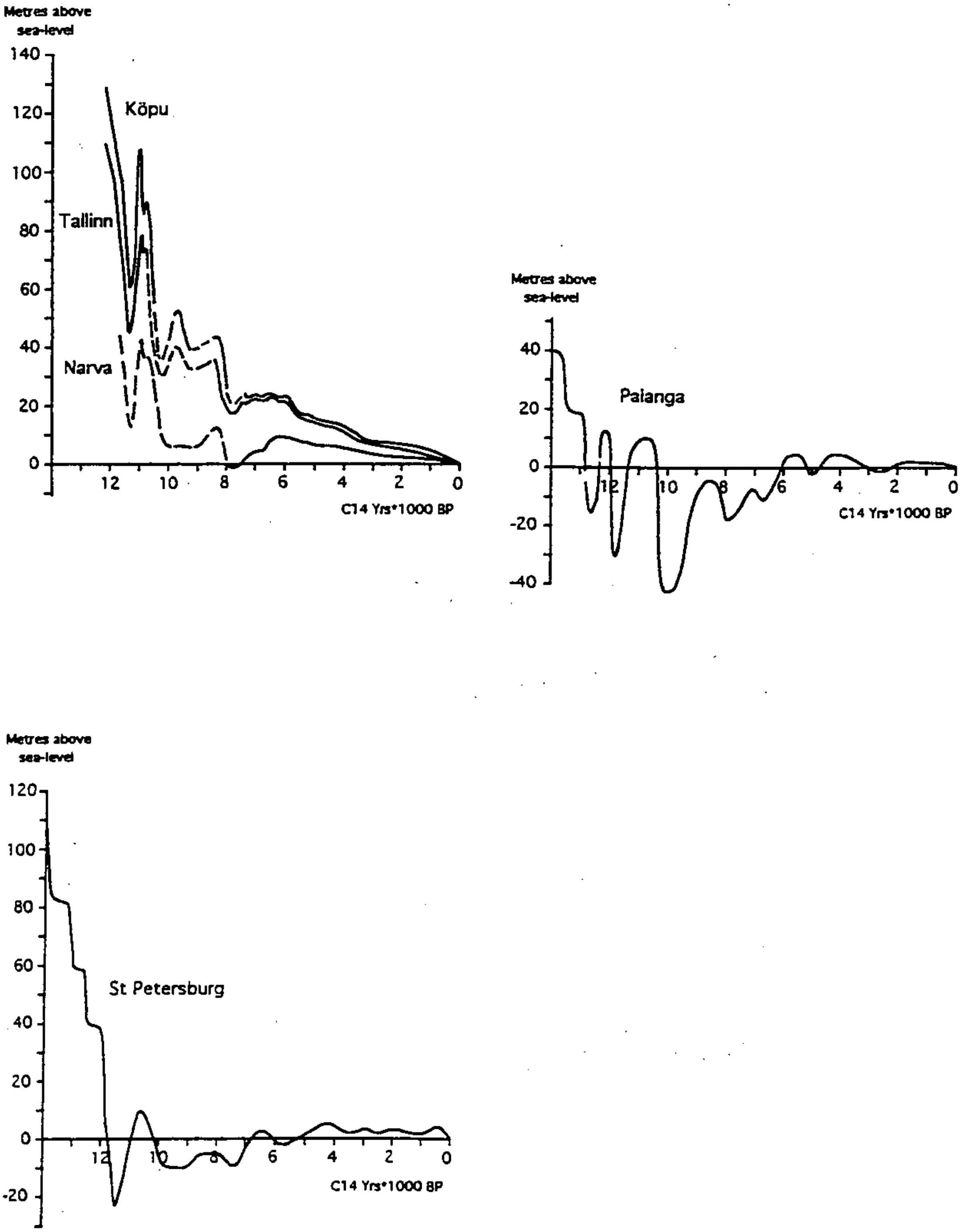




Figures 5.1d. Sea Level Curves (Dolukhanov, 1979)



Figures 5.1e. Sea Level Curves (Kjemperud, 1981, 1986; Ramfjord, 1982; Hald & Vorren, 1983; Moller, 1984, 1986; Donner *et al.*, 1977; Stabell, 1980)



2. Shoreline diagrams. These are particularly useful for areas where there has been isostatic recovery after glacial occupation. They are used to correlate fragments of evidence when the time or height are uncertain. The diagrams are drawn perpendicular to the contours of uplift and are determined by regression analysis of a given set of points (Cullingford & Smith, 1966). Individual points are projected onto a plane which is perpendicular to the uplift isobases.

3. Shoreline relation diagrams. These show the relationship between the heights and ages of points related by rate of uplift. The method assumes that the rate of uplift is constant, predictable and is related directly to the age of a shoreline and its height. They were originally used to correlate different shoreline fragments before radiometric dating was available. However there are several major drawbacks with this method:
   I The eustatic component must first be removed from the data (Andrews, 1970);
   II Since the relationship must be a smooth change, reducing with time, any interruptions such as re-loading caused by an ice advance mean that data before this re-loading cannot be used;
   II The method is dependent on the accuracy of the data, which can be a problem if the right information cannot be found.

4. Isobase maps. The above three means of correlating data can be used as input to a fourth method for deriving regional and continental reconstructions for particular time slices. Information is grouped by date and plotted. Contours are then drawn which represent the relative sea level surface for each time grouping. The contours are usually hand-drawn, although interpolation methods have also been used.

5.2.3 Related information

By analysing the methods used to derive the information examined in the sections above, several types of related information can be identified and summarised:

1) Methods and guidelines

- Dating techniques (pollen, radiocarbon, etc. and rules of applying these such as means of identifying contamination in radiocarbon samples, records of global carbon variation through time, palaeomagnetic records, information about tephra layers, their chemical compositions and eruption dates etc.)

- Interpolation routines and trend surface analysis methods.
- Surveying techniques
- Details and guidelines concerning different correlation techniques

2) **Related datasets used in the derivation of sea level reconstructions.**

- Interpolation routines and trend surface analysis methods.
- Marine limit. This is really another reconstruction derivation used as a reference (Rose, 1990), and is the highest level reached by the sea after deglaciation.
- Tide Tables. These enable height relationships to be established between different countries to allow height comparisons (Jardine, 1976). The nearest point on the Admiralty Tide Tables is required for the UK (Synge, 1969).
- Correlation standards. These are often used in conjunction with traditional dating methods, although correlation alone may occur where dating is unavailable. Typical correlation reference sets include: pumice, tephra and ice-rafted debris compositions and timing, palaeomagnetic records, SPECMAP oxygen isotope curve, other sea level curves etc.
- Palaeofeature definitions and methodological information. These include height relations between morphological features and mean sea level (MSL), high water mark (HWM) or low water mark (LWM).
- Conversion relationships between radiocarbon and sidereal years.
- Information about present or past tectonic activity which might help to identify areas most likely to be affected by tectonically controlled discrepancies.
- Basic reference information such as geological and topographic maps
- Models:Compaction effects of sediments (e.g. Jelgersma, 1966)
  Geoidal variations (e.g. Clark *et al.*, 1978)
  Crustal flexure and mantle flow (e.g. Lambeck, 1991; Peltier, 1987)
  Ocean volume changes (thermal/salinity changes (e.g. Peltier, 1987)
  Tidal effects (e.g. Austin, 1991)
  Sediment loading and subsidence in coastal areas
  Hydrological models

5.2.4 Reconstruction requirements

In order to achieve sea level reconstructions the following sets of information are required:

I Background Information (Level 2 and 3 data and Related Data)

- Review of current sea level theories and state of knowledge about the area (Level 3 Data)
- Specific information about particular areas (state of current Level 2 Data)
- Current theories and state of knowledge about identification of relic sea level indicators (Related Data)

II Core data (Level 1 and Related Data)

- Sea level data (usually new) (Level 1 Data, but could be Level 2)
- Geological, hydrological, topographical, and base information (Related Data)

III Available Methodological Information Relating to Level 1 Data (Related Data)

What measurements are made and how (with particular reference to dating techniques)
Accuracy guides of methods and measurements including assumptions made
Process, static and dynamic models

IV Data handling and analysis methods relating to Level 2 and 3 Data

visualisation
generalisation of detailed information over an area to produce a regional picture
selection of particular data elements for processing
analysis of height information such as interpolation for surface creation
correlation either stratigraphically, spatially or both

As with the glacial geomorphological case study, conventional methods of research generally focus on II and IV. The main issues associated with current practices of sea level reconstruction are:

1. The heterogeneity of information which is often relatively poorly documented in numerous journals.

2. The time required to plot and contour sea level index points by hand for numerous time slices limits experimentation with errors and the inclusion and exclusion of different data.
3. Integrating sea level information with other data and model output requires transformation between co-ordinate systems and sometimes between different media. Done by hand this is both tedious and tends to cause error introduction.
4. The addition of hand-drawn contours and eye interpolation between index points is not rigorous. Thus it is difficult to obtain a quantitative measure of how well the data fits a model and there is little structure to the weighting of the particular index points.
5. Paper maps offer limited flexibility for visualising the data and results.

5.3 A GIS-based study

This section discusses an investigation into the advantages and issues of using GIS to support and carry out sea level reconstructions over a large area in North West Europe. The GIS ARC/INFO was again used. The aim was the evaluation of the potential of GIS for handling palaeoenvironmental reconstructions, and to compare these computing methods with current methods, particularly in terms of speed, accuracy, data re-use, rigour and the reproducibility of results. If data can be mapped consistently over such a large area the possibilities for testing palaeosealevel hypotheses are considerable.

5.3.1 Background to case study

Although there is a wealth of sea level information in the literature, radiocarbon dated index points are considered to be the most reliable, and comparable (in terms of regional correlation). During IGCP (International Geological Correlation Programme) Project 61, the International Databank of Radiocarbon Dated Sea Level Index Points was established (e.g. Preuss, 1979). As the name might suggest, the database design was based exclusively on radiocarbon dated material. Aspects of the design of the database used for this case study were adopted from what could be established about the UK Working Group's databank of sea level index points (for the UK only) collected for IGCP Project 200, which was the follow up to IGCP Project 61 (Shennan, 1989). However, the data model associated with that database (if such a model exists) has not been published, and the contents of the databank are available only to the Durham Group (based at Durham University and run by M.J. Tooley and I. Shennan) and those directly associated with development of the databank. It is worth noting, that this databank, and the data held, have been developed and collected over a period of 20 years. The information associated with the index points which were stored in the databank was not collected solely from the literature, but through a comprehensive form which was sent out to researchers. In many cases dating and measurements had to be repeated by the Durham group because insufficient information about the details of the techniques used and the results were available (Shennan pers. comm., 1991).

Initially, an investigation into the types and roles of data which would require analysis and storage within the GIS was undertaken. The results of this analysis, in terms of the reconstruction methodology and data categories is described in detail in the previous section. Using this information a data model (Howe, 1989) (detailed in the section 5.3.2) was constructed for the relative sea level and related information. However, it was found that few data source publications quoted sufficient information to populate this database. Shennan (1989), when experimenting with an alternative approach to studying sea level and crustal movements before the UK databank was available, suggested that sea level curves offered a number of advantages for supporting such a study. There is a significantly lower effort involved in using sea level curves as opposed to index points because of the time required for, and the problems associated with, obtaining information from the literature. Curves provide a continuous description of sea level change through time, and so a more complete picture of sea level at any instance can be obtained using them. These interpretations have been made by those who have measured the index points used to construct the curves, and know the region well. Shennan points to this factor as also being a limitation because of the different interpretations made by the original authors. For this study it was deemed important to explore, as far as possible, the complexities of a comprehensive sea level database, and therefore a data model was developed which included fields for index point data despite the lack of detailed information which could be used to populate, physically implement, and test the database. Sea level curve data alone was used for the GIS analyses, and because of the importance of these curves, the database was designed to hold index points *and* curves, and to allow a relationship between curves and index points to be stored as well. This means that were index points to be added to the database, it would be possible to identify which index points were associated with which curves, and therefore to provide a means of obtaining the original information with which the curve was constructed, and also to facilitate reinterpretation and re-drawing of the curve if that were desirable. Thus, the database is usable by sea level specialists, and those who require sea level data for related work, but perhaps do not have the detailed background knowledge and experience required to work with index points alone (they can rely on the judgement of the experts who constructed the sea level curves, and merely use those). The addition of sea level index point information linked to curve data, would also provide a means of obtaining error information. Error information was rarely available for curve data, which therefore limited error analyses to a general, qualitative discussion. Were the index points to be added, they would give sufficient information for the user to be able to draw their own conclusions, using their preferred methods, about the errors and how to incorporate them in any analyses (this is discussed under section 5.3.6 with reference to further work).

5.3.2 Sea Level data model

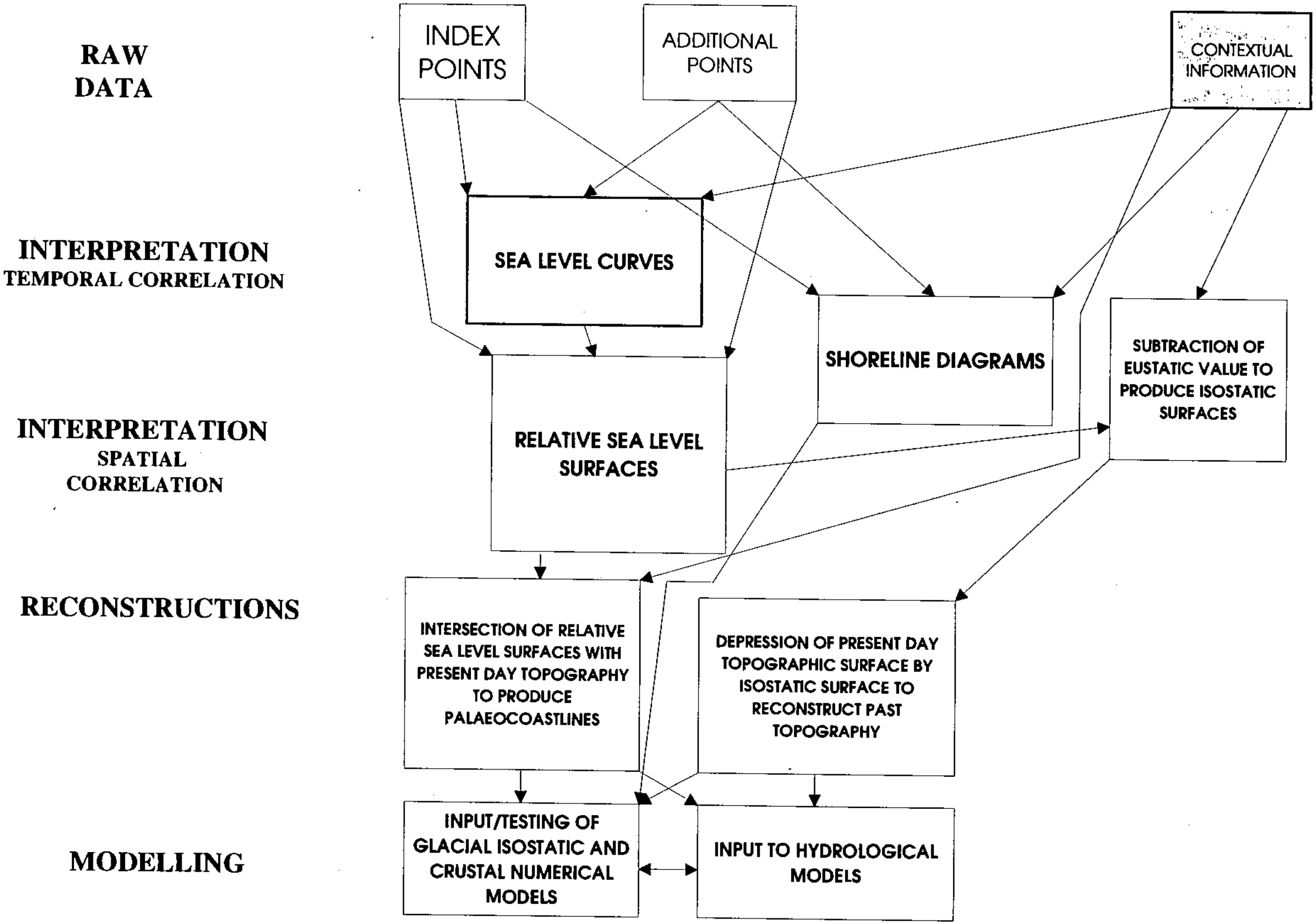
In summary, levels 1 and 2, relative sea level data for which the database was planned fall into four general categories:

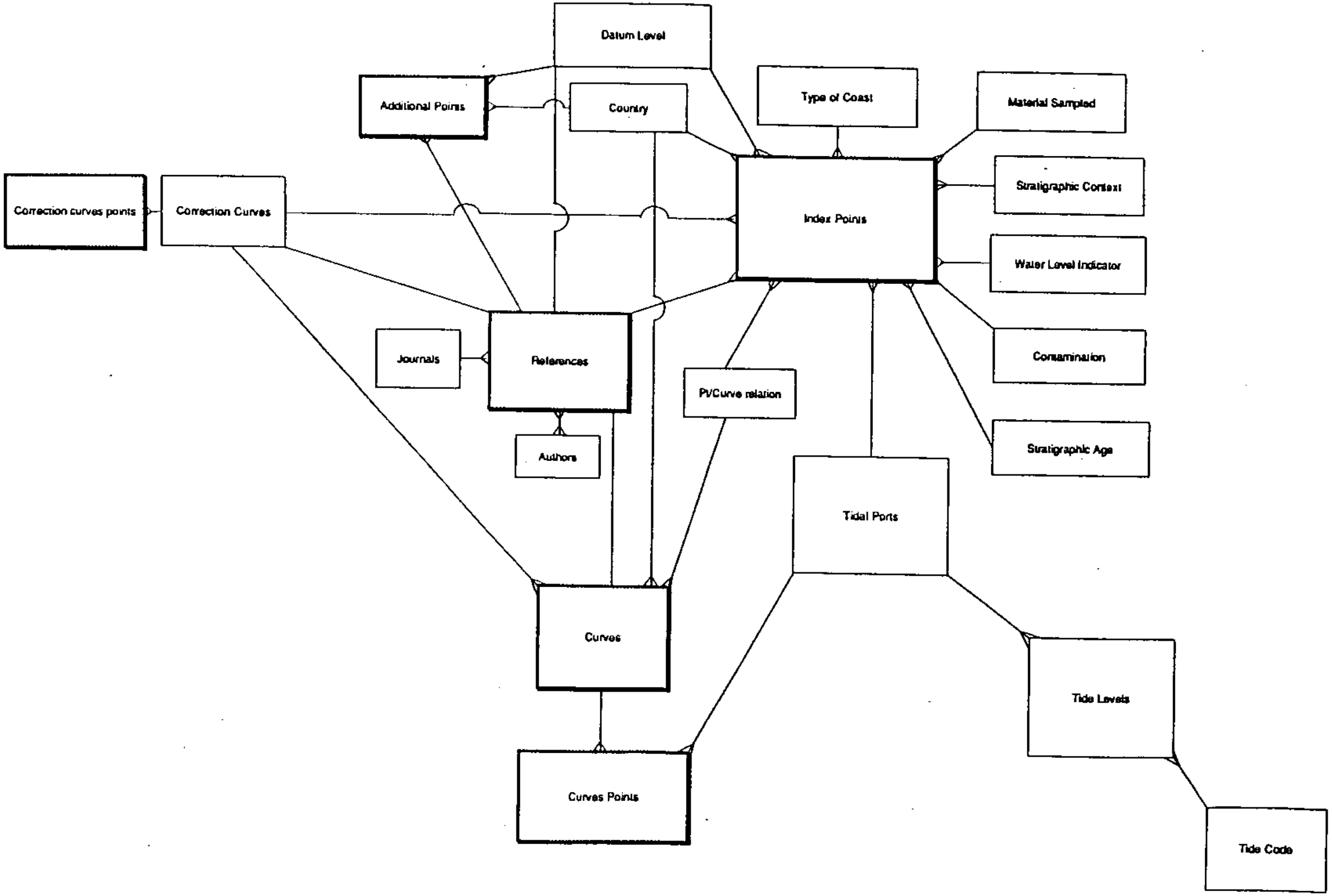
1. Sea level index points height, plus error, date plus error, dating method, description of the sequence.
2. Sea level curves
3. Additional points - more general regression/transgression records which have relative dates but are not well constrained
4. Contextual information - eustatic sea level curves - compiled to represent very large areas representing the behaviour of global eustatic sea level e.g. Fairbanks curve (Fairbanks, 1989), tidal information, and information about dated areas which were above or below sea level and may also give an indication of, for example, water depth or position with respect to sea level which will help to constrain interpretations.

The use of this information in the reconstruction process is depicted in Figure 5.2.

It should be possible for researchers using the system to filter data according to their preferences. These filters are based on such things as contamination of radiocarbon dating material, whether or not the contact is erosional, the stratigraphic and age contexts (all cited in Shennan 1989), and according to who made the measurements and the interpretations. Therefore all these items must be indexed within the database. It was also considered important to be able to recover, from the database, information about the publications associated with the data, so that the system user can obtain the original publication if necessary. The data model for the database is shown in Figure 5.3. This diagram shows what is known as an entity relationship

Figure 5.2 Manipulation and Analysis Requirements of Sea Level Data



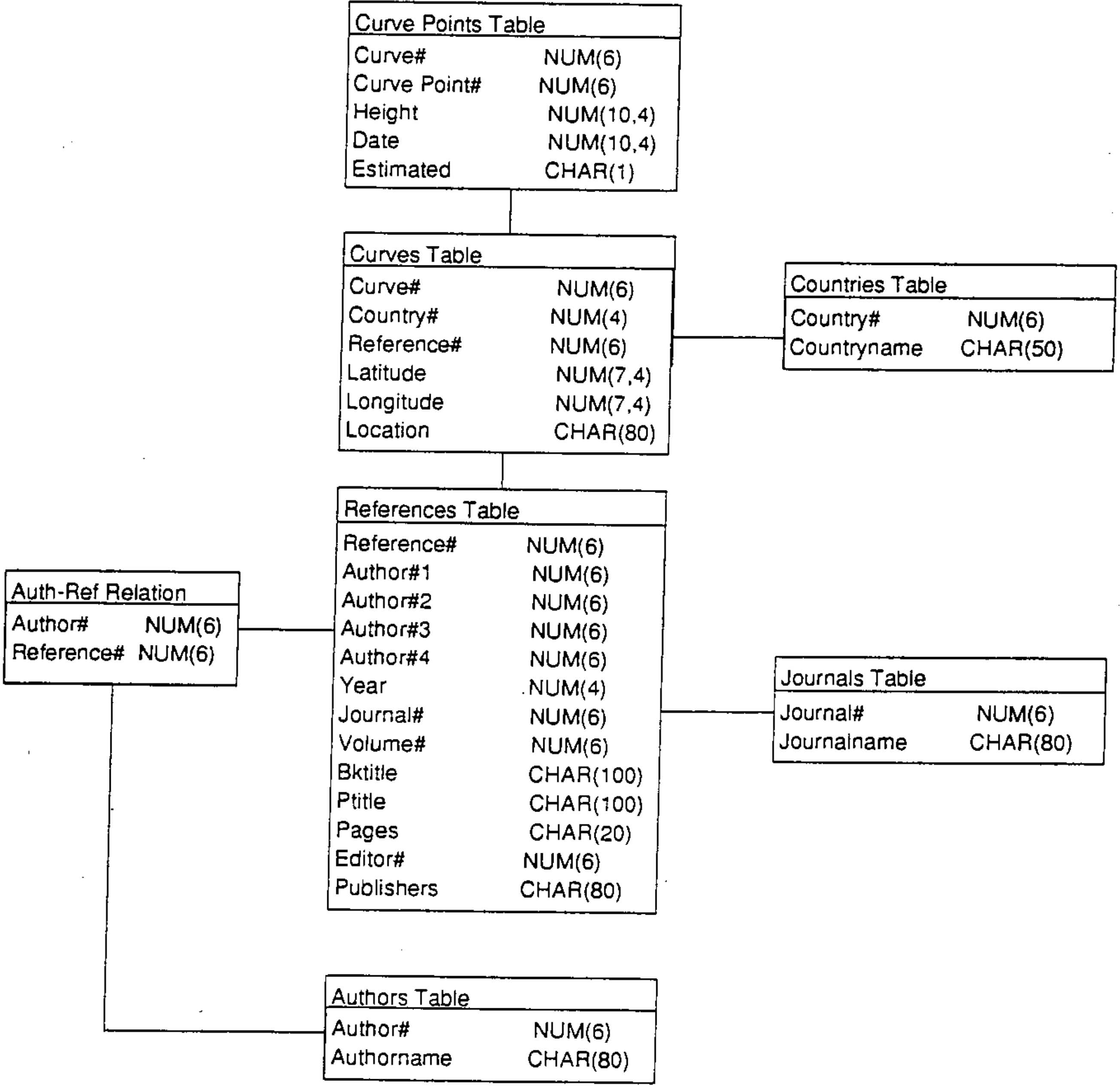

Datum Level
Additional Points
Country
Type of Coast
Material Sampled
Correction curves points
Correction Curves
Index Points
Stratigraphic Context
Water Level Indicator
Journals
References
Contamination
PI/Curve relation
Authors
Stratigraphic Age
Tidal Ports
Curves
Tide Levels
Curves Points
Tide Code

model. However, because of the size of the model and the numbers of entities, the relationships are not annotated. Those boxes in bold contain the main data components, for example the Index points box represents the table which contains the heights and dates for the points, and any site descriptions. Most of the other boxes represent 'look-up' type tables which contain information referred to by identifiers in the main table. For example, the country table contains a list of countries and corresponding country identifiers. These country identifiers are contained in the index points table (thus saving a repetition of country names throughout the index points table). This enables efficient searches on codes, so that if the user required information for all the sites in Norway where the data was based on uncontaminated peak samples, a search would be made on these codes indices. Lines connecting entities (thus implying a relationship) which end with a crows foot denote a "many" relationship. Those ending in a single line denote a "one" relationship. For example the connection between the authors and references tables is a many-to-many relationship, i.e. many authors may be connected with one reference but many references may be associated with the same author For the sea level curve database subsection, Figure 5.4 describes the contents of tables in more detail and gives some suggestions for the types and sizes of fields required for each table.

The standard concepts and notations associated with relational database modelling can be found in Date (1983) and/or Howe (1989). Briefly, though, the purpose of data modelling is to structure the contents of the database so that the information is stored in such a way that it can be retrieved efficiently, so that data redundancy is eliminated (i.e. data is not unnecessarily repeated in different parts of the database) and so that data integrity is maintained (data are not duplicated, and all the attributes are associated with the correct data entities, updates can occur easily, and all data is retrievable). This is important because most attempts at designing small databases for research have not followed these rules, but it is essential to do so in databases that are to be used by multiple individuals to ensure data integrity is maintained

Both database design and data assembly for manipulation required exhaustive literature investigations. The data assembled was collected through a collaborative effort with Pieter Dongelmans. The sea level curves resulting from his literature search are those incorporated in this system. There are 51 sea level curves covering varying time periods from present day to 14, 000 years BP. Before this time much of the radiocarbon dating is unreliable (Rose 1990; Sutherland, 1987) and the evidence

Figure 5.4. Sea Level Curve Data Model



Curve Points Table

Curve#	NUM(6)
Curve Point#	NUM(6)
Height	NUM(10,4)
Date	NUM(10,4)
Estimated	CHAR(1)

Curves Table

Curve#	NUM(6)
Country#	NUM(4)
Reference#	NUM(6)
Latitude	NUM(7,4)
Longitude	NUM(7,4)
Location	CHAR(80)

Countries Table

Country#	NUM(6)
Countryname	CHAR(50)

References Table

Reference#	NUM(6)
Author#1	NUM(6)
Author#2	NUM(6)
Author#3	NUM(6)
Author#4	NUM(6)
Year	NUM(4)
Journal#	NUM(6)
Volume#	NUM(6)
Bktitle	CHAR(100)
Ptitle	CHAR(100)
Pages	CHAR(20)
Editor#	NUM(6)
Publishers	CHAR(80)

Auth-Ref Relation

Author#	NUM(6)
Reference#	NUM(6)

Journals Table

Journal#	NUM(6)
Journalname	CHAR(80)

Authors Table

Author#	NUM(6)
Authorname	CHAR(80)

fragmentary and for much of Scandinavia, this evidence was destroyed by the presence of glaciers, since the area was largely ice-covered.

The curve locations are shown in Figure 5.5. For many of the curves there was little additional information provided, such as detailed locational information, the index points from which the curves were constructed, and height and date errors for the curves.

5.3.3 Data Capture and Transformation

The locations of the curves were stored together as a layer of points. The latitude and longitude values were input and then converted using a map projection algorithm within the GIS to the same co-ordinate system as the base map, and these locations were then linked using identity numbers to the height, time curve data in the database. Since the GIS in question did not provide for the explicit storage of vertical or temporal data this information was stored as attribute information. The most compact storage method for this time-height data and the most efficient in terms of data retrieval, might be to convert the curve to a function of height against time. This means that when a time slice is required, the equation can be solved for height for this known time. The difficulty is that the curves are not only discontinuous but, in places, extremely irregular. This method was investigated using a curve-fitting package. The curve was described by a function or functions for different segments. It was found that where there were data gaps, or where the curve changed gradient very rapidly (particularly around maxima and minima), it was not only complex to describe in mathematical terms but resulted in erroneous values for solving the equation at end-points or places where there was a drastic change in gradient. A more straightforward method was to digitise points on the curve very close together and store the height-time values as a string of x, y co-ordinates. Using this method only an extremely simple linear interpolation was needed for heights which fell between digitised points. This also provided for the storage of certainty measures for parts of the curve so that if a sophisticated interpolation routine were employed for spatial interpolation, the retrieved heights could be weighted according to their certainty. Whilst this method is uneconomical in terms of both storage space and retrieval time, sea level curve data, even for an area the size of Scandinavia, is limited, and so the storage needs were not onerous. A subsection of the original sea level database was implemented within the system to store the sea level curves. Information was not available to populate the complete sea level data model.

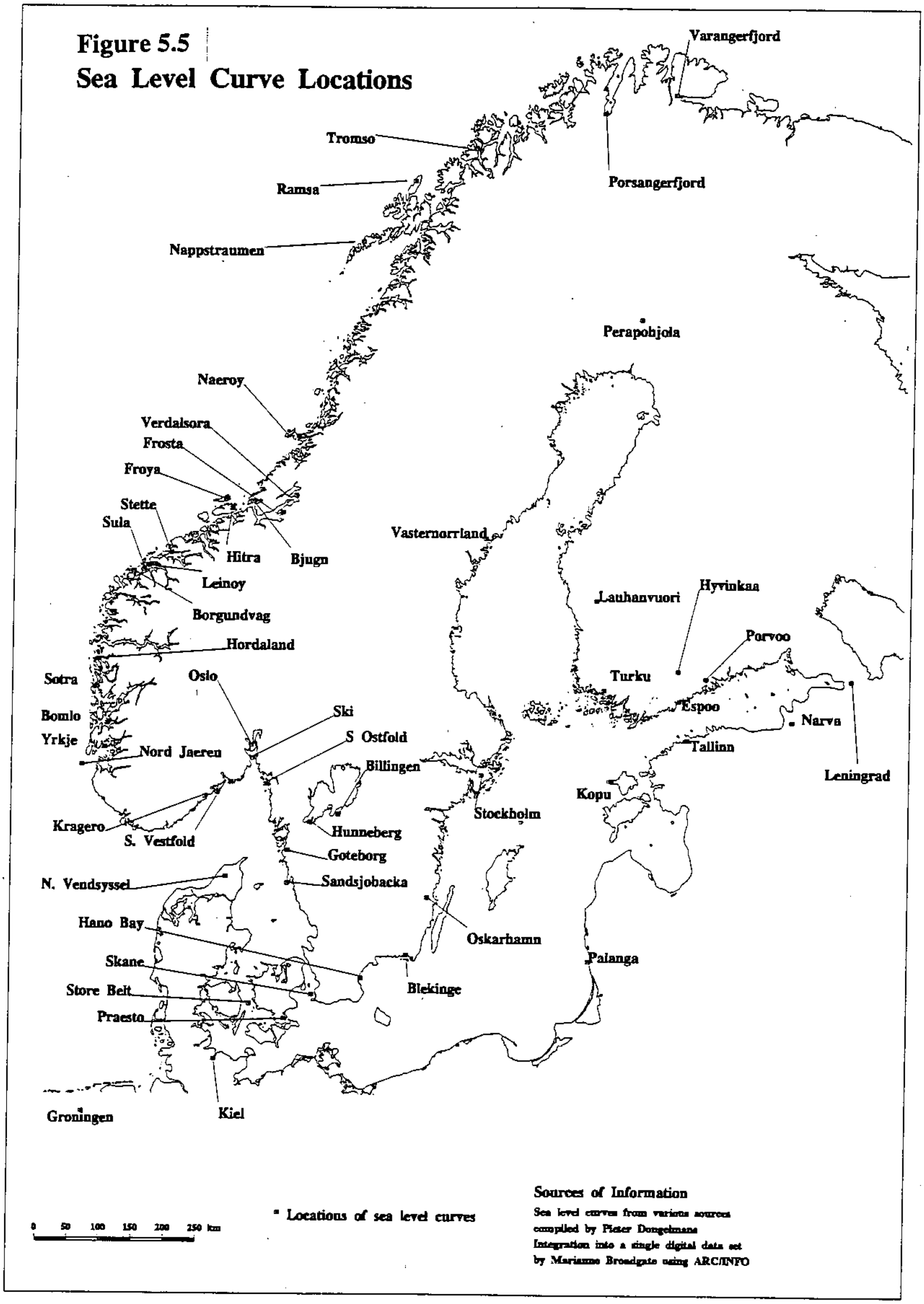


Figure 5.5
Sea Level Curve Locations

Sources of Information
Sea level curves from various sources
compiled by Pieter Dongelmans
Integration into a single digital data set
by Marianne Broadgate using ARC/INFO

5.3.4 Data Integration and Analysis

A series of programs were developed to interrogate the database and interpolate sea level heights for each curve for user selected time slices. Further programs used these height data to perform spatial interpolations to generate relative sea level surfaces. From these relative sea level surfaces, additions to the original programs, allowed the interrogation of eustatic sea level curves (Figure 5.6) for an appropriate height value and the generation of sea level surfaces with a measure of the eustatic component removed. Most of these programs were written in FORTRAN, with the spatial data manipulation and plotting being managed through the GIS by programs created using AML. The interpolation was carried out by a further software package, UNIRAS, although importing the interpolated values had to be achieved through a special program (written by Nick Hulton - see Appendix III). These manipulations are summarised in Figure 5.7 and the programs are listed in Appendix III). A user interface was also developed using AML which allowed users to interact with the programs and data in a flexible way. Users can browse data and results and experiment with the data by selecting different time slices, different eustatic sea level curves, and by adjusting the interpolation parameters (Figure 5.8). The interface is robust and forgiving and is explained in more detail in Appendix III. It will not allow users to use inappropriate numeric values and will recover if character values are entered where numbers are expected.

5.3.5 Palaeoenvironmental Reconstructions

Examples of the reconstructions produced using the system are shown in Figures 5.9, 5.10 and 5.11. These show relative sea level isobases, isostatic isobases and a three dimensional visualisation of an isobase surface for 4000, 5000 and 6000 BP, respectively. These results can be generated in less than five minutes using the system via the interface for any time slice required between 0 and 14000 years BP. The base map on which they are plotted is derived from the WDBII (World Data Base II) dataset which was originally digitised at 1:3 million scale. Figure 5.11 shows a three-dimensional view of the dataset which can be obtained using the GIS and facilitates visualisation of the surface. This stage was not automated because of the difficulty in automating the calculation of appropriate view variables for individual surfaces, although this should be possible with additional programming.

Although the results presented here are no worse, in terms of error and accuracy, than those produced using manual methods (for example Figure 5.12) given the same

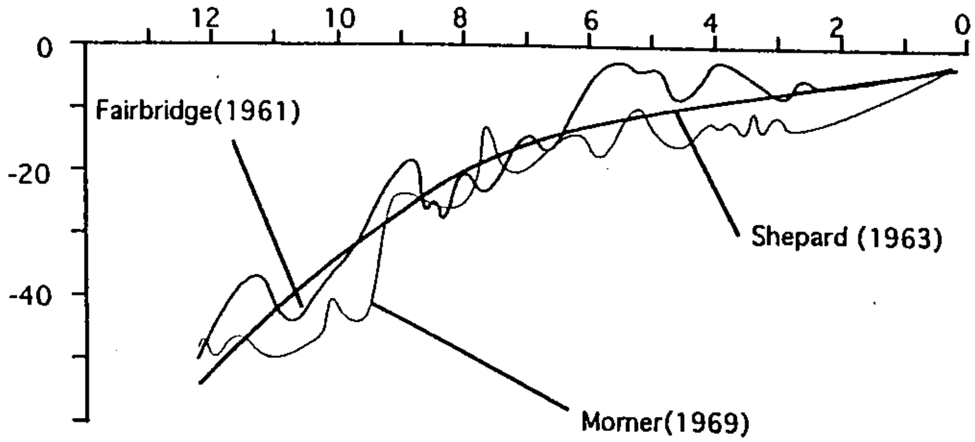
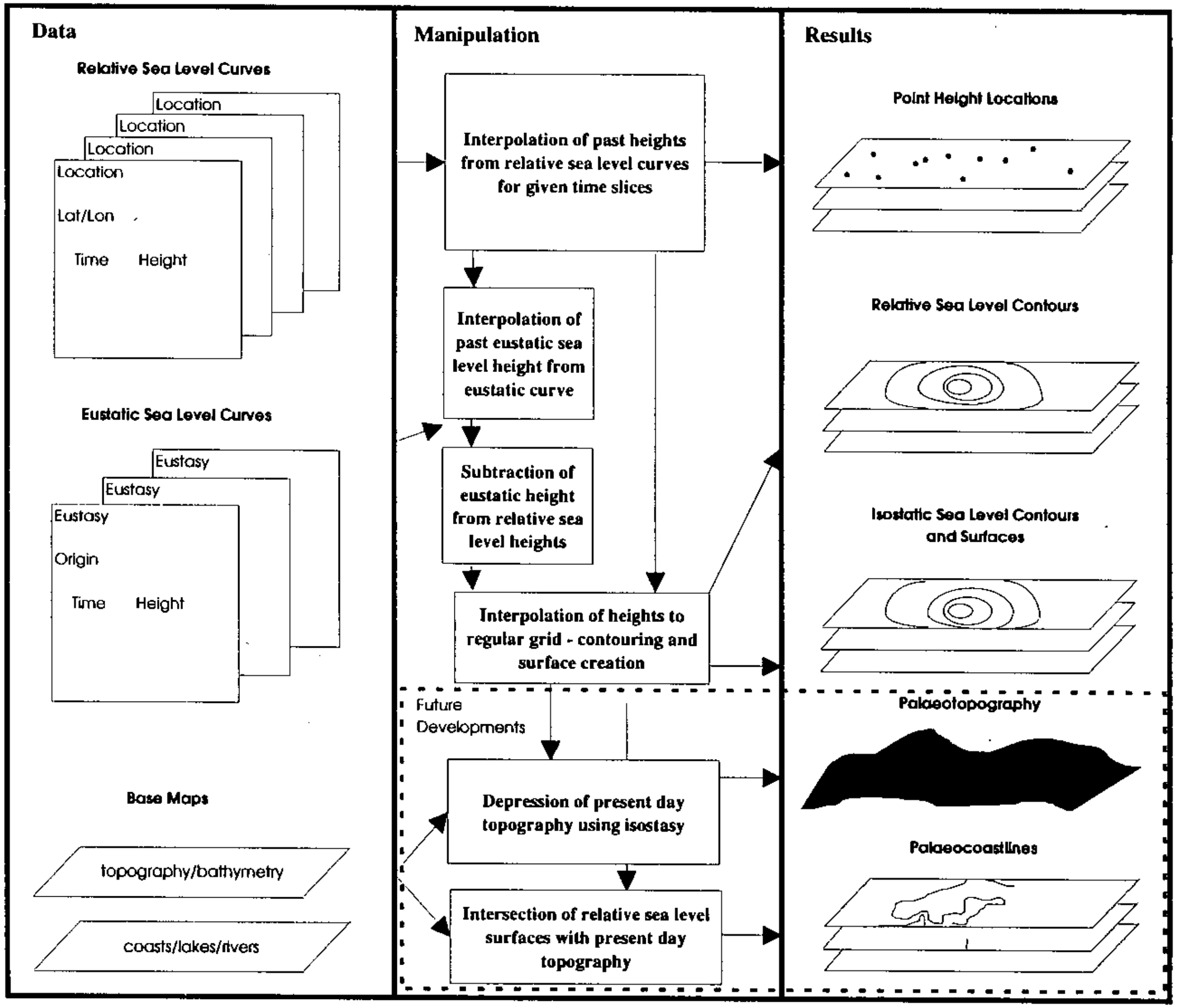


Figure 5.6. "Eustatic" Sea Level Curves

Figure 5.7 System data and results storage, and manipulation



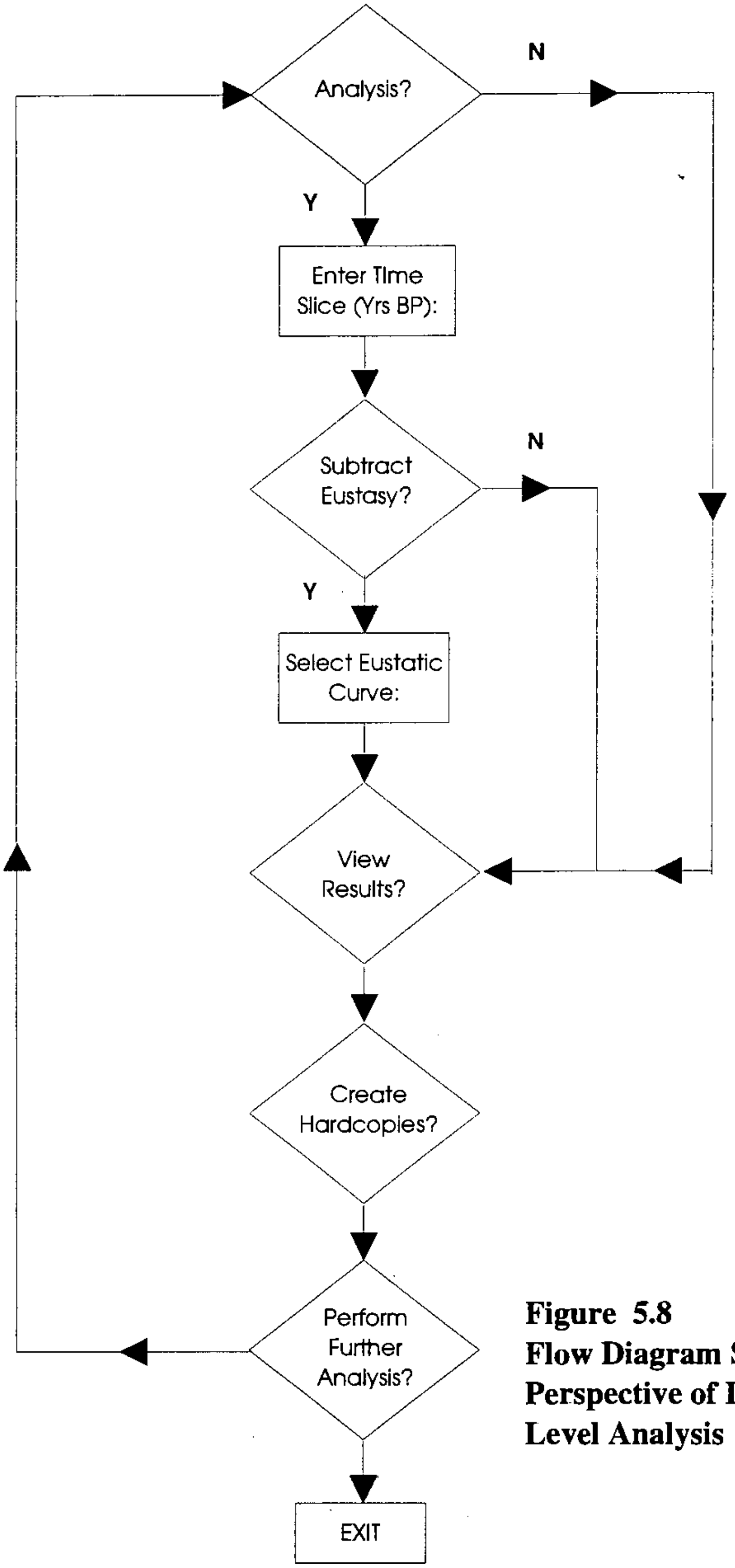
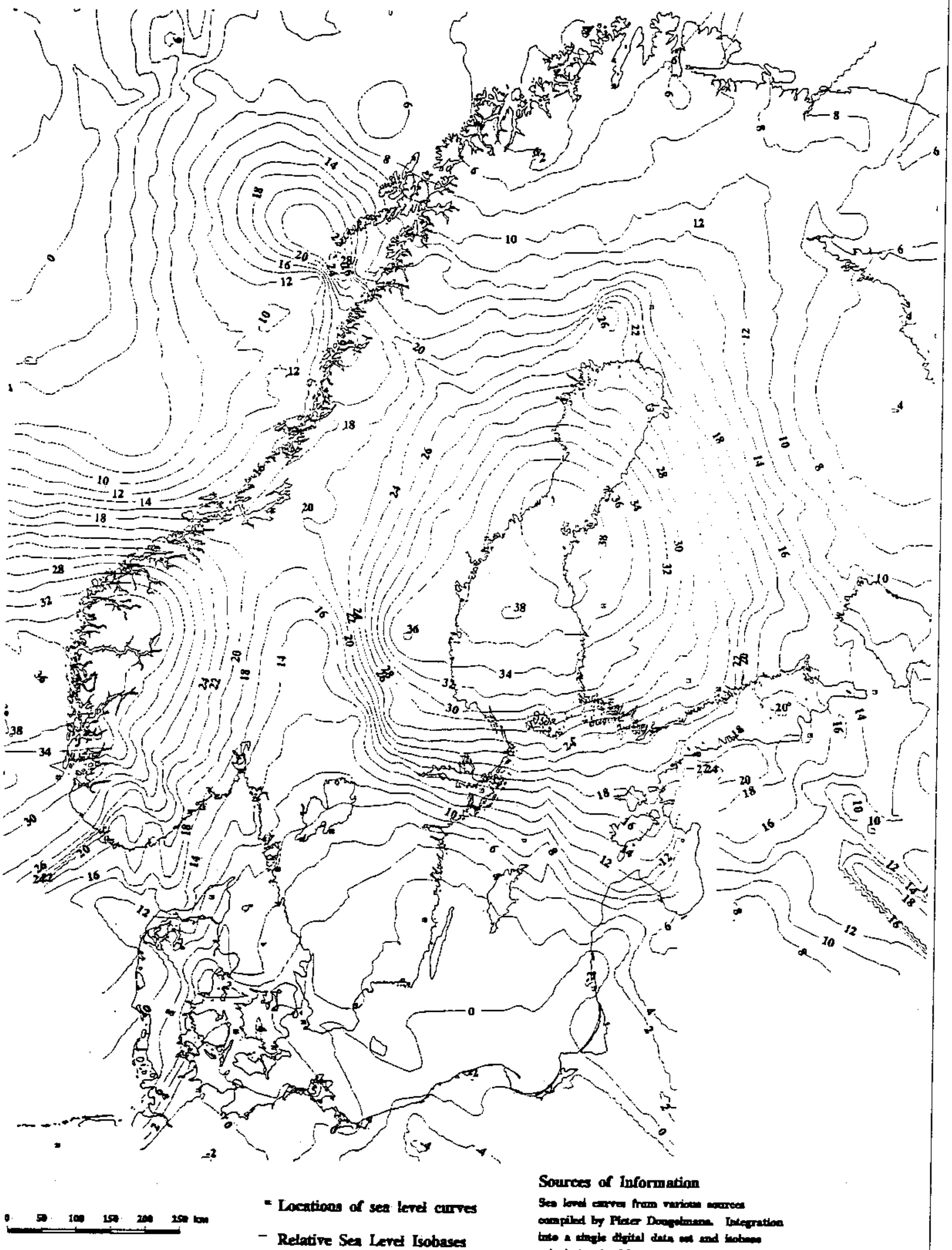


Figure 5.8
Flow Diagram Showing User Perspective of Interactive Sea Level Analysis

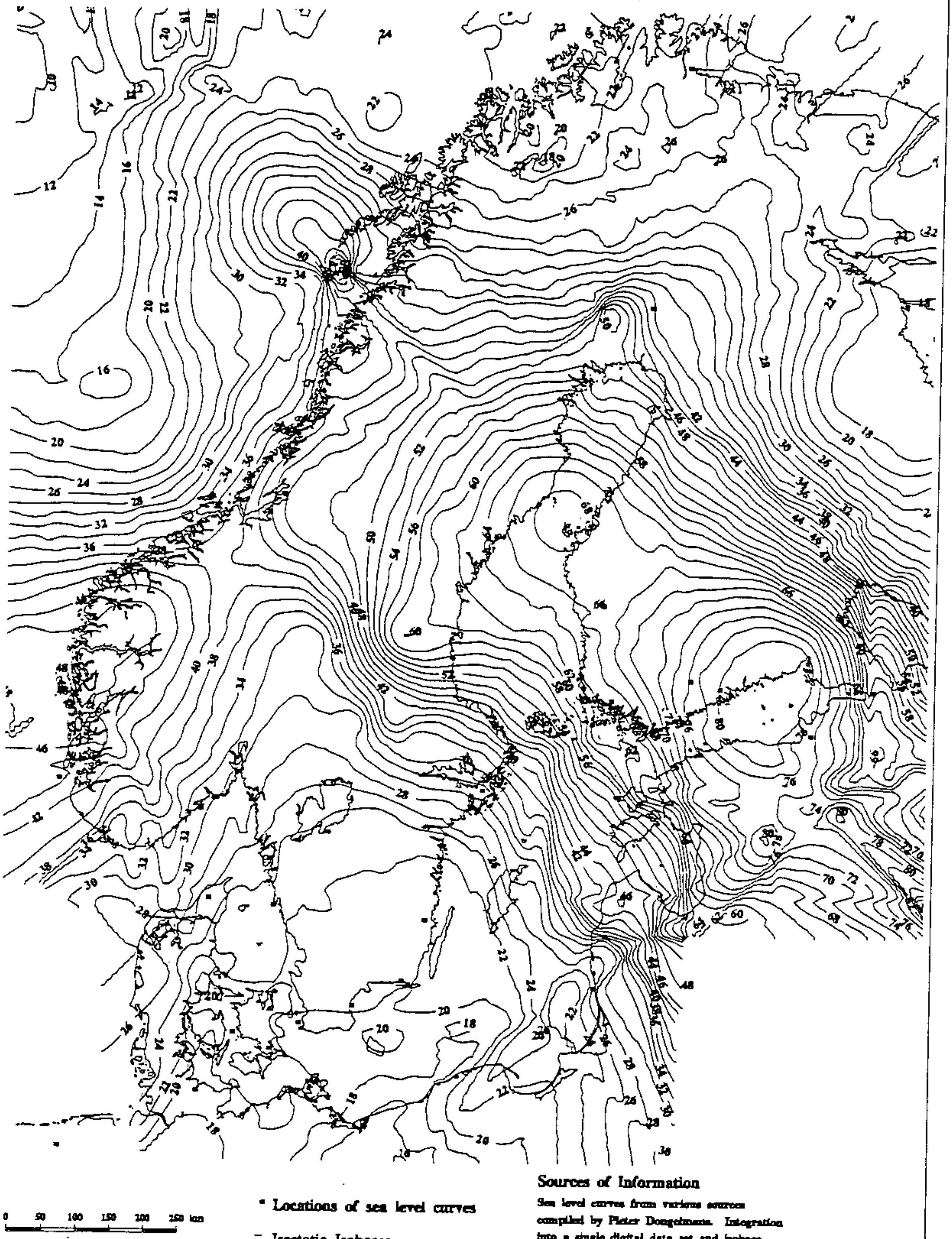
Figure 5.9
Isobase Map of Relative Sea Level (4000 Years BP)



Sources of Information

Sea level curves from various sources compiled by Pieter Dongelmans. Integration into a single digital data set and isobase calculation by Marianne Broadgate using ARC/INFO

Figure 5.10
Isobase Map of Isostasy (5000 Years BP)



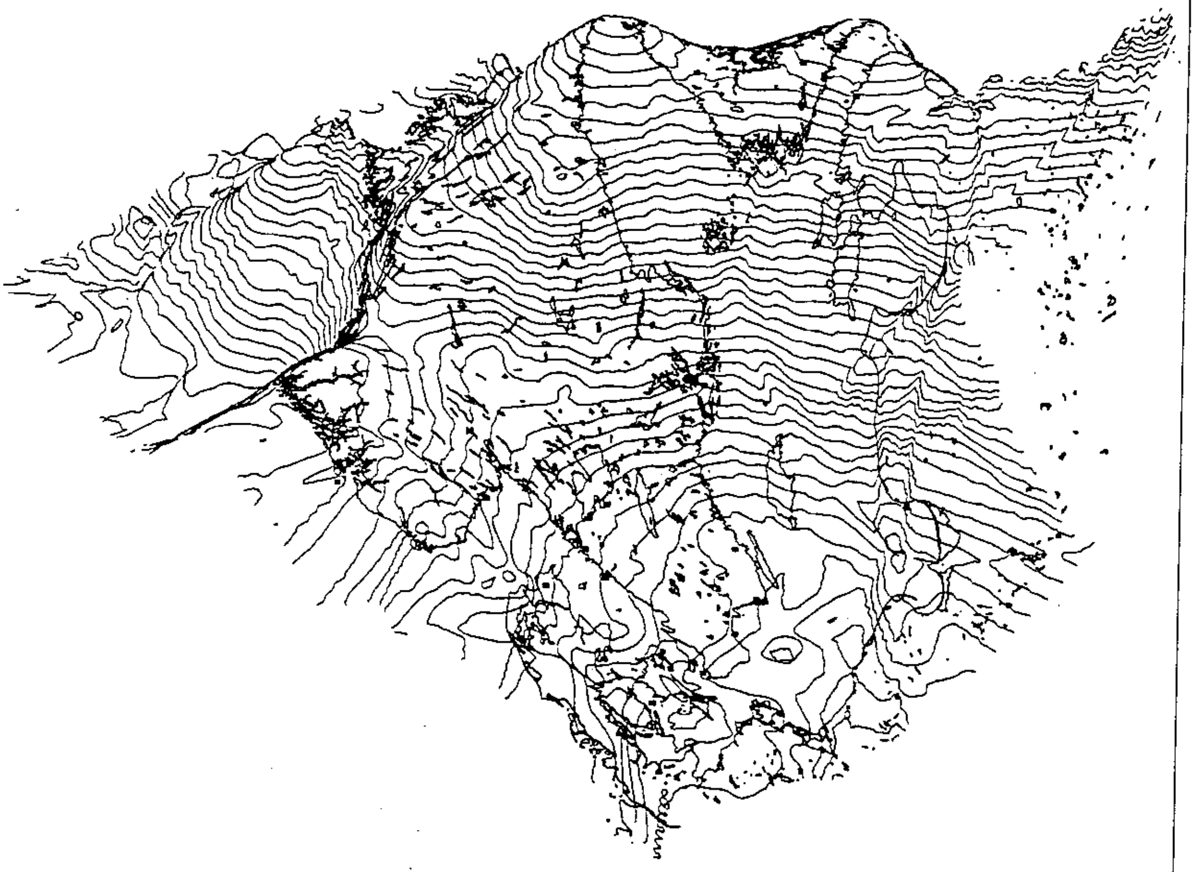
* Locations of sea level curves

– Isostatic Isobases

Sources of Information

Sea level curves from various sources compiled by Pieter Dongelmans. Integration into a single digital data set and isobase calculation by Marianne Broadgate using ARC/INFO

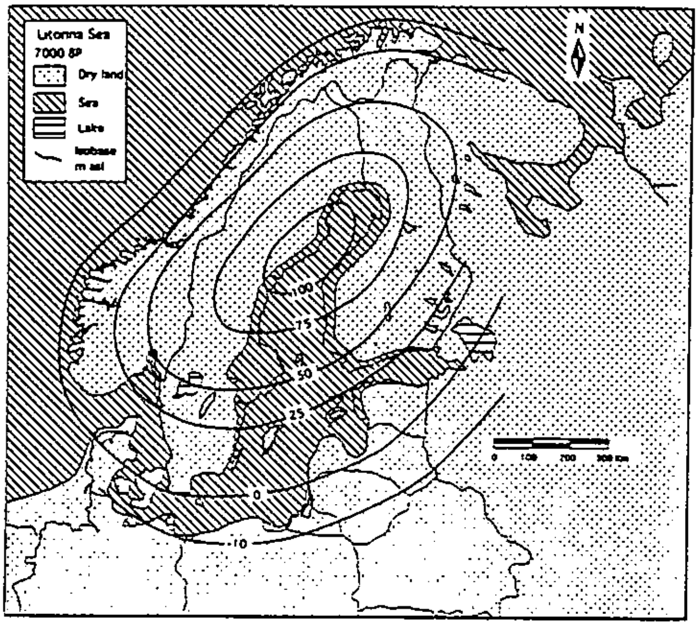
Figure 5.11
Isostatic Surface (6000 Years BP)



Sources of Information

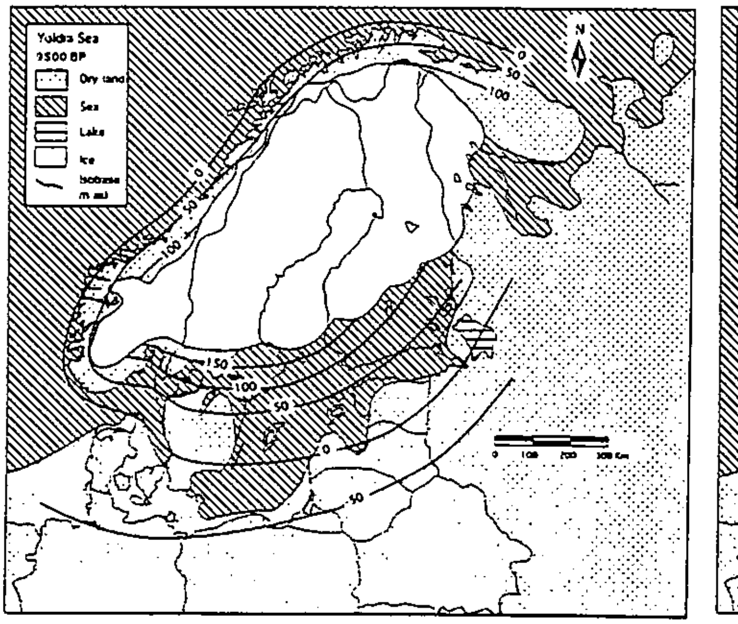
Sea level curves from various sources compiled by Pieter Dongelmans. Integration into a single digital data set and isobase calculation by Marianne Broadgate using ARC/INFO

Figure 5.12 Stages in the palaeoenvironmental and shoreline development of the Baltic-Fennoscandian Region (Dongelmans 1995)



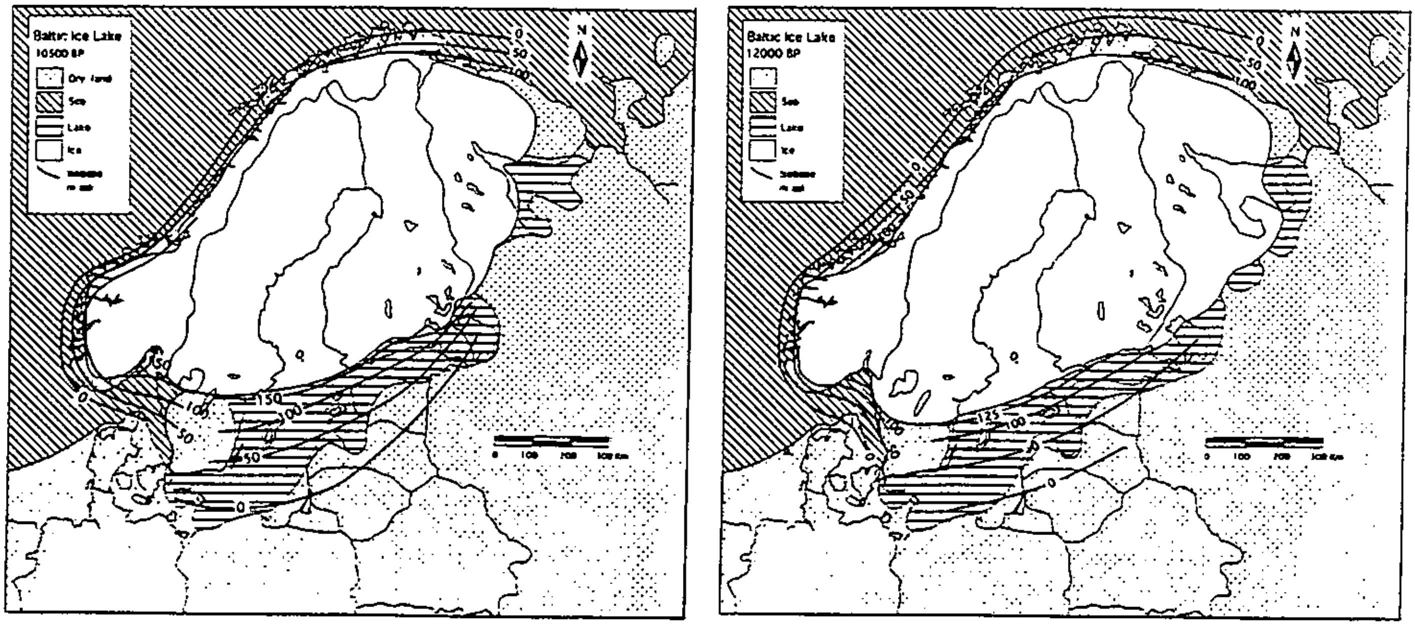
Geographic reconstruction and uplift pattern of NW Europe at 7 KA

Geographic reconstruction and uplift pattern of NW Europe at 9 KA BP.



Geographic reconstruction and uplift pattern of NW Europe at 9.5 KA BP.

Geographic reconstruction and uplift pattern of NW Europe at 10 KA BP.



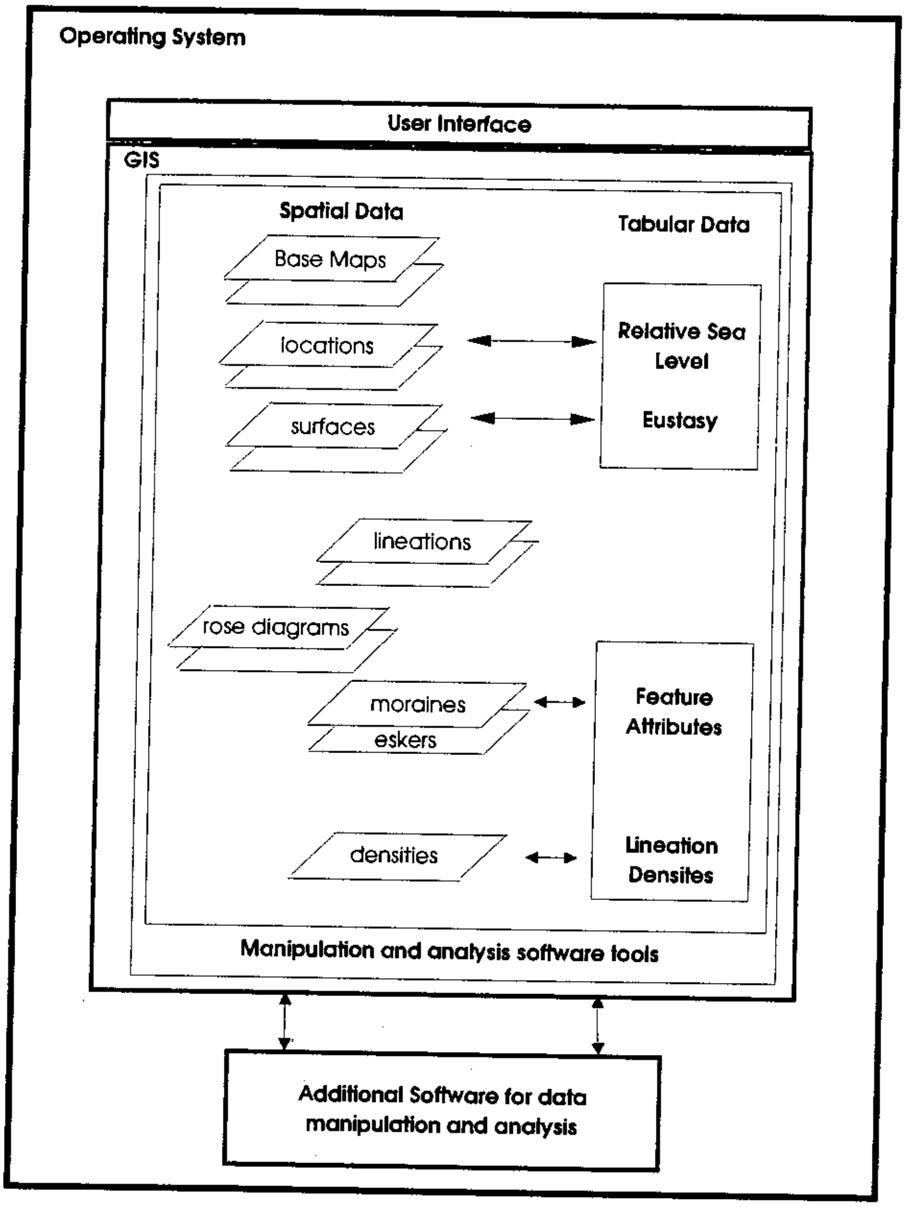
Isobase map of NW Europe at 10.500 yr BP

Isobase map of NW Europe at 12.000 yr BP source data, (since they essentially use the same data and follow the same procedures), the results could be very much improved in terms of accuracy by adding an extension to calculate and visualise error. At a basic level, the ability to use error bands on the curves to generate different surfaces for the same time slices would be an easy step, given the ease of surface generation using the system. Upper and lower error bounded surfaces, for example, could be developed using error bands. A further refinement would involve the perturbation of individual points with error bounds according to user-preferences or a weighting of points according to their proximity to measured index points from which parts of a curve have been drawn. These simple refinements would enable a more quantitative approach to error in sea level reconstructions. A measure of surface fit to the points would also be a useful addition. Unfortunately the routines used in this study did not provide a means of doing this and the error data was not available. However, the surfaces produced are created with reference to the Fennoscandian ice sheet retreat, and therefore cover the period from 9000 to 12000 years B.P. There is insufficient data coverage available for these time periods for the interpolation routine to generate relative sea level surfaces. Dongelmans' results (Figure 5.12) show uplift centred over the northwestern edge of the Baltic, and this is consistent with the computer-generated maps (Figures 5.9, 5.10 and 5.11). However, the interpolation routines struggle in areas where data is limited (for example, around the southern part of the Swedish/Norwegian border). The routine also struggles in areas where data gaps are adjacent to the edge of the data coverage area (for example the offshore area south of Tromso where an anomalous local high occurs). Compared with Dongelmans' results, it can be seen that the essential structure of the surface is very similar. Other researchers have also tried computer analysis in the past using purpose-built software. Krumbein and Greybill (1965), for example, used trend surface analysis using derived F values for evaluating the goodness of fit contributed by each surface component to produce isobase maps.

5.3.6 Further Work

The system (Figure 5.13) could be extended in several ways. Given the index point information and appropriate meta-data, the system could be further developed by populating the extended data model and incorporating error measures. These could be used to generate further palaeo-sea level surface scenarios. Further refinements in the current method could be achieved with the addition of different measures of "eustatic" sea level used to generate the isostatic surfaces from the relative sea level surfaces, thereby giving further interpretations and possible reconstructions. Using different contouring routines would also produce different surfaces, and particularly

Figure 5.13 System Summary



employing a contour routine which could utilise weighted points and would give some measure as to the accuracy of fit of the surface to the points would also be beneficial and add rigour to the method. Options to provide the on-screen display of user-selected curves together with surfaces, and the ability to generate surface cross-sections automatically (another function which, although possible, would require significant additional work to implement automatically through a user-interface), would greatly enhance the communication of the problem domain for system users.

Further developments in the system could be made to reconstruct palaeocoastlines, and to calculate volumes between surfaces. Volume estimates between isostatic surfaces would provide a rough measure of mantle volumes displaced from beneath the Scandinavian area due to ice sheet loading. These calculations could be made given an appropriate resolution of hypsometric data together with the relative sea level and isostatic surfaces. Whilst the functionality to achieve this was not available within the GIS when this work was being undertaken, the latest version of the software does now provide facilities with which this could be achieved. These calculations are extremely laborious to undertake using manual methods, but would be relatively straightforward, much faster and much more accurate if done using a GIS.

5.4 Discussion

5.4.1 GIS Benefits

The GIS benefits realised in this case study are generally the same as those encountered in the glacial geomorphology case study. The system afforded increases in speed, accuracy and rigour of data manipulation, facilitated flexible integration and data visualisation and incorporated functionality which permitted the development of a user interface, allowing the user freedom to concentrate on the data unencumbered by the details of the system. The time required to read each sea level curve and estimate the corresponding heights for particular time slices is substantial. Given that most curves are photocopied from published papers, the accuracy with which this can be achieved by hand tends to be variable. The computer routine developed can perform this operation in a few seconds with consistent accuracy. Using conventional methods of data collection and interpretation from the literature the sea level curves were photocopied from published papers and heights read off by eye for the desired time slices, copied by hand to a map and then interpolated by eye. Whilst this method is not a bad one, and can incorporate the researcher's judgement as to approximation and error, there is no quantitative measure of error in an individual's assessment of the height value for a given time and no rigour in the interpolation methods which can be provided for the edification of other researchers. Using a properly planned information system and computing methods, however, this becomes possible. Unfortunately, due to the unavailability of original data, conventional techniques of photocopying sea level curves from the literature were used at the data assembly stage. The number of possibilities which can be explored in a few hours, is far in excess of anything which could be achieved in the same time using manual methods. All the interpolations are exactly reproducible even if weightings were added as a functionality extension. With manual methods it is not clear where, or why, a researcher has assigned more or less credence to particular values, and these weightings are not explicit. Furthermore, the availability of the surface visualisation function enhances the users ability to explore and communicate results and data, and to integrate it with other information, such as rivers, coastlines and contours.

5.4.2 Data Issues

The limited success of the interpolation routine was imposed by constraints on data accuracy and availability. The sea level diagrams which were digitised were fairly crude and there was no possibility to perform weighted interpolations since appropriate information to allow data weighting was not available. One of the major problems with sea level data is that the techniques used to derive these measurements are diverse, as are the nationalities, circumstances, and aims of the investigators. It has been shown (Tooley & Shennan, 1987) that standardisation of methodologies of data collection, techniques and data presentation can ensure the comparability of results at any scale. IGCP (International Geological Correlation Programme) Projects 61 and 200 have attempted to standardise the methodology of sea level investigations (Tooley & Shennan, 1987), although it is acknowledged that methodologies and techniques which are too rigid are neither practical nor desirable. However, it is suggested that researchers should be aware of the suite of methods and techniques employed in the study of sea level in order to enable useful comparison. However, this is not possible if sufficient data are not available. Shennan (1989) noted that the disadvantage of using sea level curves is related to incompatibilities in the methods used to derive them. There are currently limited incentives for field researchers to make this data available. As a result the quality of Level 1 information is, on the whole, low, and it is impossible to determine the compatibility of different information. Furthermore, if the sea level curve data were to be supplemented with individual sea level points, there would be a risk of duplication. It is often difficult, when using multi-source data from publications, to discern whether index points published for an area have also been used in the derivation of sea level curves, and therefore whether one is duplicating data in the analysis.

5.4.3 System Issues

Many of the system issues were the same as those encountered in the glacial geomorphology case study. Again, the lead-in time for system establishment was considerable. In the case of sea level, the time required to digitise and georeference the data was significantly less than that for glacial geomorphology. However, because the system development began with a much older version of ARC/INFO, the lack of functionality meant that considerably more time was spent on the initial system development, and subsequently, on system maintenance (discussed later in this section). Lack of functionality is a persistent problem in commercial GIS packages which are developed mainly for business purposes. Scientific research projects, with their small budgets and complex requirements are the least attractive market for GIS vendors. In the case of sea level data, this lack of GIS functionality in the earlier version, was supplemented by functionality from other packages, and therefore involved linking, in this case, UNIRAS with ARC/INFO via FORTRAN programmes. The macro language was, again, unsuitable for such scientific applications development. Furthermore, it would have been desirable to have functions which permitted interpolation of sea level points on a geoidal surface. Using different projection algorithms changes the relative spacing of sea level points, which is likely to affect the interpolation results. It was also difficult to control the handling of edge effects in the interpolation, and to display curves and peruse the database. The time and effort required to develop a robust user interface was substantial and is therefore a consideration when estimating the cost and time required for system development. Again, lineage tracking, and metadata facilities were not available. This caused problems because it is important to know which interpolation results were generated using which sets of parameters.

The complexity of the sea level data model poses a particular issue if one considers that if different institutes were to develop sea level databases, they are unlikely to use exactly the same data model and codes. Integration of data across institutes then, would be a major problem, and would have implications for the increased complexity of lineage and metadata maintenance across systems.

The most significant issue, was the rate of change of software and hardware upgrades in relation to the time required to develop a system and maintain the system in the face of these changes. Maintaining the customised software through GIS upgrades was compounded by changes in the other software packages and compilers which were employed to extend the functionality of the system. The system underwent two GIS version changes, three interpolation package upgrades, two FORTRAN upgrades and a change in operating systems (VMS to UNIX). This reflects the rapidity of change that a typical system may encounter in two or three years. Even operating systems become more popular and others become obsolete. This problem has been experienced by others, for example during the development of a GIS for the FAO to support desert locust forecasting and monitoring (R.Healey pers. comm., 1995)

Re-mapping the old implementation onto the new system involved the re-writing of many of the original programs. It highlights the advantages for keeping as much of the design as possible within a single Geographical Information System Package thereby limiting the frequency of changes for which many problems can be referred to the software company. It should be noted that the database, so carefully planned for at the outset, was foregone in the final system and the curve data used by the resulting system is stored merely as flat operating system files. This was due to the operating system move, since the new platform had different database software loaded and operating and storing the data as files was much easier to re-implement. These issues have implications for the long-term planning of system development to secure adequate resources.

5.5 Conclusions

In summary, the study exemplifies the advantages of employing a GIS to facilitate palaeoenvironmental reconstruction in terms of managing the information, handling and visualising the complexities of time and space, and freeing the users from laborious, time-consuming data manipulation which are the requirements of manual methods, so that they can concentrate on experimenting with the data by exploiting the fast and accurate analysis provided by the system. However, several substantial issues have emerged from this study which, whilst they are manifested in issues associated with the quality of the data and the capabilities of the system, have implications for the approaches to scientific study and the international organisation of research.

In summary, this case study resulted in the following demonstrable GIS benefits and issues:

Demonstrable benefits:

- spatial framework for sea level and related datasets
- compact storage of detailed information
- increased processing speed and accuracy
- rigorous and quantitative analysis
- speed and flexibility of experimentation
- the possibility to design a user interface and allow freedom to concentrate on data analysis and theory exploration

Palaeoenvironmental issues:

- poor level one data
- limited methodological standardisation
- incompatibility of sea level curves
- problems of data integrity

GIS Issues:

- time for system establishment
- limited functionality
- lack of metadata, error and lineage tracking facilities
- rate of upgrades and related maintenance overheads
- slow and cumbersome macro language manipulation

In general terms both case studies reveal the following issues:

1. The lack of long-term, international planning by the scientific community in terms of data resources. For example it is no accident that the HEFC (Higher Education Funding Council) now requires HE establishments to have an information strategy. This indicates the importance now attached to information resource management.

2. The restrictions imposed by using proprietary systems which were developed mainly for business and data display and retrieval purposes, rather than analysis, and which impose a structure on applications which makes systems difficult to use and adapt and develop in a way and at a speed which is appropriate for scientific researchers.

3. The failure of the scientific community to adapt the research paradigm to the changing demands on environmental research (local to global) which fully exploit the data available and address the scientific issues that such global scale research requires.

4. The failure of the scientific community to adapt computing tools and develop new methods for research which view systems as a long-term investment incorporated as part of the research development rather than used like a component tool in part of a larger process.

Chapter 6 A New Conceptual Framework

6.1 Introduction

The previous chapters demonstrate that current GIS do not fully support the study, management and analysis of complex palaeoenvironmental data. A PalaeoEnvironmental Research Information System (PERIS) model is proposed in this chapter, that provides a new approach for palaeoenvironmental reconstruction and research, designed to overcome many of the current limitations. The model is based on object oriented concepts, and provides an innovative approach leading to a range of new methods for palaeoenvironmental reconstruction, and a novel framework for data sharing and management. This is a suggested framework in which palaeoenvironmental reconstruction could take place, but no formal evaluation has yet been undertaken.

The palaeoenvironmental and GIS issues identified in the previous chapters are briefly reviewed to reveal the need for a change in the current research paradigm which GIS engenders (Section 6.2). The advantages of object oriented approaches are then discussed (Section 6.4) and palaeoenvironmental reconstruction methodology is redefined in terms of an object oriented approach (Section 6.4). The new object oriented conceptual framework (PERIS), introduced in Section 6.5, is at a high level of abstraction. The formalisation of reconstruction methodology provides a basis for an innovative approach to palaeoenvironmental reconstruction which addresses the pressing issues encountered in the current research paradigm. The model assumes an environment of global information sharing and exchange (Section 6.7). Similar developments in the current international information infrastructure are considered (Section 6.8). Extending the model philosophy into the scientific infrastructure provides a framework for improvements in data management and communication (Section 6.9).

6.2 Changing Paradigms

Increasing pressures on the palaeoenvironmental research community to help answer questions about the global environment have led to a change in emphasis from local field studies, towards spatial integration of palaeoenvironmental evidence over very large areas. Sources of new and higher resolution information have increased the potential of palaeoenvironmental data to reveal much more about the nature and form of palaeoenvironments through time. However, the information is not being exploited to the full because several factors are currently hampering the progress of palaeoenvironmental reconstruction in important ways. These factors have been identified in a general sense in Chapter 2, and explored in more detail for two palaeoenvironmental data sets in Chapters 4 and 5. Briefly summarised, they are:

Palaeoenvironmental methods and data management issues

- Poor data documentation and archiving (particularly of Level 1 data)
- Little methodological standardisation
- Problems with data integrity (for example data duplication)
- Lack of methods for analysis on a spheroidal earth
- Limited spatial analysis methods
- Few rigorous, quantitative methods

The case studies have clearly shown that GIS (Science and Systems) offers powerful techniques which address many of these palaeoenvironmental issues. However there have also been shortfalls in system capabilities, and in the ability of both systems and science to offer solutions for palaeoenvironmental reconstruction. These shortfalls in GIS emerge from the case studies (Chapters 4 and 5) and are summarised below:

GIS technology issues

- Time required to gain system expertise (poor user interfaces)
- Time required for system establishment
- Limited scientific functionality in commercial systems
- Lack of metadata storage and tracking facilities
- Rate of upgrades of commercial systems and system maintenance
- Slow and cumbersome macro language facilities
- "Black box" functionality (lack of algorithm documentation)

The significant difficulties in palaeoenvironmental reconstruction indicate the need for a paradigm change. The issues associated with current Geographical Information *Systems* in the context of palaeoenvironmental research can be addressed by developments in Geographical Information *Science.* Having considered both palaeoenvironmental and GIS issues, a position has now been reached from which to modify the current research paradigm to improve palaeoenvironmental research. The case studies pursued reconstruction using the traditional palaeoenvironmental paradigm, and GIS improved the manipulation of data and facilitated quantitative and rigorous spatial analysis and visualisation over large areas. However, the cartographic construct prevailed. The data is thematically partitioned, and thus can only be used to reconstruct separate aspects of, what is in fact, a complete environmental system, where different features are juxtaposed, interact and evolve through time. GISs offer the powerful combination of complex data management and visualisation capabilities, and the possibility of manipulating data in three- (or even four-) dimensional space. However the philosophy behind their design, like the palaeoenvironmental methodology, remains based on mapping concepts. New possibilities are available which could be used to overhaul the traditional paradigm (Figure 6.1), and move from static maps to dynamic reconstruction.

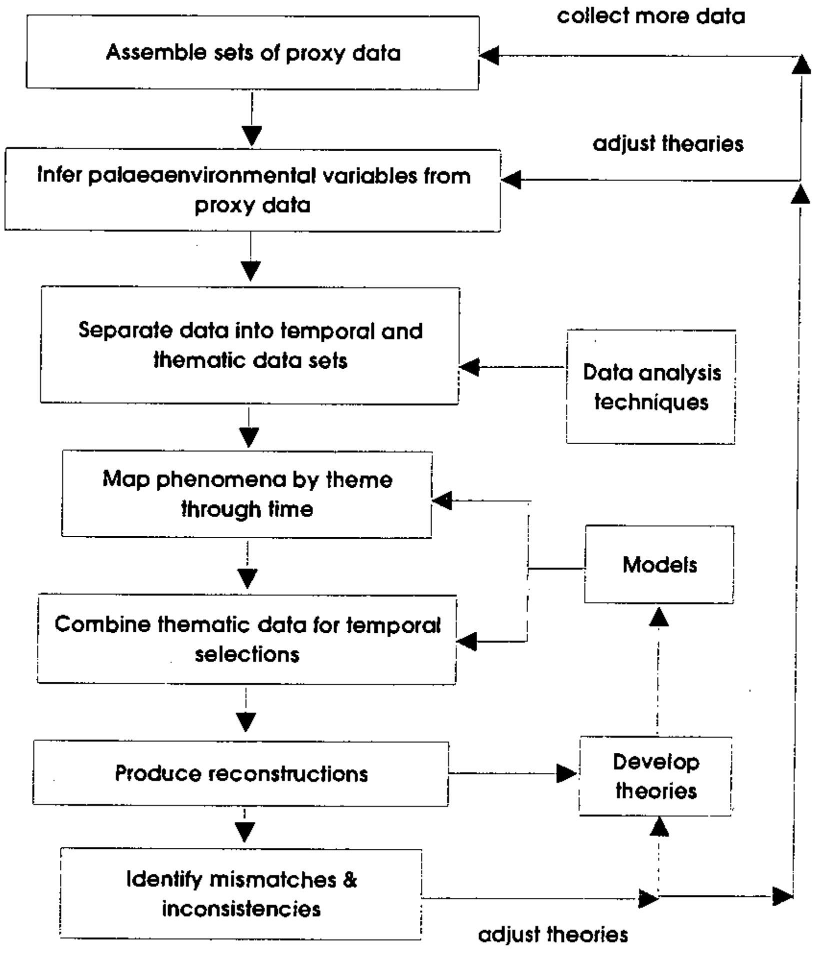
6.3 Object Oriented Concepts

Many of the shortcomings of current GIS summarised above, have emerged in other areas of environmental research. Difficulties centre round the formulation and representation of environmental models in GIS. The structure of the GIS has determined the framework within which the environmental application must exist, which therefore imposes stringent constraints on the treatment and handling of data models. Current GIS methods operate, for the most part, on thematically layered, two-dimensional data. This structure requires geometrically indexed methods of data representation (Raper & Livingstone, 1995) and does not permit the handling of discrete three-dimensional entities, overlapping features (Goodchild, 1992) or temporally changing phenomena (Langran, 1991). These GIS features reflect the map-based paradigm for data representation which preceded environmental modelling approaches, and causes users to be distracted from scientific tasks by data management and system tasks. The underlying data structures do not appropriately reflect the user's ideas. Therefore using these structures for purposes for which they are unsuited has a negative impact on system performance (Gunther & Lambert, 1994).

Recently there has been a trend to challenge this segmentation of entities into separate layers, and, rather than map the application onto the system, to determine alternative approaches to spatial representation for environmental models (Livingstone & Raper, 1994). Object-oriented analysis and design approaches (Booch, 1991) have been explored and this has led to progress in other areas (for example Raper & Livingstone, 1995; Freska & Barkowsky, 1996; Gunther & Lamberts, 1994).

Object orientation is an approach for modelling the world in terms of interacting objects in relation to a particular problem domain (in this case palaeoenvironmental reconstruction). At the core of object oriented philosophy is the belief that humans

Figure 6.1 The current reconstruction process



think naturally in terms of objects, and therefore by modelling systems using key abstractions (objects), problem solving is made much easier. Using the object oriented approach, all actions are carried out via objects. Objects have behaviour, can interact with (be changed by, and change) other objects, and can also be aggregates (an object can be made up of component parts).

This approach was developed because objects encapsulate much of the complexity of the real world in terms of single data abstractions which are modular (self-contained). Previously, system designers and software programmers were having difficulties modelling the complexity of the real world. The key idea of data abstraction is that definition in terms of objects which are independent entities, develops into a system which is much easier to maintain.

Object orientation was thought to be a suitable approach for considering palaeoenvironmental reconstruction because of the complexity of the problem, caused by the multiple, interdependent relationships of data, methods and reconstruction features. Some means of abstracting the key elements of reconstruction is required in order to analyse and improve the methodology. An object oriented philosophy seems an appropriate option.

For the purposes of computer system analysis and design, objects are tightly defined using terminology associated with their behaviour and structure. However, use of such terminology at the level of abstraction adopted here is inappropriate, and would be more confusing than helpful. Object oriented concepts are being used here in a problem analysis, rather than a system design context, and therefore such terminology is not relevant. One of the advantages of the object oriented approach is that only one model of the system exists. The development of the system involves progressively adding more detail until the model can be executed on a computer. This level of detail will not be reached in this discussion, but the model developed here would represent the most general level of abstraction which could be developed further to an implementable system design.

6.4 Object Oriented Reconstruction

Using the object oriented approach for palaeoenvironmental reconstruction requires the re-definition of palaeoenvironmental data and models in terms of objects. Identification of palaeoenvironmental entities is fundamental to palaeoenvironmental research itself. The abstraction of entities for constructing scientific theory is a point of philosophical debate, and the position accepted for the purpose of this discussion is that entities are defined according to a theory (Haines-Young & Petch, 1986). In this case there are likely to be different abstractions for the same "real world" and thus different "world views" will depend on the theoretical basis being used and the task to be undertaken. To identify appropriate constructs for palaeoenvironmental science, a consideration of the theories and views is required.

Palaeoenvironmental research comprises many facets, but generally reconstruction is achieved by assembling fragments of evidence for multiple environmental features simultaneously, in space and time, to obtain a series of "snapshots" of the palaeoenvironment through time. The fragments of evidence are identified according to the paleoenvironmental feature or parameter to which they are thought to relate. Therefore this feature or parameter (which may be contained within, or influence, features) could be selected as the basic construct in palaeoenvironmental research. For example, particular sites contain landforms or materials thought to relate to parts of past glacier or shoreline features. These features then, rather than a space-time framework, provide the integrating medium for the fragments of palaeoenvironmental data. The reconstructed features also provide the means of analysing palaeoenvironmental behaviour which is expressed by their evolution and interaction.

Palaeoenvironmental reconstruction is achieved via two strategies. The first involves assembling field and measurable information to infer the boundaries and characteristics of palaeoenvironmental features (empirical and qualititative interpretational models of the data). Inferences used to derive these models are based on knowledge of present day processes. The second involves developing numerical models which describe the processes that act to change these features, using information based on physical principles observed in present day environments.

One of the reasons why palaeoenvironmental reconstruction is difficult is the complexity of putting this information together because it is uncertain in time, and sometimes also in space. Even the feature inferences themselves may be in doubt. Data is sparse and evidence may often conflict (for example where two data points appear to occupy the same spatiotemporal position but indicate different environments). Where incompatibilities occur the impact of conflicting evidence must be reassessed and the data model, or the data, adjusted to reconcile the conflicts. There are three main factors which currently hamper solutions to these problems:

1. Data is divided into layers, partitioned into themes, and each layer contains information relevant to several features. This makes it difficult to integrate all the information from the different layers for one feature.

2. Thematic separation causes further complications to arise because data interpretations (linked by site and theory) in different layers are interdependent. Reconciling data conflicts by changing an interpretation for one point may have a knock-on effect for data in other layers. Managing these interrelationships can be problematic.

3. Reconstruction features exist as mental concepts within the mind of the scientist and their expression is achieved via the unsatisfactory medium of schematic diagrams on two-dimensional paper. Therefore there is no quantitative or rigorous approach to feature reconstruction.

Process models have improved the situation by allowing some features, or parts of features to be expressed as mathematically derived bodies which have definite surfaces or boundaries and can therefore be viewed more easily and described using empirical measures. They can be used to help visualise features. However they differ markedly from data models. Data constructed model features, are characterised by fuzzy and incomplete boundaries. In many cases parts of features are completely unknown in nature and extent.

Therefore there are essentially two different sorts of palaeoenvironmental feature reconstruction, which can be considered "object types" in an object oriented approach:

1. **Data Constructed Model** (which represents the structure of real world domains constructed using palaeoenvironmental data)
2. **Process Model** (which represents theories such as exchange of mass or energy within a system, based on mathematical principles and present day observations)

The Data Constructed Model comprises quantitative and qualitative information which helps to define the boundaries and nature of a feature. Data may be assigned to different space-time manifestations of a feature with the assignation being determined by other models (for example a core sequence correlated with calculated Milankovitch cycles, Imbrie *et al.*, 1984). In some cases Process Models can be used to assign interpretations and temporal positions to palaeoenvironmental data where very little information is available. However, process models are often very crude and do not adequately express more than the general form and evolution of the feature. They are therefore used to help identify candidate parameters which may control, or be influenced by, climate change, rather than to simulate a feature in detail. The success with which they do this is tested by comparison with palaeoenvironmental data and Data Constructed Models.

6.5 The PERIS Model

An object oriented model for a PalaeoEnvironmental Reconstruction and Information System (PERIS) is proposed, which has the Data Constructed and Process Model object types, identified above, as central to the system. This approach has many features in common with an approach suggested by Raper and Livingstone (1996) for testing present day coastal geomorphological theories. The Data Constructed Model and Process Model object types are comparable with their geomorph_info and geomorph_system object classes although the definitions of the objects and their behaviour differ. It is proposed that reconstruction take place within the object oriented system, through the Data Constructed and Process Model Object types. Essentially the process will involve construction and incremental improvements in definition of the object through addition of data elements and the definition of object behaviour (Figure 6.7). This can be done simultaneously for more than one object, with object interactions controlling the validity of a particular reconstructed scenario. To clarify this procedure, the object types will be defined from Data, Functional and Behavioural perspectives. These definitions will then be elucidated in terms of reconstructing a glacial Data Constructed Model object using the system.

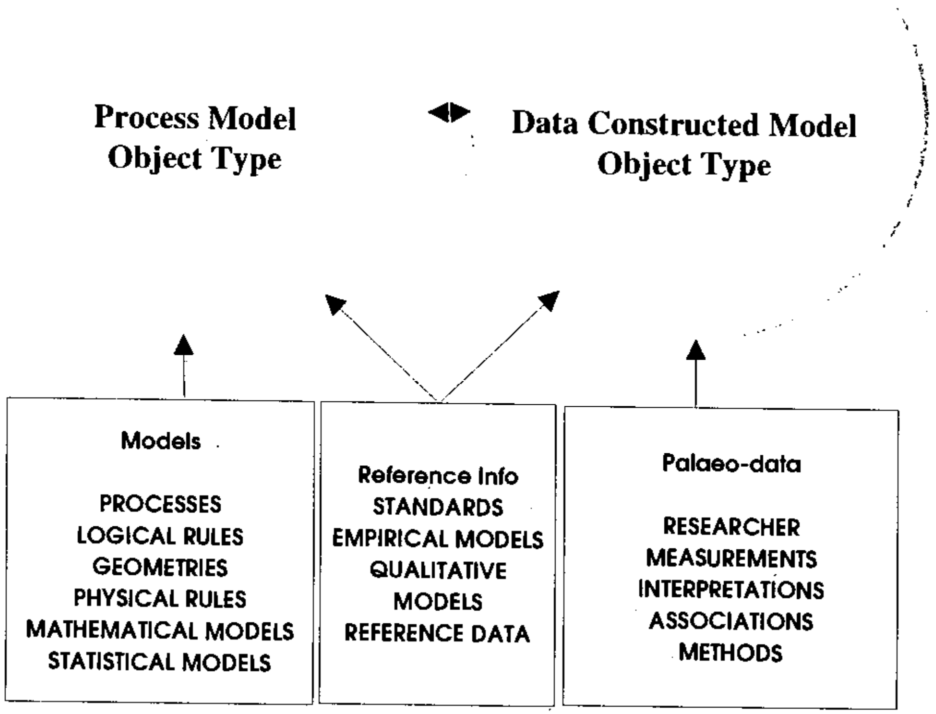
1. Data Perspective

The data perspective defines the major data elements of which the object type is composed. For each of the object types, these are:

Data Constructed Model

- Known, inferred and unknown feature structures and boundaries
- May be an aggregate encapsulating component parts
- Boundaries and parts defined by palaeo-data elements, possibly using present day data elements for reference
- Sets of rules defining behaviour, constraints and thresholds between different object states, and object interactions

Figure 6.2 Simplified, schematic view of Palaeoenvironmental Information System



Process Model

- Model code describing relationships and interactions
- Rules defining behaviour, constraints and thresholds between different object states and the use of different sets of code
- May be an aggregate encapsulating component parts
- Initial conditions
- Input data
- Output data

2. Functional Perspective

A functional perspective views the responsibilities of each object type and the operations it must perform:

Data Constructed Model

- controls behaviour of, and interaction between, any component parts
- requests data from the database, selected according to criteria such as feature type, geographical area under consideration, methodological sympathies of scientists and data quality.
- controls the allocation of data to different parts of the object structure and different states, including allocating data weightings for more reliable data.
- carries out analysis of data (e.g. interpolations, extrapolations, interpretations)
- checks and controls internal logic:

Data rules	- maintains and checks data links. For example if several data points came from the same correlated core and the correlation of one of the data points had to be adjusted, the object would use the links to flag other data which may be affected by this interpretational change.
Physical rules	- ensuring valid parameters and component part interactions (e.g. "rivers cannot flow uphill")
State rules	- controls the transition between states if certain thresholds are exceeded, which in turn controls the set of applicable physical rules and are linked to inter-object interactions.

- controls interaction with other objects such as mutual spatio-temporal occupancy and adjacency conditions (for example glaciers cannot exist within a certain distance of tropical vegetation, and terrestrial and deep water marine objects cannot occupy the same spatiotemporal position).
- tests for inconsistencies and flags data elements which don't "fit" current model

Process Model

- requests model code from the database, based on feature type and other conditions
- controls validity of model formulation and inter-linking of any component parts
- controls transition between states and selection of appropriate code and parameters for different states.
- requests input data and parameters
- carries out inter-object comparisons of output (with Data Constructed Model) and validity checks (with other Process Models)

3. Behavioural Perspective

External events that stimulate the object can be defined by taking a behavioural perspective:

Data Constructed Model

- requests from the user (e.g. to query an object and determine its attributes)
- instructions from the user (e.g. changes in logic, addition of data, weightings allocations for data, addition of new analysis methods)
- instructions from the user for comparisons with other Data and Process Models

Process Model

- requests from the user (e.g. to query an object and determine its attributes)
- instructions from the user (e.g. changes in logic, additions of code, changing input data, model parameters, and initial conditions)
- instructions from the user for comparison with other Process and Data Constructed Models

6.6 Reconstruction using PERIS

Considering the last glaciation in North West Europe, reconstruction focusing on a glacial Data Constructed Model object is considered to demonstrate the use of the proposed PERIS system model and the meaning of the criteria above. There are three broad stages involved. The first two are concerned with object formulation and reconstruction. The third step is a hybrid of the first two steps which is repeated iteratively until the user is satisfied. Further stages involve comparison between Data Objects and Model Objects, and may be followed by repetitions of the first two stages to further develop and refine the reconstruction and associated theories. Interaction between the user and objects would take place through a user interface which would control the underlying processes and liberate the user from such concerns.

Reconstruction through a Glacial "Data Constructed Model" Object

STAGE 1 Object and Rule formulation

The user will define the nature of the object, in this case "ice sheet", and the region of interest, here, "NW Europe". It may also be desirable to retrieve information about the behaviour of large ice sheets (past and present) and any previous reconstructions that have been made for the area. The user will then proceed through a number of steps to define:

- Any component parts of the object - for example ice streams associated with the deglacial phase might be considered for one object state
- The palaeo-data selection criteria - This might initially comprise macroscale glacial geomorphological features, measured by a particular research group during a recent project.
- The rules defining the behaviour of objects in particular states, and which govern the change between states. For example, if it was thought that when the glacier reached a certain size at a particular temperature regime, ice streams would develop, or when it met the sea, ice calving would commence and change the flow type. These rules might be "borrowed" from present day glacial research.

STAGE 2 Reconstruction using data and rules

The data which has been retrieved from the database according to the selection criteria will be Level 1, 2 and 3 data. The user may wish to begin with Level 3 data to define the more certain aspects of the ice sheet. In some of the southern areas for example, deglacial retreat patterns may be clear and well-dated, and these could provide the initial boundaries for the model in the south. There may not be much information in the northern area and therefore this boundary might be an inferred line or might be classed as unknown. However, there may be evidence (theoretical or data-supported) to suggest that the ice sheet did not extend further north than the edge of the continental shelf, but that it was further north than a range of high mountains. Therefore a zone between the northern mountains and the edge of the continental shelf could be declared as the zone within which the edge of the ice sheet existed.

The user may then wish to apply the rose diagram analysis to the Level 2 macroscale lineations data set to define the location of ice streams and use this information together with the retreat patterns to define the evolution and temporal existence of the ice streams. As ice streams are identified the lineations can be assigned to the appropriate ice stream and temporal position (which may be defined as a temporal zone of maximum and minimum duration, rather than a definite point in time). Thus the lineations can be displayed together (but possibly using colours to indicate those assigned to the same time zone), or separately. A degree of experimentation may be necessary, in trying out different sets of lineations in different time zones, to find the most satisfactory combinations. Ice streams do not necessarily have clear boundaries, and their location could be described by some probabilistic surface which describes the likelihood of a feature in a particular area being part of the ice stream.

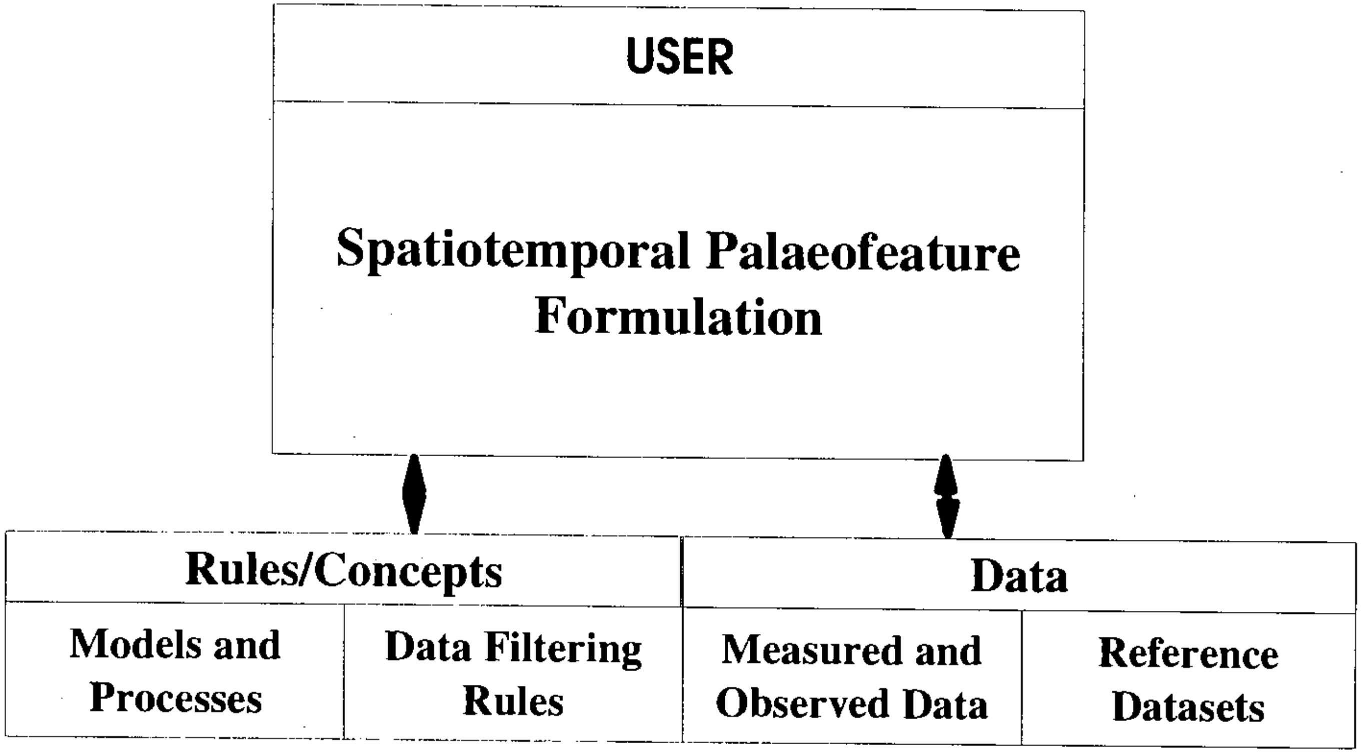
Present day topography may be requested to define the glacier sole for the late glacial phase, and also to establish the position of the continental shelf mentioned earlier.

STAGE 3 Reconstruction refinement

Reconstruction refinement (summarised in Figure 6.3) could involve several things.

1. Changing or adding data selection criteria and rule logic (STAGE 1)
   Requesting Level 2 field information would help to further constrain the nature and locations of the glacier frontal positions, and the timing of particular ice streams. This field data might be linked to the macroscale information, or the user may wish to make links which might exist. The strength of these links could be variable (strong if the link had been made by the field scientist, weaker if the link had been made by the user who knows the data less intimately).
2. Re-analysing data, or analysing new data using new functions (STAGE 2)
   The field data would then be fitted to the structure of the object, and information which did not "fit" could be more deeply queried, so that the user could consider alternative interpretations, or adjust the model. If model adjustment occurred, the object would automatically check the previously fitted information to ensure that it complied with the new model. If data required new analysis, functions could be requested from the database, or developed within the system by the user (possibly using visual programming CASE (computer aided software engineering) tools).
3. Defining inter-object interactions and comparing the glacial Data Constructed Model Object with a sea level Model Object, or a glacial Process Model Object. Interobject interactions might specify that a sea level object cannot overlap a glacial object, but that a glacial object can overlap a sea level object within certain distance and depth restrictions. Significant discrepancies between the results from a Process Model glacial object and the Data Constructed Model

Figure 6.3 Tailoring the data view to individual theories and methodological preferences via manipulable objects



Object for the same area and time range might result in adjustments to the Data Constructed Model or Process Model objects (or both).

The Process Model object type may be constructed by "plugging together" sets of component models, with the model construction and running being performed by a piece of software called a "Model Manager" such as that suggested by Bennett *et al.* (1993). The Model Manager would also control the transition between model states and the exchange of new code in moving from one state to another.

Design features

The system offers several substantial advantages over current reconstruction methods. From a practical point of view, the system is responsible for validity and consistency checking, and for data retrieval. Artificial Intelligence methods could be used to manage the implementation of these rules. Circular hypotheses could be flagged, such as the fact that calculated Milankovitch cycles had been used to correlate the deglacial positions of the Data Constructed Model Object, *and* to drive the Process Model Object with which it was being compared. Furthermore tests could be made to find the effective sampling resolution for features. Tobler (1988), for example, recommends that a sampling interval which is one fifth the size of the feature is required to resolve that feature. This would add weight to the validity of particular reconstructions. Chapters 4 and 5 have shown how accurately georeferenced digital datasets can be manipulated, viewed and overlaid with other data very easily. These functions allow the scientist to concentrate on formulating the reconstruction undistracted by the burdens of manual data manipulation. In addition, the system provides much more scientific flexibility, with the user able to define objects in any way desired, and have control over the quality, and, to a large degree, the interpretation, of the data. Furthermore, the system could be developed directly into a system implementation because it is conceived in object terms, and can therefore be further developed into a detailed system design. The object oriented approach has further advantages because it expresses palaeoenvironmental reconstruction in terms which it is possible for both the palaeoenvironmental scientist and the software engineers and system designers to understand.

However, the system must be supported by a suitably structured database, or system of databases. Given the issues discussed in Chapter 3 concerning the difficulty of integrating heterogeneous databases because of different data standards, data classification systems and incompatible data structures, it is clear that an international infrastructure is required to support such a system.

6.7 PERIS Infrastructure

The diversity of scientists which could use PERIS means that it must be supported by an international infrastructure which can provide the database PERIS needs. Clearly it is necessary to identify what is required of a database to support PERIS and then to consider what infrastructure must be put in place to support the database.

PERIS requires access to five distinctive datasets:

1. Palaeoenvironmental data (Levels 1, 2 and 3) and metadata, including core/site origins and associated with particular methods, researchers, data themes, uncertainty information, dates etc.
2. Model code and state transition parameters
3. Reference information about techniques, methods and standards
4. Present day studies, observations and theories
5. Basic reference information
6. Results of other reconstructions

These requirements are essentially the same as those identified in Chapter 2. However, PERIS requires a structure through which users can find particular data for a specific study. The structure must allow them to "filter" the information according to some selection system. This will mean providing a set of search keys for database query. Selection on the following criteria would constitute a minimum requirement:

- Location
- Reconstruction feature type
- Site type
- Dating quality
- Method, Technique, Sampling strategy
- Research scientist or research group

In order for the system to create the logical links between data elements, links between Levels 1, 2 and 3 data and their metainformation (such as methods and standards used) must exist in the database. This is particularly crucial where suites of data are correlated, because some change in interpretation, either of the standard, or of a particular sample, may affect the correlated values of the other data. Given the importance of the metainformation, the site search key could be considered the primary identifier. Being able to associate a set of measurements, which are linked because they were measured at the same site, by the same researchers, using the same methods, and interpreted in relation to one another, is of prime importance.

A distributed database systems approach allows databases in different geographic locations to be accessed remotely over a network, but to the computer user, the effect is as if they were accessing files in their local system (Stafford, 1994). Warner (1991) suggests that such decentralisation is the way forward. Centralised systems cannot compete with the demands of the information age in terms of efficiency and accessibility. PERIS could therefore exist in an environment where the underlying database is of a distributed nature, and data, methods and modelling tools would be provided by sites throughout the world. Thus the burden of data capture and system maintenance could be spread across different sites. PERIS would be available at each location from which the distributed database could be accessed.

However, given the issues associated with data integration, which include incompatibilities in data structures, classification systems, data models and data capture practices (Sections 3.3 to 3.6), the introduction of data standards and internationally agreed protocols is a prerequisite to the establishment of PERIS. Thus a PERIS database would require an international infrastructure which encompasses means of planning, implementing and running a distributed database system. This system would incorporate agreed search keys, data standards and compatible data structures and data models. The distributed system would thus operate on centralised concepts (Figure 6.4) and its development raises several substantial scientific and organisational issues.

Potentially the most important scientific questions concern the development of data standards and a classification system to provide search keys for the palaeoenvironmental data and to facilitate data integration. Such a system must incorporate the interests of all scientific needs both past and future, and therefore a balance must be struck between creating a system which is too complex to be usable, and one that is too restricted and unable to accommodate the flexibility required of scientific data to facilitate research innovation. In addition to this, substantial work will be required to develop techniques to describe, and handle, uncertainty in data and in the reconstructions, and to implement the logical rules associated with the data, object behaviour and inter-object interactions.

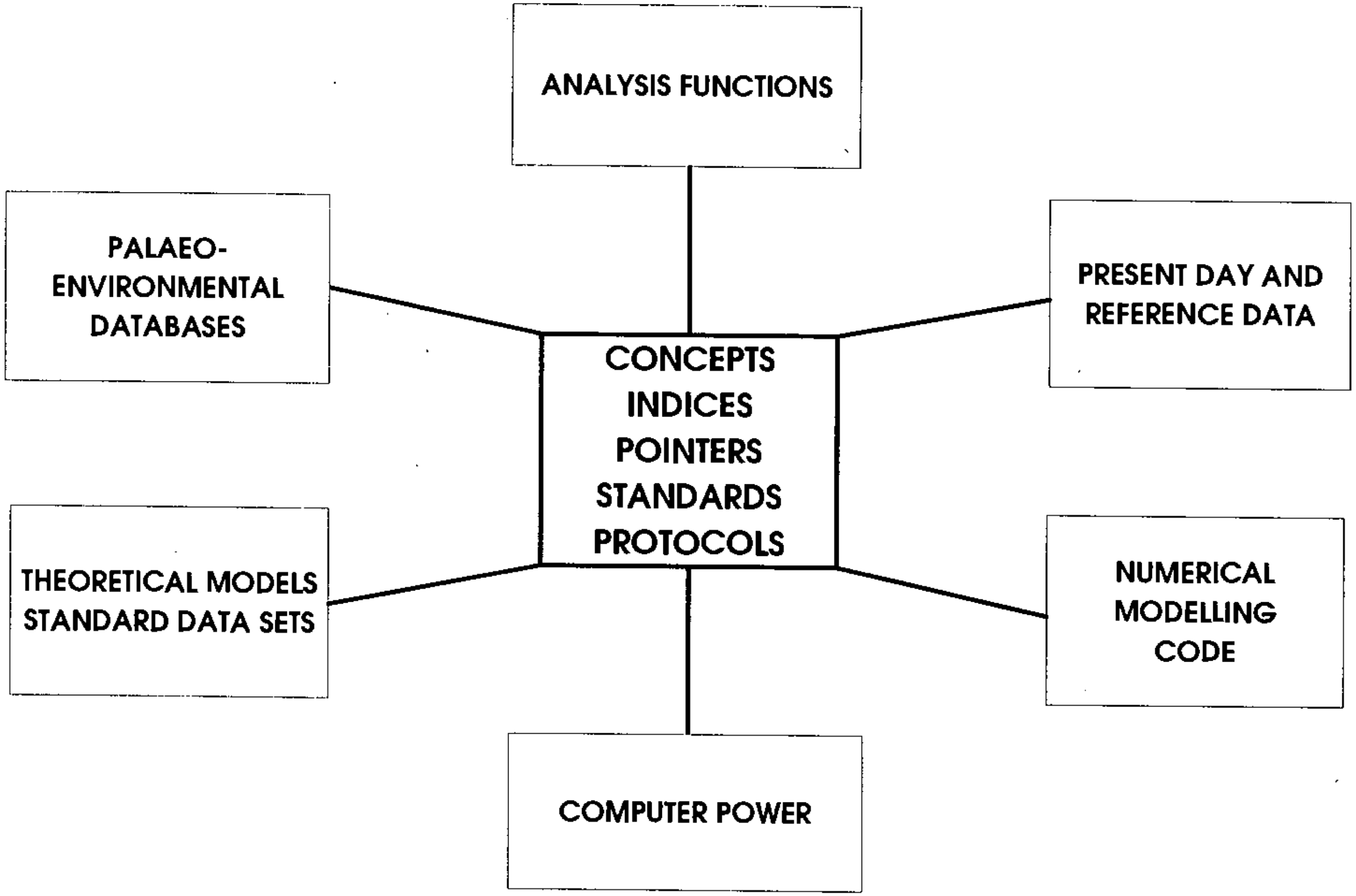


Figure 6.4 Centralisation of concepts for the distributed system

Developing a data model to handle the palaeoenvironmental data, and a metadata framework to enable the tracking of lineage information, will also be a challenge. Essentially no framework exists for version management, linking metadata to source data, model code, model results and model verification data. However, some research is beginning in this area (Jelinski *et al.*, 1994; Evans, 1994; Chrisman, 1994a; Strebel *et al.*, 1994) and could be adopted together with other efforts to develop a metadata framework for coverage and attribute data (Lanter, 1991, 1992). A further, related problem, concerns the volume of information associated with, and produced by, modelling. For simulation modelling, in particular, and experiments involving monte carlo methods, the quantity of data generated can be enormous. These alone will require special management. Further issues concern the development of the database to include new types of information resulting from new methods and sources, not incorporated in the original data model.

Practical issues centre around the modifications which will be required in organisational and scientific practices in order to accommodate PERIS, and the infrastructural changes associated with software maintenance, data capture and the implementation of data standards. Initially, canvassing the scientific community to resolve the scientific issues, will probably be the most significant barrier to progress. Evans and Ferreira (1993) cite the key research areas in spatial information sharing as lying in the interaction between predominantly organisational and predominantly technical issues. Another key issue concerns the availability of, and access to, data. Database management systems have the capability to permit access to parts of any database to certain individuals only, but the question arises of whether such security is desirable. Real integration of multidisciplinary palaeoenvironmental datasets cannot be achieved if those datasets are studied in isolation, and the true potential of the system will not be fulfilled unless multiple datasets are available for theory testing. The publication system, whereby individuals gain credit and status through literature publication of data, is one method by which data can become public property. However, this published data is often insufficiently detailed. There need to be changes to information management policies to increase rewards for data contributors (Porter & Callahan 1994). Funding Councils could require that projects contribute to the database as part of their contracts.

Other issues include the question of data integrity, data ownership, and database security which inevitably lead to the legal issues of copyright and multiple users of multiple data sources (Epstein, 1988). These issues are fraught with problems, many of which have not been resolved in the information technology field. Some means of implementing data standards will also be required. This could be facilitated by the use of Artificial Intelligence software to check for standards and make any necessary conversions, or warn where standardisation has not been used. As more data is input directly in digital form, data standards will become less of a problem to implement, because data capture software will be able to handle the coding and format of the data automatically. A more difficult issue will be preventing data duplication in different parts of the system, particularly where pre-existing analogue data is being digitised. Artificial intelligence methods may hold part of the solution to this problem, and could be used to check for similar information. Major developments will also be required in the area of user interfaces to make systems much easier to use. The amount of training required to use and develop a GIS for research purposes is currently substantial. Finally, an investigation is required into existing digital databases and their potential for incorporation within the PERIS structure.

It is clear that substantial long-term funding will be required to develop the methods and infrastructure required by PERIS and to undertake manual to digital conversion of data.

6.8 Current Information Infrastructure Development

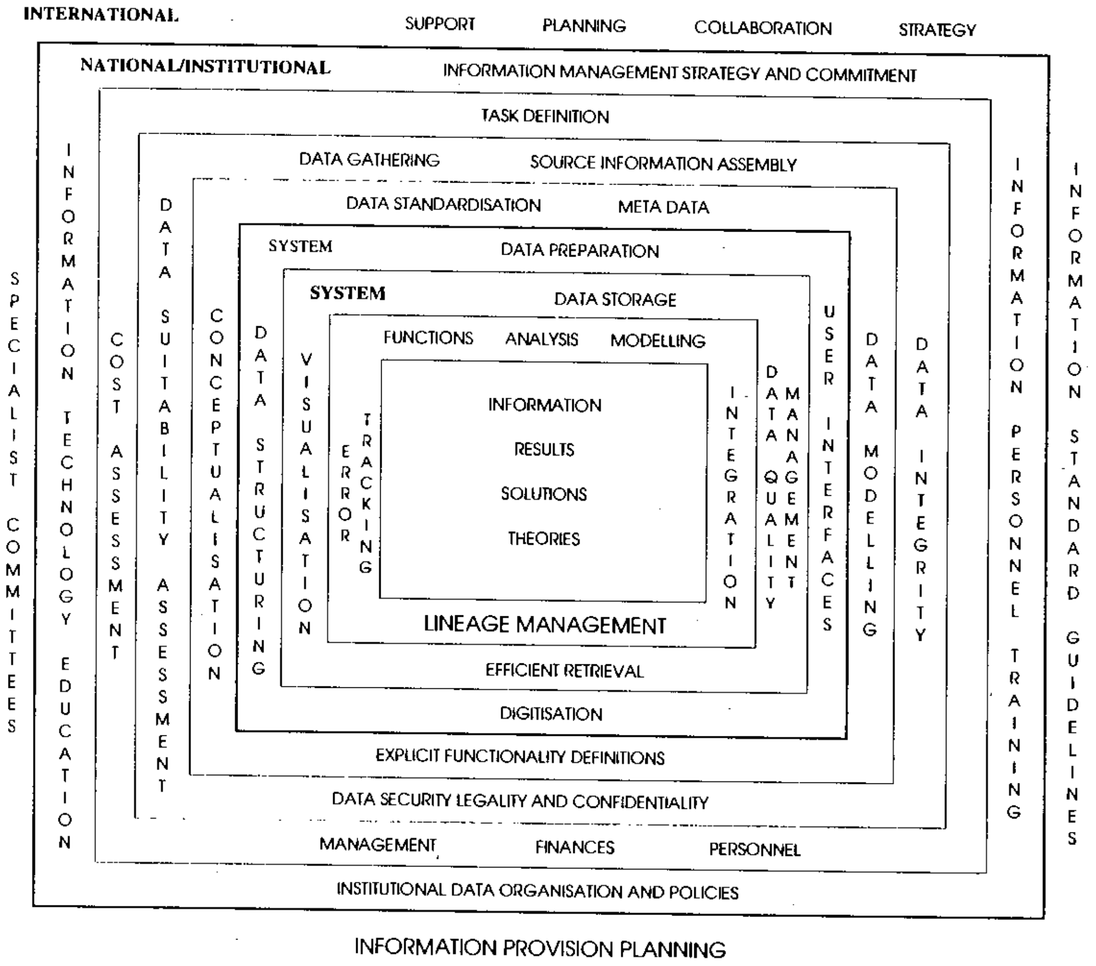
The benefits of a digital data infrastructure have been recognised by the European, US and United Nations science programmes, to name but a few. The end of the 1980's heralded a new era of global science with the development of global databases (Mounsey & Tomlinson, 1988). Various operational global databases now exist which demonstrate that the technological knowledge and hardware are available to support global information systems. The World Data Centres, projects such as the International Geosphere Biosphere Programme (IGBP), the EOS data centre and the National Oceanic and Atmospheric Administration (NOAA), are probably the most notable from a palaeoenvironmental perspective. WDC-A and NOAA indeed hold some palaeoclimatological data. These, and other similar digital database projects and information strategies are described in more detail in Appendix I. The appearance of Digital Chart of the World (DCW) as the first high quality base data set with global coverage marked a turning point in the development and use of global digital data.

Many of the databases and programmes discussed in Appendix I have related aims and interests, but operate separately with limited reference to one another. In fact, the duplication of effort amongst organisations on projects which have been initiated in the last five to ten years is remarkable. Despite all this activity, a comprehensive means of discovering what datasets exist, obtaining details about the datasets (coverage, quality and lineage), and accessing the data, is still no nearer (see also Section 3.8). Many of these projects do not address the issue of multi-thematic data integration, or have only recently realised the importance of this issue. The US NGDC's Global Change Research Program includes data integration as one of its most important areas of study (Hastings *et al.*, 1991). It has recently been recognised in the European Union EGII (European Geographic Information Infrastructure) document (September 1995), that the biggest impediments to an open and coherent geographic information society, are organisational and political and therefore that the issues need to be addressed at the highest levels if the opportunities provided by Geographic Information Technology are to be fully grasped.

A co-ordinated digital access service for environmental scientists is already being proposed as part of the US Global Change Research Program in the Draft Implementation Plan for the US Global Change Data and Information System (GCDIS) (CEES, 1993). The plans are to create a service which is a clearinghouse/'card catalogue' for environmental information related to global change, to organise data sources from many disciplines and organisations. In addition the Federal Geographic Data Committee and National Research Council Committee on mapping in the US is developing a plan for a National Spatial Data Infrastructure (NSDI) (Chrisman, 1994).

In order to achieve global communication and data sharing in technological terms, some degree of standardisation of communication protocols (TCP/IP, ASCII), query languages (SQL) and so on, have emerged (Croswell & Ahner, 1990), and other technology standards are being formulated and co-ordinated by the ISO (International Standards Organisation). In GIS terms, the stranglehold of proprietary systems is the biggest impediment to the development of GIS as a fully fledged research tool. The Open GIS Foundation (OGIS) (Buehler & McKee, 1996) has been established to provide the basis for an extensible software system, free from the closed system architecture, "black box" functionality and file interchange problems which are the bane of researchers using current proprietary systems.

Figure 6.5 Concentric Methodological Support Structure for Successful GIS



The current mode of GIS application project development is short-term, *ad hoc*, unstructured and system-centric. Figure 6.5 illustrates the concentric methodological support structure which is required for the development of a successful GIS. Outer support layers ensure the success of consecutive inner layers. Without the outer layers of an international infrastructure, inner, individual system, layers, will not be successful long-term. Figure 6.6 summarises the current development of GIS, whereby the technology is adapted as a useful, but relatively peripheral tool. Initially the organisational structure remains the same until there is a realisation that the technology is indispensable, but requires substantial changes in working practises in order to evolve and to allow integration with other systems. Figure 6.7 shows which of the necessary supporting layers exist in any form at the present time. Factors illustrated in italics are those which exist, but to a highly inadequate degree. Many important factors are entirely absent. Figure 6.8 illustrates the evolution of change at present from the system outwards. The ideal evolutionary path, from the infrastructure inwards, is also illustrated. Progress in practical terms will involve an iterative process involving both of these, with a realisation of what is require from systems, and an attempt at an international level to organise data and strategies to accommodate these requirements. The present system-centric evolutionary direction often results in disillusionment with the system because as projects progress it becomes more difficult to adjust the often incompatible data classifications and structures to new demands and the input of new data. Thus a systems response to growing demand becomes slower and more difficult to achieve when expectations of the system are growing.

System developers in the scientific field are limited in the number of system development models they can follow. The application, in scientific contexts, of structured methodologies to the design of information systems for exploratory science usually fails (Lucas, 1975; Preheim, 1992). Most large and successful systems are set up for business where needs, and operations, are very different from those of the researcher. Onsrud and Pinto (1989) note that in a typical GIS journal paper, the author's main aim is to implement a system successfully, not to carry out research.

6.9 Palaeoenvironmental Information Strategy

There are several key stages, therefore, which are required in the establishment of an information infrastructure for palaeoenvironmental data and research to facilitate the adoption of the PERIS model. A global information strategy for palaeoenvironmental information should be established to avoid the current development of fragmented un-

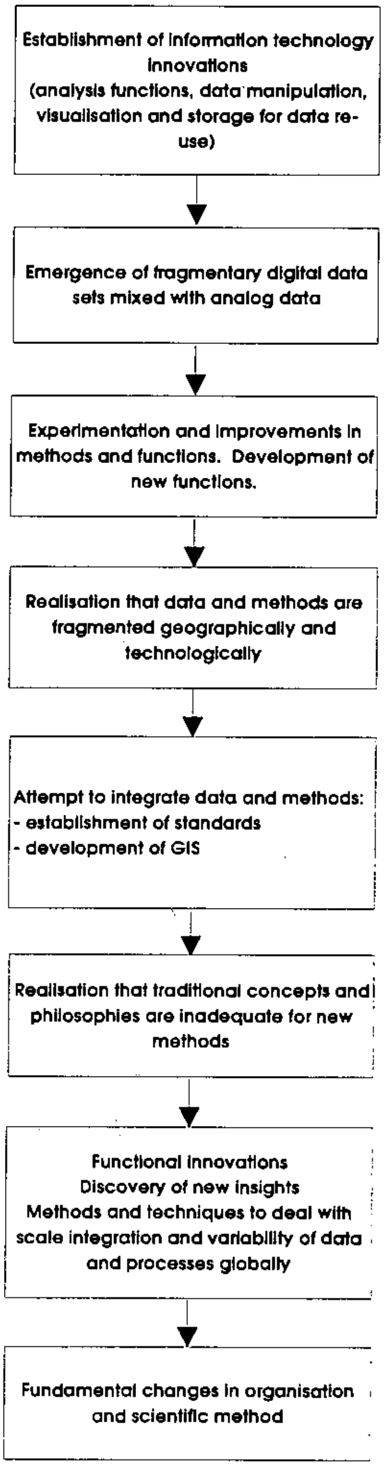


Figure 6.6 Current mode of development caused by the technological revolution

Figure 6.7 Existing Methodological Support Structure for GIS

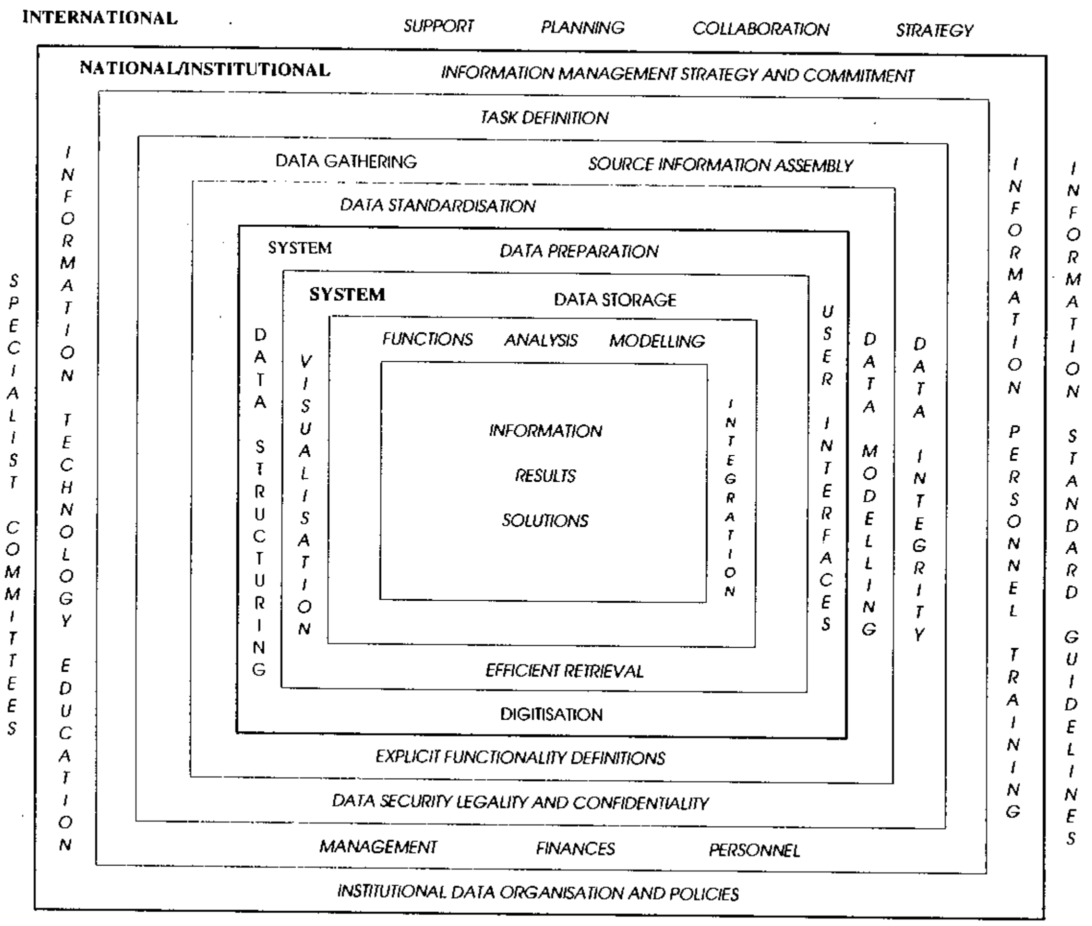
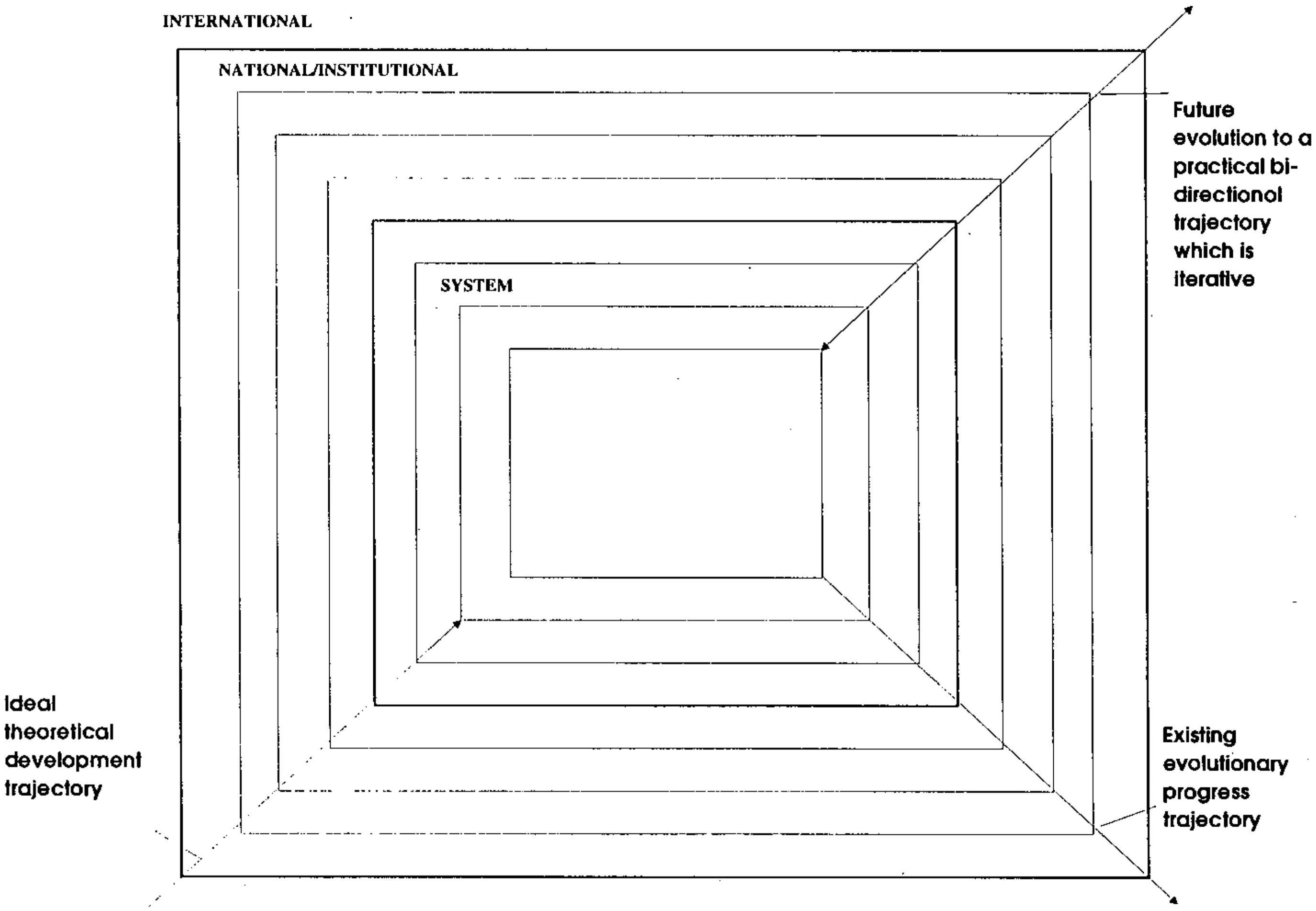


Figure 6.8 Evolving Methodological Support Structure for GIS



coordinated data and software, limit the misuse of tools ("black box" GIS functions, and data without metadata) and therefore the loss of crucial information. The order in which developments must take place is also important. Figure 6.9 summarises the main stages of development which must take place. Initially there must be changes in organisational co-ordination and an international forum must be established to oversee progress. This progress should occur in stages listed below:

1. Establishment of an international network and a series of committees.
    - These committees would be responsible for carrying out the necessary planning and decision making, disseminate information, looking into investment and develop standards and protocols. These should probably be coordinated by a major palaeoenvironmental research body such as the International Union for Quaternary Research.
    - The national scientific bodies, institutes, groups and individuals who have an interest in palaeoenvironmental information and who use and collect data should be identified.
    - The data and methods used by these palaeoenvironmental groups and individuals, which will be required and used in PERIS should be identified.
    - The PERIS model should be elaborated and a framework developed for the data and methods which can evolve into a set of data models.
    - Protocols, standards and methods should be developed for the capture and storage of these data and methods.
2. System Development
    - Adequate funding and personnel should be identified and prepared for system development.
    - Suitable hardware and software should be identified for the system implementation.
    - Prototypes should be developed along with validating frameworks, to assess the utilisation of GIS. Prototype testing should be carried out by as many users as possible over a broad cross-section of the palaeoenvironmental community.
    - Identification of further developments and plans to undertake these developments should then be carried out.

6.7 Conclusions

The object oriented approach, and the infrastructure to support it, provide a framework for reorganising palaeoenvironmental reconstruction which would fully

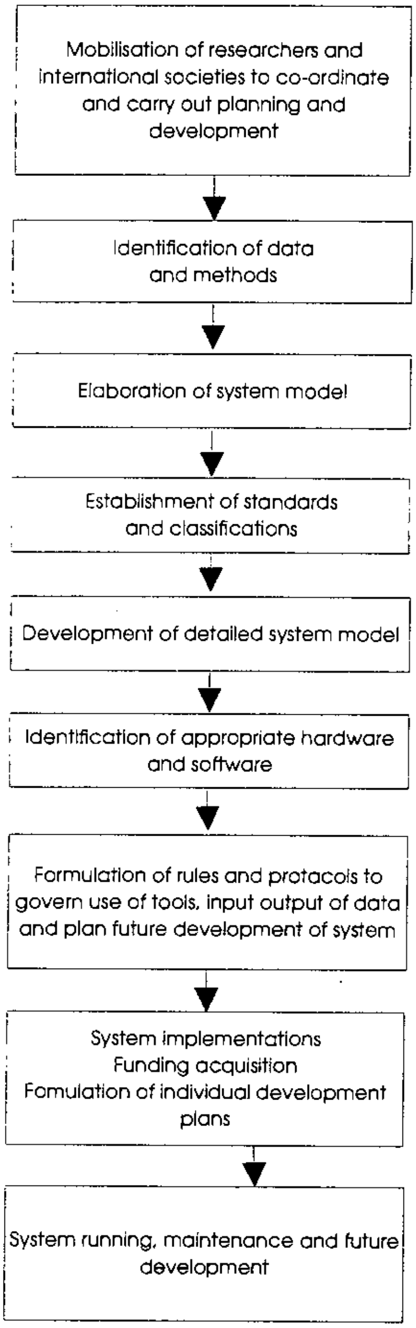


Figure 6.9 Method
for the development of PERIS

utilise the potential of all data available and provide a much more rigorous and flexible means of performing palaeoenvironmental reconstructions and developing research, although formal evaluation of will be the next requirement. Such an approach has always been conceivable, but this route has never been followed before because:

1) the quantity of data required to manipulate multiple objects in a meaningful way has not previously been available.

2) the incentives and pressure on the scientific community in terms global environmental change have never been so great

but most importantly,

3) computer systems which could manage the information and carry out the complexity of rule implementation, data gathering, expression of 4-d ideas and visualisation of data, were not available. Manual methods are very difficult to apply, and this is impossible to achieve with any rigour.

It is clear from the discussion of infrastructural issues, that unless an international context is established, each individual project GIS will have short-term success. Scientific data management is partially a scientific task (Strebel *et al.*, 1994) and some of the functions required for palaeoenvironmental research are unique to the science. Therefore unless the palaeoenvironmental scientific community takes it upon itself to make developments in this field, most will not be forthcoming.

Chapter 7 Conclusions

7.1 Palaeoenvironmental Science Needs GIS

The demands on palaeoenvironmental research to answer questions about global environmental changes have led to new information handling requirements. At the level of field observations global positioning systems, electronic surveying equipment, satellite imagery and field-based computing systems are improving the accuracy and efficiency of data collection. In the laboratory, computers are being used to record digital measurements directly. In deriving palaoenvironmental proxy values from this data, mathematical techniques supported by the speed and accuracy of computer processing are enhancing scientist's ability to interpret their results. Finally mathematical models of environmental processes have allowed scientists to gain better insights than data alone will allow. The large numbers of calculations required to develop and run these models have only been possible with the advent of computing technology.

However, despite exploiting computers to record and process field and laboratory data, reconstructing palaeoenvironments spatially is still largely being achieved using manual methods. The quantity of complex information which scientists must synthesise could be much better exploited through improvements in several areas. Information technology can be exploited to meet these requirements. GIS, in particular, can provide the spatial framework to support the management and analysis of data for palaeoenvironmental reconstructions. This thesis provides a conceptual overview of GIS in the context of palaeoenvironmental research.

7.2 Demonstrable GIS Benefits

The two case studies discussed in Chapters 4 and 5 clearly exemplify the benefits of GIS. Both case study data sets were used to derive inferences about the last glaciation which are closely related. However they exhibited very different information handling and analysis requirements. For these reasons they provided a representative case history against which the potentials of GIS could be tested for handling the properties of palaeoenvironmental data.

The GIS substantially improved many aspects of palaeoenvironmental reconstruction. The provision of a common spatial reference system allowed the integration of a number of datasets from very different sources. The synthesis was achieved over a larger area, and with greater accuracy than had previously been possible using manual methods. This was the first time such detailed datasets had been synthesised over such an extensive region.

A set of programs were developed to analyse and display the data. The programs are user-friendly, flexible and interactive. They allow the user to experiment with different analysis parameters and to visualise the data and analysis results in ways which are entirely user-controlled. The numbers of analysis scenarios and data views that can be created, are far in excess of any previously achieved. These scenarios can be generated in a fraction of the time required for manual synthesis and allow the user to focus on the analysis and results. Manual methods require the user to transcribe information between differently scaled maps. Significant amounts of time are spent reducing the detailed information, through generalisation, to a scale which is manageable. This generalisation is achieved by eye and is not only time-consuming but hard to achieve without significant information loss. The GIS processing imposed rigour on the analysis results which was not possible using manual methods. The reconstructions made using this information are therefore demonstrably better founded.

The results of the analyses and the original data were very easy to visualise in the computing environment. They could be displayed on screen, or printed onto paper quickly and easily. The three dimensional display of the relative sea level and isostatic surfaces demonstrated how visualisation can be used to enhance exploratory data analysis and theory generation. These surfaces can be displayed together with coastline and river information, and even combined with the glacial information if so required by the user.

GIS provides a flexible spatial framework within which this data can be managed, and used. It is held in its original, detailed form, but integrated over a large area. It is simple to apply this information to new problems because it can be transformed, scaled and analysed accurately and quickly. Particular areas of interest can be located and extracted very easily. It is also easy, to allow co-workers in disparate geographical locations to access the information through digital networks. GIS significantly improves the management, analysis, visualisation and dissemination of palaeoenvironmental research.

7.3 Further Developments are Urgently Required

Although the case studies clearly demonstrate the value added benefits of using GIS, several significant issues are apparent. These issues are fourfold. They concern inadequacies in the scientific method; the conceptual developments required to exploit GIS fully; limitations imposed by the research infrastructure; and the limitations of proprietary GIS to fulfil scientific requirements.

The limits of the current research paradigm are currently being reached. It is necessary to go beyond the cognitive abilities of the individual to synthesise large amounts of complex information unaided. The need to consider the implications of palaeoenvironmental change through time on a global scale demands new ways of managing information. This is necessary in order to integrate different data sources and use information to its full potential. The international and interdisciplinary nature of this research means that scientists will need to use data that they did not derive. They will need detailed metadata in order to understand this data and to be able to integrate it effectively. The current research paradigm makes no provision for structuring the recording or exchange of this metainformation.

There are several long-term consequences of this omission. In the first instance integration over large regions may result in unsound reconstructions. Secondly scientists will be unable to apply "old" data to new ideas. Given the cost of data collection, this is both uneconomic and limits the amount of information available for testing models. Thirdly, the extent to which scientists can exploit GIS will be curtailed. The resources required to establish an information system are too onerous to be undertaken at the beginning of individual projects. In order to reap the benefits of an information system it must support data use which encompasses many projects. This means that data must be incrementally integrated into the central resource. Variations in information requirements cannot be incorporated into the system if they were not accommodated at the outset in the system planning and design stages.

Methodological developments are required to structure this information in terms of its quality and its potential use. This framework could impose certain international standards on data documentation to ensure that the most necessary information is recorded at the data collection stages. These standards would facilitate both data sharing and the design and planning of GIS for long-term use.

However in order to fully exploit GIS other conceptual issues must be addressed. What data models are to be used to represent the data items and reconstructed features at different scales? The geomorphological case study showed that different representations of geomorphological features are appropriate for different scales of analysis (morphological features which have height and areal extent at one scale, versus lines comprising two points at another). How to accommodate different definitions of boundaries for features and then represent these, is another issue.

Current proprietary GIS do not support the storage or use of complex metadata. Neither do they incorporate much of the functionality required for scientific research. Most are not user-friendly and incorporate algorithms which are not properly documented. They also operate, for the most part, on a two-dimensional, layer-based paradigm which is unsuitable for the accommodation of natural environmental models on a geoidal earth. Developments which address these shortfalls are required.

7.4 The PERIS Model

The benefits of the digital age must be exploited by palaeoenvironmental researchers. Chapters 2 and 3 reviewed the palaoenvironmental requirements and GIS issues associated with the planning and design of a palaeoenvironnmental information system. The case studies described in chapters 4 and 5 demonstrate these issues in some detail. The requirements of palaeoenvironmental research illuminate the shortcomings of GIS in the analytical domain, and the strengths of GIS and its technical requirements highlight the shortcomings in the organisation and practice of palaeoenvironmental research. From this, the above sets of information handling, research infrastructural, and GIS issues, emerged. These issues form the basis for planning a specially designed PalaeoEnvironmental Reconstruction and Information System (PERIS).

The PERIS model is proposed as a suitable framework for exploiting the benefits of GIS whilst addressing the current shortfalls. It is based on object oriented concepts which appear to offer the best means of handling environmental features. Most work on extending GIS into the temporal dimension is also based on object orientation. Although it is not developed in detail and requires further, more formal, evaluation, it offers a conceptual model for palaeoenvironmental research. It also incorporates some ideas for the development of an international palaeoenvironmental data infrastructure. An agenda is suggested to develop the infrastructural support and the system model, which ensures that databases and approaches will be compatible internationally but will encompass the flexibility required for scientific research.

The new model facilitates individual exploration of data, tailored to user requirements, and much more freedom for experimentation of individual ideas through the ability to define many of the system variables and objects in individual user terms and to manage large quantities of data efficiently and effectively.

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[1] Abbreviations for names, organisations and publications follow the style given in the *Chemical Abstracts Service Source Index* (published by American Chemical Society)

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APPENDIX I

The global information network

Large digital databases of scientific data have been available for over three decades (Kemp, 1993). The space agencies have led the way in developing large systems to maintain archives of satellite remotely sensed data. For example in the US, there are three main examples; EROS (Earth Resources Observation Systems) and EOSAT (Earth Observation Satellite Company) archive and distribute Landsat data and the EOS (Earth Observing System) Programme gathers data from US, European and Japanese satellites. These programmes have instigated work on methods of storing, retrieving and managing very large databases but have not had to address the problem of integration with other thematic datasets.

The following sections provide a summary of what exists at the moment in terms of hardware, software, data and organisation with a critical appraisal of how successful these projects have been, what issues have arisen and to what extent these issues are being addressed.

I.1 SEQUOIA 2000

Probably the most comprehensive development towards an operational global information system, of direct relevance to palaeoenvironmental science and related studies, is the SEQUOIA 2000 Project which is "a long term research project to develop advanced computer technologies in support of global change science." (Gardels, 1994). The project has tremendous technological resources at its disposal, being sponsored by the Digital Equipment Corporation. The overall strategy incorporates direct input from computer scientists and earth scientists, working in collaboration, to develop the best possible tools and approaches which reflect user needs. The project covers the development of all tools, from network and file systems, to database management systems, storage and visualisation with the aim of tackling the issues of large file sizes, dispersed research and complex science all of which are fundamentally relevant to palaeoenvironmental data. Importantly, the project also incorporates the Open GIS Foundation's Open GeoData Interoperability Services testbed (OGF, 1994). The importance of OGIS in freeing system users from the closed architecture and confidential format and software restraints of many system vendors has already been discussed (Section 3.3.2.4.1) .

I.2 The European Union

The European Union has made a concerted effort to provide the basis for a successful integrated European Geographic Information Infrastructure (EGII). Whilst the mainstream effort has been to direct a unified approach to the collection, storage, maintenance and dissemination of Geographic Information, the practical implementation of these aims has itself been divided and resulted in a plethora of bureaucratic organisations and acronyms, with apparently overlapping aims. Historically, the first phase was an effort to produce comprehensive datasets of economical, environmental and communicational significance for all members of the European Union.

CORINE was initiated by the Commissions of the European Community (CEC) in 1985 with the objective of gathering co-ordinating and improving the consistency of information on the state of the environment in the European Community. There have been two main approaches to this objective. One has been the development of procedures for the collection, standardisation and exchange of data in the community and the second has been the establishment of an information system capable of providing policy-relevant information on the EC environment The main task of the CORINE central team has been to harmonise methodologies and subsequently to assemble the regional and national datasets into a consistent EC or European wide database. Within the programme a number of digital databases were created with the purpose of giving information on the status and the changes of the environment while ensuring compatibility between countries. CORINE Land Cover (the collection of Land Cover information) is one of the projects within the programme. In 1994 the size of data holdings in the CORINE information system was almost 2 gigabytes.

EUROSTAT is one of the Directorates-General of the European Commission. Its mission is to provide the European Union with a high-quality statistical information service. It has embarked on a programme of standardising concepts, terminology and methodologies in addition to the collection, processing and distribution of data for a heterogeneous population of users who require data for different purposes, in different forms and at different scales.

GISCO (Geographic Information System of the Commission of the European Communities) is the follow-up to the CORINE major computing project and operates within EUROSTAT. It was set up to identify user requirements concerning basic data to be used in GIS applications at the Commission and to propose strategies for, and to carry out, the acquisition, compilation, maintenance, updating and distribution of reference data, and undertake spatial analysis and spatial problem solving (de Esteban Alonso, 1995). GISCO is developing a wide range of value-added products resulting from the combination of georeferenced data and a statistical information System (European Statistical System, ESS). The data are maintained in a distributed fashion with certain Directorate Generals being responsible for particular datasets. The data are available free, or at a cost, depending on the user and the purpose to which is they are being put.

EUROGI (European Umbrella Organisation for Geographic Information) was initiated in 1994 to "*support and represent all GI groups at the European level*" and "*to stimulate, encourage and support the development and use of GI at the European level and to become the official partner for GI with the relevant European Institutions*" (Committee for Investigating the Feasibility of Creating a European Umbrella Organisation for Geographical Information, 1994). It represents a practical means by which issues such as data standards, data access, data integration and legalities could be addressed. It also aims to co-ordinate, focus and maximise the research and development effort within Europe and, furthermore, to provide a contact point for global harmonisation of digital data and issues. However the concern is mainly focused on the provision of economic and present day environmental data, the reduction in duplication of effort in data collection across Europe, and the integration of data on a European-wide basis via standards for increased international co-operation and innovation.

I.3 GRID

The Global Resource Information Database (GRID) (first conceived in 1985) supports the United Nations Environment Programme (UNEP) and UNEP's Environment Assessment Programme to address increasing environmental hazards and degradation of the planet. The GRID network seeks to provide up-to-date and reliable, georeferenced environmental data on a global scale across a network of co-operating centres providing environmental information for decision- and policy-making. GRID provides data cataloguing, archiving and analytical services using GIS, remote sensing, database and telecommunication technologies. Projects address the issues of data collection, archiving, management and analysis for present day and reference environmental information, some of which is of relevance to palaeoenvironmental sciences. One of GRID's prime functions is the compilation of key global and regional environmental datasets produced by monitoring activities, in particular the Global Environment Monitoring System (GEMS). More importantly one program addressed the issues of error, quality and integrity of digital geographic data with reference to the Digital Chart of the World (Langaas and Tveite, 1994), data which has facilitated many continental and global scale projects and is a vital framework data set for environmental and palaeoenvironmental studies. Palaeoenvironmental studies and data are not considered as part of the programme, but GRID demonstrates the successful co-operation of international centres for the management of large varied thematic datasets which have global coverage, are regularly updated, and are globally accessible at low cost, and thus has lessons for palaeoenvironmental scientists. Importantly, they also provide GIS analysis facilities. However it is not clear how effectively these datasets are integrated. More recently there has been a realisation that no single comprehensive metadata system exists and that the development of such a system is crucial to the continued evolution of GRID. An initiative has been set up to address this increasingly serious deficiency, and plan a comprehensive metadatabase.

I.4 NOAA

One environmental programme which does provide palaeoenvironmental data is the National Oceanic and Atmospheric Administration (NOAA) established in 1970 as part of the U.S. Department of Commerce. Its intention was the creation of a civil centre for expanding the effective and rational use of ocean resources for monitoring and predicting conditions in the atmosphere, oceans and space, and exploring the consequences of natural and manmade environmental change (Clark and Kineman, 1988). Whilst it is very much United States oriented, it was recognised that supporting global databases were required for effective accomplishment of NOAA's aims. Once data have been used by its operational components the data are available to the scientific community. Other data from external sources, which are not always used by NOAA are also compiled as a result of international agreements and projects and made available. World Data Centre-A (Section 3.4.1.5), parts of which are managed and run by some of NOAA's operational components, provides palaeoclimatological data and related items such as free software, abstracts of funded proposals, address exchange, opportunities to add individual datasets to the central data bank and indices of other sites of interest. It also provides an extensive range of palaeoenvironmental information which could act as a basis for development of a fully fledged palaeoenvironmental system. However, once again it does not appear to address the issues of data integration and comprehensive metadata management. The datasets, collected through a process of voluntary contributions, mainly comprise reference datasets and standards such as the GRIP ice core data (e.g. Wolff *et al.*, 1995) and Fairbanks sea level curve (Fairbanks, 1989), and summary compilation datasets such as the CLIMAP project 18K database (CLIMAP, 1981).

I.5 The World Data Centres

World Data Centres (WDCs) were the result of an international effort towards the collection, archiving and dissemination of geophysical and solar data during the International Geophysical Year 1957 (ICSU, 1987), and were the forerunner for global data collection, storage and dissemination. The numbers of world data centres and their locations are as follows (Allen, 1988):

WDC-A - located in US (9 centres)
WDC-B - located in Russia (2 centres)
WDC-C1 - located in Europe (8 centres)
WDC-C2 - located in Japan (8 centres)

They are the result of a non-Governmental initiative, based on voluntary scientist-to-centre submission of data according to agreed standards developed by relevant international scientific bodies in each discipline. They have now been in operation for almost forty years and originated mainly in the pre-computer era originally for geophysical data (meteorology, snow and ice cover, geomagnetism, gravity, solar activity etc.). Some WDC-C's were mainly specific data analysis and processing services rather than comprehensive archives. The central monitoring of data flow and copying between centres and scientists was co-ordinated in Brussels. In 1980 a decision was reached by the ICSU (International Committee of Scientific Unions) for a concerted move to digital databases. Originally there was a trend for a few comprehensive data centres because it was more economical to centralise the costs of staff, resources and specialised equipment which was required. However cheaper, higher capacity, faster Personal Computers (PCs) and communications networks, and the advent of improved software allowing the automation of many time-consuming jobs and processing by less highly trained personnel has heralded the possibilities of a trend reversal allowing an increase in centre numbers within Universities and Institutions (Allen, 1988).

The original WDC principles are still active and are based around a free data exchange policy controlled by international data standards of accuracy, clarity and durability (e.g. Chrisman, 1984). It was based on the premise that planning should include provision for data collection, archiving and distribution and operated on a principle that data are completely accessible to all scientists in all countries without exception. There are some charges related to handling costs to those researchers who are not sources of data or for very large or specialised requirements.

These centres are significant because they hold and manage very large data volumes of both palaeoenvironmental data and many other datasets relevant to palaeoenvironmental reconstruction. These other datasets are present day comparative or reference datasets. A further significance concerns the principles of accessibility of data to scientists, on which the data centres operate in terms of organisation, data exchange and dissemination. The way in which these aspects have evolved is worth noting. They are also closely related to NOAA and underpin the significant International Geosphere Biosphere Project (IGBP). The International Council of Scientific Unions (ICSU) supported the setting up of the International Geosphere-Biosphere Programme (IGBP) (Evteev and Rostotsky, 1985), often referred to as Global Change, to "describe and understand the interactive physical, chemical and biological processes that regulate the total Earth System, the unique environment it provides for life, the changes that are occurring in that system and the manner by which these changes are influenced by human actions" (Report of *ad hoc* Planning group for IGBP (1986), quoted in IGBP (1988)).

I.6 GISDATA

One of the most significant initiatives recently has been the European Science Foundation's GIS Data Integration and Database Design Project (GISDATA). This is supported by fourteen European national research councils and has good collaborative links with other GIS research initiatives such as the NCGIA (National Centre for Geographic Information and Analysis) of the US National Science Foundation as well as agencies such as EUROSTAT and the European Environmental Agency. It was launched in January 1993 and is due to run until the end of 1996. The programme aims to address the ever more pressing issues of European-wide limitations in spatial data integration, database design and social and environmental applications, to facilitate the development of appropriate methodologies for GIS research at the European level and to build-up a European network of researchers with particular emphasis on young researchers in the GIS field (ESF, 1991). It is important that those involved in palaeoenvironmental studies are involved in this sort of initiative otherwise the special needs of palaeoenvironmental studies will not be well represented in the output from these projects.

I.7 Project Alexandria

The Alexandria Project is one of six projects sponsored by the US National Science Foundation (NSF), the Department of Defense's Advanced Research Projects Agency (ARPA), and the National Aeronautics and Space Administration (NASA), as part of the inter-agency Digital Library Initiative (DLI). It is a consortium of researchers, developers and educators exploring a variety of issues related to a distributed data library for geographically-referenced data, the centrepiece of which is the Alexandria Digital Library. This library is on-line and accessible through the web, although still in the developmental stages, and currently incorporates a text data set of maps and imagery for California. It is the most significant example of moves to design a database which supports spatially indexed data for browsing and down-loading

I.8 GENIE

One attempt to provide a user interface and metadata browser, has been the GENIE (Global Environmental Network for Information Exchange) project. The project began as a government funded research project for the provision of a Global Environmental Change Data Network Facility to construct a fully-distributed multi-site metadata capture and enquiry system. This project has been a valuable step forward towards assembling information about data bases with collaboration from scientists working with the data and managing the data centres. The system is still under development and promises to offer a flexible and innovative system which is distributed in nature and has an ability to search via concepts as well as characters. It is planned that it will retain a complete history of transactions making it possible to identify what was said to whom at any point in time. However, it has run into financing difficulties and in terms of its aims some fundamental organisational changes are required in addition to the metadata management and user interface facilities it provides. What is required is a robust, comprehensive framework within which would reside a central index for global information. One of the main drawbacks is that the system is de-coupled from the data on which it holds information and therefore this information is often no longer a true representation of the data holdings, and those managing the data receive no feed back on queries made about their data (Medyckyj-Scott *et al.*, 1996).

APPENDIX II

The User Interface for Rose Diagram and Lineation Density Calculations

This interface is written using the ARC Macro Language (AML) which calls FORTRAN programmes to undertake the rose diagram and lineation density calculations. The analysis is described below in the stages represented by the boxes in Figure 4.9.

1. The user is asked whether they wish to analyse the lineations, or merely view the data and the results of previous analyses.

2. If the user chooses to undertake analysis a menu appears which displays the names of the different data layers available for analysis. The user can choose any of these layers (they contain different lineation interpretations at different scales). Once a data layer is selected there is an option which allows the user to select a smaller sub-area for the analysis. This is useful because analysing the entire Scandinavian area can take several minutes of programme run time if the machine is busy. To do this the system moves to the arcedit module, the area covered by the data layer is displayed and the user must select two corner points to define the analysis window. The programmes use these x, y coordinates to "cookie cut" an area from the data layer and create a new data layer.

3. The user must then indicate through a series of questions which particular rose diagram analyses they wish to make. Yes/No variables are then set for each analysis type which are passed to the FORTRAN programme which undertakes the analyses. Some subroutines are not run if certain analyses are not selected which saves time. They are also asked what window cell size they would like for each rose diagram analysis, to allow different degrees of generalisation and the size of units they would like used for the rose diagram. This option has been added because in areas of intense lineation density neighbouring rose were being obscured, but in areas of low lineation density, the diagrams were sometimes too small to interpret using a standard unit size.

4. The FORTRAN programme operates in the following way. The AML UNGENERATE command is used to produce an ASCII file of x, y coordinates for the lineations (two coordinates for the end of each lineation). The FORTRAN programme is then called which sets up a three dimensional array. Each element in the array corresponds to a directional band within a particular rose diagram square (the 3 dimensions of the array are the 36 directional bands, the number of cells in the

x direction, and the number of cells in the y direction). The programme then reads each of the lineations in turn from the ASCII file, calculates within which grid square the centroid of the lineation is located, and within which five degree directional band the lineation direction lies and increments an element of the array accordingly. Once all lineations are read and all directions and locations calculated, a subroutine is called which calculates the coordinates of the rose diagrams for each grid cell area using this information and the rose diagram unit size given by the user. The lineation density calculation operates in an almost identical way but only a two dimensional array is required to calculate the number of lineation centroids which fall within each grid cell. Control is then returned to the AML programme and the rose coordinates are then written to an ascii file and imported into the GIS using the AML GENERATE command.

5. The user is then asked whether they wish to view the diagrams or continue with further analyses. This option is added because viewing the diagrams means moving to the ARCPLOT module which is very slow, and it may be preferrable to continue with the analyses and view the results in a single session rather than move between modules several times.

6. The user is asked whether they wish to create lineation density plots and is invited to enter a grid cell resolution for these plots. The AML programme does a quick calculation to check the grid cell resolution against the size of the data layer to ensure that a reasonable value has been entered and requests that the user enter a different value if this is not the case.

7. The lineation density calculations proceed in a similar manner to those of the rose diagram calculations using FORTRAN programmes as described above.

8. The user is asked whether they would like to browse the results of the calculations and generate plots of these results. All these operations are performed through the ARCPLOT module.

9. Finally the user has the option to exit, or to perform further analyses.

```
/* startlin.aml
/*
/* called from arc with the new arc command LINS
/* or from system with shell script lins
/* starts analysis and plotting of lineations programs
/* runs lin.aml
&amlpath /home/egeo17/arc/glac/lins/aml
&terminal 9999
&thread &Create lin &r lin.aml
&thread &delete &self
```

```
/* lin.aml
/*
/* called from startlin.aml
/* Main controlling AML which creates rose diagram, principle direction
/* and lineation density plots for user-defined area

/* ensure that globals don't already exist

&amlpath /home/egeo17/arc/glac/lins/aml

&r setpaths.aml

&terminal 9999

&sv covsel = [query 'Do you wish to do some analysis Y/N']

/* set variable to show status of arcplot
&sv .vcv = .false.

&label begin

&if [variable .newcov] &then
  &dv %.newcov%
&if [variable .lincov] &then
  &dv %.lincov%
&if [variable .qcov] &then
  &dv %.qcov%
&if %covsel% &then

&do

&label chcov

&type 'Select a coverage'

&sv .lincov = [getcover /home/egeo17/arc/glac/lins]

/* look at coverage

&sv .vcov = [query 'Do you wish to view this coverage']
&if %.vcov% &then
&do
&thread &create aplot &r linaplot.aml
&sv .vcv = .true.
&end
&sv .qcov = [query 'Do you wish to use this coverage']

&if ^ %.qcov% &then
   &goto chcov

/* decide whether to clip down the coverage or not

&sv .qclip = [query 'Take a subsection of this coverage']

&if %.vcv% &then
quit
&sv .vcv = .false.

/* if coverage is to be clipped quit arcplot and run the clip aml
/* to create a new coverage %.newcov%

&if %.qclip% &then

&do

/* create clip box coverage and clipped coverage
/* /home/egeo17/arc/glac/lins/rdclip/%.newcov%
/* according to the user-defined limits

  &r rclip.aml

&end

&if [variable .newcov] &then
   &sv .lincov = %.newcov%

&sv .qros = [query 'Create Various Rose diagrams for selected area']

&if %.qros% &then

  /* create rose and principle direction coverages

  &r rnewroslin.aml

&sv .qden = [query 'Create Lineation densities for selected area']

&if %.qden% &then

  /* create lineation density plots

  &r linden.aml

&end

/* view plots

&label view

&sv vw = [query 'View plots']
&if %vw% &then
 &do
  &r rviewplot.aml
  &sv .vcv = .false.
  &goto view
 &end
&sv .vcv = .false.

/* create plotfiles of rose, principal direction and lineation density
/* plots

&label hardcopies

&sv quer = [query 'Create and print hardcopies']
&if %quer% = .true. &then
   &do
      &r rhardplot.aml
      &goto hardcopies
   &end

&sv qbeg = [query 'Perform further analyses']
&if %qbeg% &then
  &do
  &s covsel = .true.
  &goto begin

&return

&end

```

```
/*  clip.aml
/*
/* Arcedit
/* AML for clipping down big coverages to create
/* smaller ones for which rose diagrams and diagrams of principle
/* directions can then be created
&amlpath %.linpath%/aml

&severity &error &routine error

&if [exists %.linpath%/clip_c -cover] &then
    kill %.linpath%/clip_c


arcedit
disp 9999 2
&terminal 9999

/* if program is not being called from another AML then get a cover to clip
/* select large coverage from which to create clipped coverage
/* from menu which appears at top right of screen

/*&if not [exists %.backcover% -cover] &then

/*  &s .backcover = [getcover %.linpath%]

/*&else

  &s .backcover = %.lincov%

/* plot the big coverage and any other related datasets (coastlines etc)
/* to locate the area for clipping

mapex %.backcover%
backcover %.backcover% 3
backcover %.basepath%/ceurc_lcc 1
backenv arc
draw

/* create clip box to clip the large coverage with, to create the
/* smaller coverage

/* create coverage using large coverage bnd file

create %.linpath%/clip_c %.backcover%

/* choose to draw a box of a single arc

editfeature arc
arctype box

/* get lower left and upper right coordinates of box
/* select lower left coord

&type Select the lower left point using the mouse
&getpoint &map &mouse

/* read mouse-selected points into variables

&sv llx %pnt$x%
&sv lly %pnt$y%
&type selected point is %llx% %lly%

/* select upper right coord

&type Select the upper right point using the mouse
&getpoint &map &mouse

/* read mouse-selected points into variables

&sv urx %pnt$x%
&sv ury %pnt$y%
&type selected point is %urx% %ury%

/* read these points into the buffer which will then be used by
/* the add command
/* usage is: &pushpoint key xcoord ycord

&pushpoint 2 %llx% %lly%
&pushpoint 2 %urx% %ury%
&pushpoint 9 0 0
add


/* draw to check where the clip box is

setdrawsymbol 0 4

&pause

/* exit arcedit

quit
y
y

/* build the clip coverage

build %.linpath%/clip_c poly

&type clip box coverage successfully created

/* show coverage names so a name isn't chosen which already exists

/*lc %.clippedpath%

/* ask user for new coverage name

/*&sv .newcov = [response 'Enter new clipped cover name' ]
/*  &if [exists %.clippedpath%/%.newcov% -cover] &then
/*    kill %.clippedpath%/%.newcov%

&sv newcov = [entryname %.lincov%]
&sv .newcov = %.clippedpath%/%newcov%
&if [exists %.newcov% -cover] &then
   kill %.newcov%
        /* clip large cover with clip box cover

        clip %.backcover% %.linpath%/clip_c ~
%.newcov% line

        /* kill clip box coverage to save hassle and space

        kill %.linpath%/clip_c

&workspace %.linpath%/aml

/*arcplot
/*disp 9999 2
/*mapex %.clippedpath%/%.newcov%
/*linecolor 3
/*arcs %.clippedpath%/%.newcov%
/*linecolor 1
/*arcs %.basepath%/ceurc_lcc
/*&pause

&s .lincov = %.newcov%

&return

&routine error
&thread &create term &tty
```

```
quit
&thread &delete &self
&return



&end
```

```
/* gridplot.aml
/*
/* plots .dencov density coverage on screen in arcplot
/* called by linden.aml
/*
&amlpath /home/egeo17/arc/glac/lins/aml

disp 9999 2
mapex /home/egeo17/arc/glac/lins/linden/%.dencov%_d
/*pageunits cm
textquality proportional
textfont 93715
/*pagesize 29.7 42.0
/*box 0.9 0.9 28.8 41.1
/*maplimits 0.9 4.0 28.8 35.0
mapposition cen cen
/*mapunits meters
/*mapscale 5000000
linecolor 1
shadeset /home/egeo17/arc/glac/lins/linden/blue.shd
gridnodatasymbol 1
gridshades /home/egeo17/arc/glac/lins/linden/%.dencov%_d value /home/egeo17/arc/glac/lins/linden/density.rmt
linecolor 8
arcs /home/egeo17/arc/bmap/ceurc_lcc
/*linecolor 1
/*box  2.0 2.5 7.0 2.6
/*line 2.0 2.5 2.0 2.7
/*line 3.0 2.5 3.0 2.7
/*line 4.0 2.5 4.0 2.7
/*line 5.0 2.5 5.0 2.7
/*line 6.0 2.5 6.0 2.7
/*line 7.0 2.5 7.0 2.7
/*line 2.0 2.55 3.0 2.55
/*line 4.0 2.55 5.0 2.55
/*line 6.0 2.55 7.0 2.55
/*move 2.0 3.0
/*textsize 0.3 0.2
/*text 0 cc
/*move 3.0 3.0
/*text 50 cc
/*move 4.0 3.0
/*text 100 cc
/*move 5.0 3.0
/*text 150 cc
/*move 6.0 3.0
/*text 200 cc
/*move 7.0 3.0
/*text 250 cc
/*move 7.5 3.0
/*text km cc
/*move 4.5 3.5
/*textsize 0.4 0.25
/*text 'Scale 1:5 000 000' cc
/*move 14.85 37.0
/*textsize 0.9
/*text 'Lineation Density Plot of Satellite Mapped Landforms' cc
/*linecolor 1
/*keyposition 2.0 20.0
keyshade /home/egeo17/arc/glac/lins/linden/density.key
/*move 2.0 22.0
/*textsize 0.5
/*text 'Lineation' ll
/*move 2.0 21.0
/*text 'Densities' ll
```

```
/* hardplot.aml
/*
/* called from lin.aml
/* this program creates hard copies of analyses
/* it is called by lin.aml
/* it sets the angle of the plot (portrait or landscape)
/* and the size/type of the plot (a3 colour/a4 b&w)
/* eventually it will be able to plot any combination
/* of any analyses plots including plots created during
/* past sessions.

&amlpath /home/egeo17/arc/glac/lins/aml

&call whichplots

&call angleplot

&call sizeplot

&r h%lp%%size%psplot.aml

&return

&routine whichplots

/* &s .choice = [getchoice LINEATIONS CLIPPEDLINS DENSITIES ROSE -prompt ~
/*'select the coverage type to plot']

&s .choice = [getchoice LINEATIONS ROSE CLIPPEDLINS -prompt ~
'select the coverage type to plot']

&type 'Select a coverage to plot'
&if %.choice% = LINEATIONS &then
    &s .plotcov = [getcover /home/egeo17/arc/glac/lins]
/*&if %.choice% = DENSITIES &then
/*    &s .plotcov = [getcover /home/egeo17/arc/glac/lins/linden]
&if %.choice% = ROSE &then
    &s .plotcov = [getcover /home/egeo17/arc/glac/lins/rose]
&if %.choice% = CLIPPEDLINS  &then
    &s .plotcov = [getcover /home/egeo17/arc/glac/lins/rdclip]
/*later additions for clipboxes - n.b. need to save clip boxes in
/*clip.aml

&return

&routine angleplot

&sv qlp = [query 'portrait plot']
   &if ^ %qlp% &then
      &do
        &sv qlp = [query 'landscape plot']
           &if %qlp% &then
              &sv lp = l
           &else
              &do
                 &type 'defaulting to portrait plot'
                 &sv lp = p
        &end
     &end
   &else
     &sv lp = p

&return

&routine sizeplot

&sv siz = [query 'a4 plot']

   &if ^ %siz% &then
     &do
        &sv siz = [query 'a3 plot']
        &if %siz% &then
           &sv size = a3
        &else
           &do
              &type 'defaulting to a4'
              &sv size = a4
           &end
     &end
   &else
     &sv size = a4

&return
```

```
/* hla3psplot.aml
/*
/* called from hardplot.aml
/* aml to run already existing allplot.aml aml which plots the base
/* map and all the data sets on a landscape A3 colour plot with
/* university crest

&sv file = tmp
&sv newfile = a3%file%
&sv plotfile = a3ps%file%

&if [exists %newfile%] &then
&sys rm %newfile%

/* open new plot file to write aml commands to

&sv plotf_u1 = [open %newfile% openstat1 -write]

/* check status and unit number
&type %plotf_u1%
&type %openstat1%

/* set variable names to records for plot set-up

&call setuplines

/* write setup variables to new aml file

&do index1 = 1 &repeat %index1% + 1 &while [variable setup%index1%]
      &s record = [value setup%index1%]
      &s writestat = [write %plotf_u1% [quote %record%]]
&end

&call lines

/* set variable names to records strings to write to new file

&do index2 = 1 &repeat %index2% + 1 &while [variable line%index2%]
      &sv record = [value line%index2%]
      &sv wstat2 = [write %plotf_u1% [quote %record%]]
&end

/* close arcplot command aml file

&s closestat1 = [close %plotf_u1%]

/* create HP plot file

&call aplot

/* check plot

draw %newfile%.gra 9999 2

/* convert gra plot file to postscript file
/* and plot landscape style

   postscript %newfile%.gra %newfile%.ps


&sv q = [query 'Send this A4 plot to the A4 plotter']

&if %q% &then
   lpr -P psglg4 %newfile%.ps

&return

&end

&routine setuplines

      &s setup1 = mapex %.plotcov%
      &s setup2 = pageunits cm
      &s setup3 = textfont 93715
      &s setup4 = textquality proportional
      &s setup5 = pagesize 29.7 42.0
      &s setup6 = box 1.5 1.5 28.8 41.1
      &s setup7 = maplimits 0.9 6.0 28.8 38.0
      &s setup8 = mapposition cen cen
      &s setup9 = textsize 0.9
/* add more set-up variables below this line (e.g. legends etc)
&return

&routine lines

&s line1 = linecolor 1
&s line2 = arcs /home/egeol7/arc/bmap/ceurc_lcc
&s line3 = linecolor 2
&s line4 = arcs %.plotcov%
&s line5 = move 10.0 27.0
&s line6 = text %.plotcov%
&return

&routine aplot

arcplot
disp 1040
%newfile%
&r %plotfile%
quit

&return
```

```
/* hla4psplot.aml
/*
/* called from hardplot.aml
/* aml to run already existing allplot.aml aml which plots the base
/* map and all the data sets on a landscape A3 colour plot with
/* university crest

&sv file = tmp
&sv newfile = a4%file%
&sv plotcov = [entryname %.plotcov%]

&if [exists %newfile%.aml -file] &then
  &sys rm %newfile%.aml
&if [exists %newfile%.gra -file] &then
  &sys rm %newfile%.gra
&if [exists %newfile%.ps -file] &then
  &sys rm %newfile%.ps


/* open new plot file to write aml commands to

&sv plotf_ul = [open %newfile%.aml openstat1 -write]

/* check status and unit number
&type %plotf_ul%
&type %openstat1%

/* set variable names to records for plot set-up

&call setuplines

/* write setup variables to new aml file

&do index1 = 1 &repeat %index1% + 1 &while [variable setup%index1%]
      &s record = [value setup%index1%]
      &s writestat = [write %plotf_ul% [quote %record%]]
&end

&call lines

/* set variable names to records strings to write to new file

&do index2 = 1 &repeat %index2% + 1 &while [variable line%index2%]
      &sv record = [value line%index2%]
      &sv wstat2 = [write %plotf_ul% [quote %record%]]
&end

/* close arcplot command aml file

&s closestat1 = [close %plotf_ul%]

/* create HP plot file

&call aplot

&s qchp = [query 'View plotfile']

/* check plot file
&if %qchp% &then
  &call chaplot.aml

/* convert gra plot file to postscript file
/* and plot landscape style

   postscript %newfile%.gra %newfile%.ps 0.65 ~
/home/egeo17/arc/glac/lins/aml/epsfile

&sv q = [query 'Send this A4 plot to the A4 plotter']

&if %q% &then
   &sys lpr -P psglg4 %newfile%.ps

&return

&end

&routine setuplines

      &s setup1 = mapex %.plotcov%
      &s setup2 = pageunits cm
      &s setup3 = textfont 93715
      &s setup4 = textquality proportional
      &s setup5 = pagesize 42.0 29.7
      &s setup6 = box  1.5 1.5 41.5 29.2
      &s setup7 = maplimits 1.6 1.6 41.3 29.0
      &s setup8 = mapposition cen cen
      &s setup9 = textsize 0.9
/* add more set-up variables below this line (e.g. legends etc)
&return

&routine lines

&s line1 = linecolor 1
&s line2 = arcs /home/egeo17/arc/bmap/ceurc_lcc
&s line3 = linecolor 1
&s line4 = arcs %.plotcov%
&s line5 = move 10.0 27.0
&s line6 = text %plotcov%
&return

&routine aplot

arcplot
disp 1040
%newfile%
&r %newfile%.aml
quit

&return

&routine chaplot.aml
   arcplot
   disp 9999 2
   &r %newfile%.aml
   &sv hit [response 'Hit any key to continue']
   quit
&return
```

```
/* hpa3psplot.aml
/*
/* called from hardplot.aml
/* aml to run already existing allplot.aml aml which plots the base
/* map and all the data sets on a landscape A3 colour plot with
/* university crest

&sv file = tmp
&sv newfile = a3%file%
&sv plotfile = a3ps%file%

&if [exists %newfile%] &then
&sys rm %newfile%

/* open new plot file to write aml commands to

&sv plotf_u1 = [open %newfile% openstat1 -write]

/* check status and unit number
&type %plotf_u1%
&type %openstat1%

/* set variable names to records for plot set-up

&call setuplines

/* write setup variables to new aml file

&do index1 = 1 &repeat %index1% + 1 &while [variable setup%index1%]
      &s record = [value setup%index1%]
      &s writestat = [write %plotf_u1% [quote %record%]]
&end

&call lines

/* set variable names to records strings to write to new file

&do index2 = 1 &repeat %index2% + 1 &while [variable line%index2%]
      &sv record = [value line%index2%]
      &sv wstat2 = [write %plotf_u1% [quote %record%]]
&end

/* close arcplot command aml file

&s closestat1 = [close %plotf_u1%]

/* create HP plot file

&call aplot

/* check plotfile

draw %newfile%.gra 9999 2

/* convert gra plot file to postscript file
/* and plot landscape style

   postscript %newfile%.gra %newfile%.ps

&sv q = [query 'Send this a3 plot to the a3 plotter']

&if %q% &then
   lpr -P csglg0-a3 %newfile%.ps

&return

&end

&routine setuplines

      &s setup1 = mapex %.plotcov%
      &s setup2 = pageunits cm
      &s setup3 = textfont 93715
      &s setup4 = textquality proportional
      &s setup5 = pagesize 29.7 42.0
      &s setup6 = box 1.5 1.5 28.8 41.1
      &s setup7 = maplimits 1.4 1.4 28.7 41.0
      &s setup8 = mapposition cen cen
      &s setup9 = textsize 0.4
/* add more set-up variables below this line (e.g. legends etc)
&return

&routine lines

&s line1 = linecolor 1
&s line2 = arcs /home/egeo17/arc/bmap/ceurc_lcc
&s line3 = linecolor 1
&s line4 = arcs %.plotcov%
&s line5 = move 14.85 39.0
&s line6 = text %.plotcov%
&return

&routine aplot

arcplot
disp 1040
%newfile%
&r %plotfile%
quit

&return
```

```
/* hpa3psplot.aml
/*
/* called from hardplot.aml
/* aml to run already existing allplot.aml aml which plots the base
/* map and all the data sets on a landscape A3 colour plot with
/* university crest

&sv file = tmp
&sv newfile = a3%file%
&sv plotfile = a3ps%file%

&if [exists %newfile%] &then
&sys rm %newfile%

/* open new plot file to write aml commands to

&sv plotf_u1 = [open %newfile% openstat1 -write]

/* check status and unit number
&type %plotf_u1%
&type %openstat1%

/* set variable names to records for plot set-up

&call setuplines

/* write setup variables to new aml file

&do index1 = 1 &repeat %index1% + 1 &while [variable setup%index1%]
      &s record = [value setup%index1%]
      &s writestat = [write %plotf_u1% [quote %record%]]
&end

&call lines

/* set variable names to records strings to write to new file

&do index2 = 1 &repeat %index2% + 1 &while [variable line%index2%]
      &sv record = [value line%index2%]
      &sv wstat2 = [write %plotf_u1% [quote %record%]]
&end

/* close arcplot command aml file

&s closestat1 = [close %plotf_u1%]

/* create HP plot file

&call aplot

/* check plotfile

draw %newfile%.gra 9999 2

/* convert gra plot file to postscript file
/* and plot landscape style

   postscript %newfile%.gra %newfile%.ps

&sv q = [query 'Send this a3 plot to the a3 plotter']

&if %q% &then
   lpr -P csglg0-a3 %newfile%.ps

&return

&end

&routine setuplines

      &s setup1 = mapex %.plotcov%
      &s setup2 = pageunits cm
      &s setup3 = textfont 93715
      &s setup4 = textquality proportional
      &s setup5 = pagesize 29.7 42.0
      &s setup6 = box 1.5 1.5 28.8 41.1
      &s setup7 = maplimits 1.4 1.4 28.7 41.0
      &s setup8 = mapposition cen cen
      &s setup9 = textsize 0.4
/* add more set-up variables below this line (e.g. legends etc)
&return

&routine lines

&s line1 = linecolor 1
&s line2 = arcs /home/egeo17/arc/bmap/ceurc_lcc
&s line3 = linecolor 1
&s line4 = arcs %.plotcov%
&s line5 = move 14.85 39.0
&s line6 = text %.plotcov%
&return

&routine aplot

arcplot
disp 1040
%newfile%
&r %plotfile%
quit

&return
```

```
/* hpa4psplot.aml
/*
/* called from hardplot.aml
/* aml to run already existing allplot.aml aml which plots the base
/* map and all the data sets on a landscape A3 colour plot with
/* university crest

&sv file = tmp
&sv newfile = a4%file%
&sv plotcov = [entryname %.plotcov%]

&if [exists %newfile%.aml] &then
  &sys rm %newfile%.aml
&if [exists %newfile%.gra] &then
  &sys rm %newfile%.gra
&if [exists %newfile%.ps] &then
  &sys rm %newfile%.ps

/* open new plot file to write aml commands to

&sv plotf_ul = [open %newfile%.aml openstat1 -write]

/* check status and unit number
&type %plotf_ul%
&type %openstat1%

/* set variable names to records for plot set-up

&call setuplines

/* write setup variables to new aml file

&do index1 = 1 &repeat %index1% + 1 &while [variable setup%index1%]
      &s record = [value setup%index1%]
      &s writestat = [write %plotf_ul% [quote %record%]]
&end

&call lines

/* set variable names to records strings to write to new file

&do index2 = 1 &repeat %index2% + 1 &while [variable line%index2%]
      &sv record = [value line%index2%]
      &sv wstat2 = [write %plotf_ul% [quote %record%]]
&end

/* close arcplot command aml file

&s closestat1 = [close %plotf_ul%]

/* create HP plot file

&call aplot


&s qchp = [query 'View plotfile']

/* check plot file
&if %qchp% &then
  &call chaplot.aml

/* convert gra plot file to postscript file
/* and plot landscape style

   postscript %newfile%.gra %newfile%.ps 0.7

&sv q = [query 'Send this A4 plot to the A4 plotter']

&if %q% &then
   &sys lpr -P psglg4 %newfile%.ps

&return

&end

&routine setuplines
      &s setup1 = mapex %.plotcov%
      &s setup2 = pageunits cm
      &s setup3 = textfont 93715
      &s setup4 = textquality proportional
      &s setup5 = pagesize 29.7 42.0
      &s setup6 = box 1.5 1.5 28.8 41.1
      &s setup7 = maplimits 1.6 1.6 28.7 41.0
      &s setup8 = mapposition cen cen
      &s setup9 = textsize 0.9
/* add more set-up variables below this line (e.g. legends etc)
&return

&routine lines

&s line1 = linecolor 1
&s line2 = arcs /home/egeo17/arc/bmap/ceurc_lcc
&s line3 = linecolor 1
&s line4 = arcs %.plotcov%
&s line5 = move 14.85 39.0
&s line6 = text %plotcov%
&return

&routine aplot

arcplot
disp 1040
%newfile%
&r %newfile%.aml
quit

&return

&routine chaplot.aml
   arcplot
   disp 9999 2
   &r %newfile%.aml
   &sv hit [response 'Hit any key to continue']
   quit
&return
```

```
/* KILLCOVS.AML
/*
/* Kills rose coverages if they exist
/*
/* the values of .qr* are 1 if true and 0 if false
/*
/*         olin.gen - ungenerated line coverage file
/*         lin.gen - ungenerated weeded line coverage file
/* .qr1 - requests rose diagrams where rose length is proportional
/*         to the number of lineations in the grid cell
/*         newlin.gen
/* .qr2 - requests calculation of principal directions from the rose
/*         diagrams of .qr1
/*         prin.gen
/* .qr3 - requests calculation of secondary directions from the rose
/*         diagrams of .qr1
/*         sec.gen
/* .qr4 - requests calculation of rose diagrams where numbers of lineations
/*         are represented by fixed lengths to ensure that all directions
/*         are visible and high numbers in one direction do not cause
/*         lengths which stray into other grid cells
/*         prop.gen
/* .qr5 - requests calculation of representative rose diagrams where the
/*         lengths of all the lineations represented are exactly the same
/*         regardless of the number of lineations in a particular direction
/*         rep.gen
/* .qr6 - requests calculation of the principal direction which will be
/*         plotted as a fixed length to help interpretation of .qr5 diagrams
/*         repprin.gen
/*

&args roscov gcs

/* check that coverages do not already exist and if they
/* do delete them

&if %.qr1% eq 1 &then
   &do
      &if [exists %.rospath1%/%roscov%_%gcs% -cover] &then
          kill %.rospath1%/%roscov%_%gcs%
   &end

&if %.qr2% eq 1 &then
   &do
      &if [exists %.rospath2%/%roscov%_%gcs% -cover] &then
          kill %.rospath2%/%roscov%_%gcs%
   &end

&if %.qr3% eq 1 &then
   &do
      &if [exists %.rospath3%/%roscov%_%gcs% -cover] &then
          kill %.rospath3%/%roscov%_%gcs%
   &end

&if %.qr4% eq 1 &then
   &do
      &if [exists %.rospath4%/%roscov%_%gcs% -cover] &then
          kill %.rospath4%/%roscov%_%gcs%
   &end

&if %.qr5% eq 1 &then
   &do
      &if [exists %.rospath5%/%roscov%_%gcs% -cover] &then
          kill %.rospath5%/%roscov%_%gcs%
   &end

&if %.qr6% eq 1 &then
   &do
      &if [exists %.rospath6%/%roscov%_%gcs% -cover] &then
          kill %.rospath6%/%roscov%_%gcs%
   &end

&return

&end
```

```
/* KILLGEN.AML
/*
/* Kills rose rose generate files
/* if they exist.
/*
/* the values of .qr* are 1 if true and 0 if false
/*
/*        olin.gen - ungenerated line coverage file
/*        lin.gen - ungenerated weeded line coverage file
/* .qr1 - requests rose diagrams where rose length is proportional
/*        to the number of lineations in the grid cell
/*        newlin.gen
/* .qr2 - requests calculation of principal directions from the rose
/*        diagrams of .qr1
/*        prin.gen
/* .qr3 - requests calculation of secondary directions from the rose
/*        diagrams of .qr1
/*        sec.gen
/* .qr4 - requests calculation of rose diagrams where numbers of lineations
/*        are represented by fixed lengths to ensure that all directions
/*        are visible and high numbers in one direction do not cause
/*        lengths which stray into other grid cells
/*        prop.gen
/* .qr5 - requests calculation of representative rose diagrams where the
/*        lengths of all the lineations represented are exactly the same
/*        regardless of the number of lineations in a particular direction
/*        rep.gen
/* .qr6 - requests calculation of the principal direction which will be
/*        plotted as a fixed length to help interpretation of .qr5 diagrams
/*        repprin.gen
/*

&args roscov

/* check that generate files and coverages do not already exist and if they
/* do delete them

&if [exists %.genpath%/olin.gen -file] &then
    &sys rm %.genpath%/olin.gen

&if [exists %.genpath%/lin.gen -file] &then
    &sys rm %.genpath%/lin.gen


&if %.qros% &then
  &do
&if %.qr1% eq 1 &then
   &do
      &if [exists %.genpath1%/r1.gen -file] &then
          &sys rm %.genpath1%/r1.gen
   &end

&if %.qr2% eq 1 &then
   &do
      &if [exists %.genpath2%/r2.gen -file] &then
          &sys rm %.genpath2%/r2.gen
   &end

&if %.qr3% eq 1 &then
   &do
      &if [exists %.genpath3%/r3.gen -file] &then
          &sys rm %.genpath3%/r3.gen
   &end

&if %.qr4% eq 1 &then
   &do
      &if [exists %.genpath4%/r4.gen -file] &then
          &sys rm %.genpath4%/r4.gen
   &end

&if %.qr5% eq 1 &then
   &do
      &if [exists %.genpath5%/r5.gen -file] &then
          &sys rm %.genpath5%/r5.gen
   &end

&if %.qr6% eq 1 &then
   &do
      &if [exists %.genpath6%/r6.gen -file] &then
          &sys rm %.genpath6%/r6.gen
   &end
 &end

&return

&end
```

```
/* linaplot.aml
/*
/* called at various stages from lin.aml to plot the lineations
/* coverage chosen
&amlpath /home/egeo17/arc/glac/lins/aml
&if [variable .qcov] &then
&do
&if %.vcv% &then
&goto start
&end
arcplot
disp 9999
&label start
clear
mapex %.lincov%
linecolor 1
arcs /home/egeo17/arc/bmap/ceurc_lcc
linecolor 3
arcs %.lincov%
&thread &focus &on lin
&return
```

```
/* linden.aml
/*
/* called from lin.aml
/* AML to create Grids of lineation densities for user-defined grid
/* cell sizes gcs.  Uses lin.gen file created by cproslin.aml.
/*
/* Asks for grid cell size gcs
/*
/* call fortran program which calculates an ascii grid file
/* /home/egeo17/arc/glac/lins/linden/linden.asc of lineation
/* densities for cell size gcs
/*
/* creates grid %.newcov%_d from linden.asc file
/*
/* plots grid and background coverages (coastline and lineations)
/*
/* NOT YETdeletes grid on request
/*
/* deletes linden.asc file to clear for next run
/*

&amlpath /home/egeo17/arc/glac/lins/aml

/* extract coverage name for naming density plots

&s .dencov = [entryname %.lincov%]

&setvar GCS [response ' Enter grid cell size for density plots']

&if [exists /home/egeo17/arc/glac/lins/linden/linden.asc] &then
   &sys rm /home/egeo17/arc/glac/lins/linden/linden.asc

&if ^ %.gros% &then
  &do
    &r killgen.aml
    UNGENERATE LINE %.lincov% /home/egeo17/arc/glac/lins/olin.gen

    /* Weed out extra points on lines

    &sys /home/egeo17/arc/glac/lins/progs/wd
  &end

&sv x = [task /home/egeo17/arc/glac/lins/progs/lind %gcs%]
/*&type %x%

/* create and plot new density grid in directory
/* /home/egeo17/arc/glac/lins/linden

&if [exists /home/egeo17/arc/glac/lins/linden/%.dencov%_d -grid] &then
   kill /home/egeo17/arc/glac/lins/linden/%.dencov%_d
asciigrid /home/egeo17/arc/glac/lins/linden/linden.asc /home/egeo17/arc/glac/lins/linden/%.dencov%_d

/* view grid

grid
&if [exists /home/egeo17/arc/glac/lins/linden/m%.dencov%_d -file] &then
killmap /home/egeo17/arc/glac/lins/linden/m%.dencov%_d
map /home/egeo17/arc/glac/lins/linden/m%.dencov%_d

&r gridplot.aml

/* exit grid return to ARC

&pause
quit

&return
```

```
/* rosplot.aml
/*

&args roscov

&amlpath /home/egeo17/arc/glac/lins/aml

/* set variables

&sv gcs = %.gcs% / 1000
&sv rospatha = [value .rospath%.qra%]
&if [variable .qrb] &then
    &sv rospathb = [value .rospath%.qrb%]

/* check whether already in arcplot

&if %.rosaplot% &then
&do
   &if %.rosaplot% &then
     &goto start
&end

/* go into arcplot

arcplot
disp 9999 2
&sv .rosaplot = .true.


&label start

/* clear screen and delete old mapcomposition

clear
  &if [exists %rospatha%/m%roscov% -file] &then
       killmap %rospatha%/m%roscov%

/* open new mapcomposition

map %rospatha%/m%roscov%

/* plot coverages on screen

textfont 93715
textquality proportional
textsize 0.3
move 0.5 0.5
text %roscov%_%gcs%

MAPEX %.lincov%
linecolor 3
arcs %.lincov%
linecolor 1
arcs /home/egeo17/arc/bmap/ceurc_lcc

LINECOLOR 4
ARCS %rospatha%/%roscov%_%gcs%

&if [variable .qrb] &then
  &do
     linecolor 6
     arcs %rospathb%/%roscov%_%gcs%
  &end

&pause

   killmap %rospatha%/m%roscov%

&return

&end
```

```
/* rosquer.aml
/*
/* asks user which rose diagrams they wish to create and sets
/* query variables .qr* to 1 (true) or 0 (false)

&sv qr1 = [query 'Calculate rose diagrams']
&if %qr1% &then
   &sv .qr1 = 1
&else
   &sv .qr1 = 0

&sv qr2 = [query 'Calculate principal directions']
&if %qr2% &then
   &sv .qr2 = 1
&else
   &sv .qr2 = 0

&sv qr3 = [query 'Calculate secondary directions']
&if %qr3% &then
   &sv .qr3 = 1
&else
   &sv .qr3 = 0

&sv qr4 = [query 'Calculate proportioned rose diagrams']
&if %qr4% &then
&sv .qr4 = 1
&else
   &sv .qr4 = 0

&sv qr5 = [query 'Calculate direction representation plots']
&if %qr5% &then
   &sv .qr5 = 1
&else
   &sv .qr5 = 0

&sv qr6 = [query 'Calculate principal representations']
&if %qr6% &then
   &sv .qr6 = 1
&else
   &sv .qr6 = 0

&return

&end
```

```
/* rviewplot.aml
/*
/* called from lin.aml
/* this program creates hard copies of analyses
/* it is called by lin.aml
/* it sets the angle of the plot (portrait or landscape)
/* and the size/type of the plot (a3 colour/a4 b&w)
/* eventually it will be able to plot any combination
/* of any analyses plots including plots created during
/* past sessions.

&amlpath /home/egeo17/arc/glac/lins/aml

&call whichplots

&sv .clr = .true.

&r viewplot.aml
&sv .vcv = .true.

&label viewq
&sv qview = [query 'view further plots']
  &if %qview% &then
   &do
    &call whichplots
    &sv .clr = [query 'Clear Screen']
    &type %.plotcov%
    &r viewplot.aml
    &goto viewq
   &end
  &else
quit

&return

&routine whichplots

/* &s .choice = [getchoice LINEATIONS CLIPPEDLINS DENSITIES ROSE ~
/*PROPORTIONALROSE SECONDARYROSE PRINROSE REPROSE PRINREPROSE -prompt
/*'select the coverage type to plot']

&s .choice = [getchoice LINEATIONS CLIPPEDLINS ROSE ~
PRINROSE SECONDARYROSE PROPORTIONALROSE REPROSE PRINREPROSE  ~
-prompt 'select the coverage type to view']

&type 'Select a coverage to plot'

&if %.choice% = LINEATIONS &then
    &s .plotcov = [getcover /home/egeo17/arc/glac/lins]
/*&if %.choice% = DENSITIES &then
/*    &s .plotcov = [getcover /home/egeo17/arc/glac/lins/linden]
&if %.choice% = ROSE &then
    &s .plotcov = [getcover /home/egeo17/arc/glac/lins/rose/ros1]
&if %.choice% = CLIPPEDLINS  &then
    &s .plotcov = [getcover /home/egeo17/arc/glac/lins/rdclip]
&if %.choice% = PROPORTIONALROSE &then
    &s .plotcov = [getcover /home/egeo17/arc/glac/lins/rose/ros4]
&if %.choice% = SECONDARYROSE &then
    &s .plotcov = [getcover /home/egeo17/arc/glac/lins/rose/ros3]
&if %.choice% = PRINROSE &then
    &s .plotcov = [getcover /home/egeo17/arc/glac/lins/rose/ros2]
&if %.choice% = REPROSE &then
    &s .plotcov = [getcover /home/egeo17/arc/glac/lins/rose/ros5]
&if %.choice% = PRINREPROSE &then
    &s .plotcov = [getcover /home/egeo17/arc/glac/lins/rose/ros6]


/*later additions for clipboxes - n.b. need to save clip boxes in
/*clip.aml

&return
```

```

```

```
/* rnewroslin.aml
/*
/* called from lin.aml
/* (originally cproslin.aml before sec directions were added)
/* AML to create coverages of rose diagrams for user-defined grid cell
/* size using generate and ungenerate and calling a fortran program roslin.for
/*
/* .lincov is the global variable coverage name
/*

&amlpath /home/egeo17/arc/glac/lins/aml

/* extract coverage name for naming rose diagrams

&s roscov = [entryname %.lincov%]

/* find out which rose diagrams user wishes to create

&r rosquer.aml

/* Create generate file for coverages

&call createlin

/* Ask for grid cell size to pass to fortran program
/* get grid cell size from user

&describe %.lincov%
&sv xmin = [round [calc %dsc$xmin% / 1000]]
&sv xmax = [round [calc %dsc$xmax% / 1000]]
&sv ymin = [round [calc %dsc$ymin% / 1000]]
&sv ymax = [round [calc %dsc$ymax% / 1000]]

&type xmin=%xmin% xmax=%xmax% ymin=%ymin% ymax=%ymax%
&type ''

&label gridcellsize

&setvar gcs [response 'Enter grid cell size (km) for rose plots']

&if [null %gcs%] &then
  &goto gridcellsize

&if [type %gcs%] ne -1 &then
   &if [type %gcs%] ne -2 &then
     &goto gridcellsize

/* check that grid cell size is not below the limit

&sv xmaxgrid = [calc %xmax% - %xmin%]
&sv ymaxgrid = [calc %ymax% - %ymin%]
&sv maxgrid = [max %xmaxgrid% %ymaxgrid%]

&if [calc %maxgrid% / 200] gt %gcs% &then
  &do
     &type 'WARNING: The gridcell size cannot be bigger than max-min/200'
     &type ''
     &goto gridcellsize
  &end

&sv .gcs = [calc %gcs% * 1000]

/* check that grid cell size is not ridiculously big

&if %gcs% ge 1000 &then
 &do
  &type 'WARNING: gridcellsize too big'
  &goto gridcellsize
 &end

&sv gcs = [round %gcs%]

/* create rose diagram coverages

&call createcovs

&s qplotcov = [query 'View rose diagrams']

/* plot coverages of rose diagrams and lineations and backgrounds
&if %qplotcov% &then
&call plotcovs

&return

&end


&routine createlin

&r killgen.aml %roscov%

UNGENERATE LINE %.lincov% %.genpath%/olin.gen

/* Weed out extra points on lines

      &sys %.forpath%/wd


&return

&routine createcovs

&r killcovs.aml %roscov% %gcs%

&sv .qs = [query 'Plot using large rose diagram units']

/* Call fortran program to create rose diagram generate files

&if %.qs% &then

      &sv x = [task %.forpath%/bros [quote %.gcs% %.qr1% %.qr2% ~
%.qr3% %.qr4% %.qr5% %.qr6%]]


&else

      &sv x = [task %.forpath%/ros [quote %.gcs% %.qr1% %.qr2% ~
%.qr3% %.qr4% %.qr5% %.qr6%]]

      /* Create and plot new rose diagram coverages in directory
      /* /home/egeo17/arc/glac/lins/rose/ros*

 &if %.qr1% eq 1 &then
   &do
      GENERATE %.rospath1%/%roscov%_%gcs%
      INPUT %.genpath1%/r1.gen
      LINES
      QUIT
  &end
&if %.qr2% eq 1 &then
  &do
      GENERATE %.rospath2%/%roscov%_%gcs%
      INPUT %.genpath2%/r2.gen
      LINES
      QUIT
  &end
&if %.qr3% eq 1 &then
  &do
      GENERATE %.rospath3%/%roscov%_%gcs%
      INPUT %.genpath3%/r3.gen
      LINES
      QUIT
```

```
   &end
 &if %.qr4% eq 1 &then
   &do
       GENERATE %.rospath4%/%roscov%_%gcs%
       INPUT %.genpath4%/r4.gen
       LINES
       QUIT
   &end
 &if %.qr5% eq 1 &then
   &do
       GENERATE %.rospath5%/%roscov%_%gcs%
       INPUT %.genpath5%/r5.gen
       LINES
       QUIT
   &end
 &if %.qr6% eq 1 &then
    &do
       GENERATE %.rospath6%/%roscov%_%gcs%
       INPUT %.genpath6%/r6.gen
       LINES
       QUIT
   &end


&return

&routine plotcovs

/* plot rose diagrams and principle directions

&sv .rosaplot = .false.

&if %.qr1% eq 1 &then
&do
  &sv .qra = 1
  &if %.qr2% eq 1 &then
    &sv .qrb = 2
  &r rosplot.aml %roscov%
  &dv .qra
  &if [variable .qrb] &then
    &dv .qrb
&end

/* plot secondary directions
&if %.qr3% eq 1 &then
&do
  &sv .qra = 3
  &r rosplot.aml %roscov%
  &dv .qra
&end

/* plot rose diagrams proportional to lineations per cell
&if %.qr4% eq 1 &then
&do
  &sv .qra = 4
  &r rosplot.aml %roscov%
  &dv .qra
&end

/* plot representational rose diagrams and principle directions

&if %.qr5% eq 1 &then
&do
  &sv .qra = 5
  &if %.qr6% eq 1 &then
    &sv .qrb = 6
  &r rosplot.aml %roscov%
  &dv .qra
  &if [variable .qrb] &then
  &dv .qrb
&end
```

```

quit
&sv .vcv = .false.

&return

&end
```

```
/* setpaths.aml
/*
/* sets all the path names for the coverages, programs and files
/* any changes to path names for relocation of output or input should
/* be made here

/* set path names for the lineations

&sv .linpath = /home/egeo17/arc/glac/lins

/* set path names for basemap

&sv .basepath = /home/egeo17/arc/bmap

/* set path names for the rose coverages

&sv .rospath1 = /home/egeo17/arc/glac/lins/rose/ros1
&sv .rospath2 = /home/egeo17/arc/glac/lins/rose/ros2
&sv .rospath3 = /home/egeo17/arc/glac/lins/rose/ros3
&sv .rospath4 = /home/egeo17/arc/glac/lins/rose/ros4
&sv .rospath5 = /home/egeo17/arc/glac/lins/rose/ros5
&sv .rospath6 = /home/egeo17/arc/glac/lins/rose/ros6

/* set path names for the rose diagram generate files

&sv .genpath = /home/egeo17/arc/glac/lins
&sv .genpath1 = /home/egeo17/arc/glac/lins/rose/ros1
&sv .genpath2 = /home/egeo17/arc/glac/lins/rose/ros2
&sv .genpath3 = /home/egeo17/arc/glac/lins/rose/ros3
&sv .genpath4 = /home/egeo17/arc/glac/lins/rose/ros4
&sv .genpath5 = /home/egeo17/arc/glac/lins/rose/ros5
&sv .genpath6 = /home/egeo17/arc/glac/lins/rose/ros6

/* set path names for the fortran programs

&sv .forpath = /home/egeo17/arc/glac/lins/progs

/* set path names for lineation density coverages

&sv .denpath = /home/egeo17/arc/glac/lins/linden

/* set path names for lineation density ascii file

&sv .ascpath = /home/egeo17/arc/glac/lins/linden

/* set clipped cover pathname

&sv .clippedpath = /home/egeo17/arc/glac/lins/rdclip

/* make anymore path additions below this line
/* ------------------------------------------------------------

&return

&end
```

```
/* viewplot.aml
/*
/* called at various stages from lin.aml to plot the lineations
/* coverage chosen

&amlpath /home/egeo17/arc/glac/lins/aml



&if %.vcv% &then
&goto start
&else
&sv .colindex = 1

arcplot
disp 9999

&label start


&if ^ %.clr% &then
&goto overlay

clear
mapex %.plotcov%
linecolor 1
arcs /home/egeo17/arc/bmap/ceurc_lcc

&label overlay
/*arcs %.plotcov%
&sv .colindex = [calc %.colindex% + 1]

linecolor %.colindex%
&type %.plotcov%
/*&type %.colindex%
arcs %.plotcov%

&return
```

```
mapex /home/egeol7/arc/glac/lins/rdclip/cross
pageunits cm
textfont 93715
textquality proportional
pagesize 29.7 42.0
box 1.5 1.5 28.8 41.1
maplimits 1.6 1.6 28.7 41.0
mapposition cen cen
textsize 0.9
linecolor 1
arcs /home/egeol7/arc/bmap/ceurc_lcc
linecolor 1
arcs /home/egeol7/arc/glac/lins/rdclip/cross
move 14.85 39.0
text cross
```

```
&r setpaths.aml
&sv roscov = test
&sv gcs = 1
&r killcovs.aml %roscov% %gcs%

      GENERATE %.rospath1%/%roscov%_%gcs%
      INPUT %.genpath1%/r1.gen
      LINES
      QUIT

      GENERATE %.rospath2%/%roscov%_%gcs%
      INPUT %.genpath2%/r2.gen
      LINES
      QUIT

      GENERATE %.rospath3%/%roscov%_%gcs%
      INPUT %.genpath3%/r3.gen
      LINES
      QUIT

      GENERATE %.rospath4%/%roscov%_%gcs%
      INPUT %.genpath4%/r4.gen
      LINES
      QUIT

      GENERATE %.rospath5%/%roscov%_%gcs%
      INPUT %.genpath5%/r5.gen
      LINES
      QUIT

      GENERATE %.rospath6%/%roscov%_%gcs%
      INPUT %.genpath6%/r6.gen
      LINES
      QUIT

&sv .qr1 = 1
&sv .qr2 = 2
&sv .qr3 = 3
&sv .qr4 = 4
&sv .qr5 = 5
&sv .qr6 = 6

/* plot rose diagrams and principle directions

&sv .rosaplot = .false.

&if %.qr1% eq 1 &then
&do
  &sv .qra = 1
  &if %.qr2% eq 1 &then
    &sv .qrb = 2
  &r rosplot.aml %roscov%
  &dv .qra
  &if [variable .qrb] &then
    &dv .qrb
&end

/* plot secondary directions
&if %.qr3% eq 1 &then
&do
  &sv .qra = 3
  &r rosplot.aml %roscov%
  &dv .qra
&end

/* plot rose diagrams proportional to lineations per cell
&if %.qr4% eq 1 &then
&do
  &sv .qra = 4
  &r rosplot.aml %roscov%
  &dv .qra
&end

/* plot representational rose diagrams and principle directions

&if %.qr5% &then
&do
  &sv .qra = 5
  &if %.qr6% eq 1 &then
    &sv .qrb = 6
  &r rosplot.aml %roscov%
  &dv .qra
  &if [variable .qrb] &then
  &dv .qrb
&end

&return

&end
```

```
arcplot
disp 9999 2
mapex /home/egeo17/arc/glac/lins/work/shore/f27shr_lcc
image /home/egeo17/arc/glac/lins/f27img_lcc
linecolor 2
arcs /home/egeo17/arc/glac/lins/f27l_lcc
```

```
      PROGRAM ROSLIN
C
C Last edited 14/11/94
C
C  This program and its subroutines ZERO3D, WHGC, CALDIRB,
C  creates a generate file R1.GEN of rose diagrams for a coverage
C  from a generate file LIN.GEN (which is created by the aml which runs this)
C  for grid squares according to user input grid cell size DG.
C  also creates files R2.GEN R3.GEN R4.GEN R5.GEN R6.GEN
c
c  found in directories /home/egeo17/arc/glac/lins/rose/r*/r*.gen
c
C  which are principal directions, secondary directions, proportional
C  rose diagrams, representational rose diagrams and principle directions
C  of the representational rose diagrams respectively, on request from AML
C
C This program is called by /home/egeo17/arc/glac/lins/aml/roslin.aml
C
c . receives variables grid cell size dg, and rose requests r1->6 from
c   AML.
c . reads lines from lin.gen
c . calculates grid origins and dimensions of grid
c . assigns values to 3-d array v(x,y,z)
c - calculates which grid cell a line is in - assigns x,y
c - calculates what direction the line is in - assigns z
c - adds 1 to V for each line in a particular cell and direction
c
c   R1 = 1
c   do loop to calculate rose diagram coordinates for each v(x,y,z)
c   and write coordinates to an output generate file
c
c   R2 = 1
c   call maxv
c   - calculate prinv(x,y,maxz) - array of maximum directions for each cell
c   calculate coords and write to generate file (call rose, call writegen)
c
c   R3 = 1
c   call maxv
c   - sets all principal directions of v(x,y,z) to sec(x,y,z) = 0
c   and the rest of v(x,y,z) to sec(x,y,z) = v(x,y,z) and sets non-principle
c   directions, and directions within 5 degrees of the principle
c   directions to zero - prinv(x,y,maxz-1/maxz/maxz+1)
c   calculates coords and writes to a generate file (call rose, call writegen)
c
c   R4 = 1
c   - classifies V(x,y,z) into bands Vband(x,y,z)
c   there are 4 of these bands and the values v are scaled according to
c   the number of lineations in the maximum direction for that cell vmax(x,y)
c   then the value of V becomes Vband depending on the original value of V
c
c   R5 = 1
c   - sets all non-zero values of V(x,y,z) to VREP(x,y,z)=1
c
c   R6 = 1
c   - sets all non-principal directions z .ne. zmax for v(x,y,z)
c   to VPRINREP(x,y,z) = 0
c
c
      IMPLICIT NONE

      INTEGER NZ, NX, NY, ID, DIR, XN, YN, ZN, X, Y, Z,
     +   MAXZ, COUNT, PRINV, VMAX, REPV, PRINREPV,
     +   VBAND, MAXZ, RESULT

      PARAMETER (NX = 100 , NY = 100 , NZ = 36, ZN = 36)

      INTEGER V(NX,NY,NZ), SEC(NX, NY, NZ), PRINV(NX, NY, NZ),
     +   VBAND(NX, NY, NZ), VMAX(NX, NY), PRINREPV(NX, NY, NZ),
     +   REPV(NX, NY, NZ)

      REAL*8 LX1, LX2, LY1, LY2, GCX, GCY, PR1, PR2, PR3,
     +   RX, RY, DG, GXO, GYO,
     +   REX, REY, PR4, PR5, PR6

      CHARACTER E
      INTEGER R1, R2, R3, R4, R5, R6
      CHARACTER*80 FNAME
      PARAMETER (PR1 = 300.0, PR2 =300.0 , PR3 = 1000.0)

C Get grid cell size DG from user

      READ (5,*) DG, R1, R2, R3, R4, R5, R6

C Set units for rose diagram lengths

      PR4 = 0.125 * DG
      PR5 = 0.35 * DG
      PR6 = 0.35 * DG


C Set all V(XYZ) to zero

      CALL ZERO3D(V, NX, NY, NZ)

C Calculate Grid origin and number of grid cells in X and Y

      CALL GRIDOR(DG, GXO, GYO, XN, YN)

C Open old lineations file

      OPEN (UNIT=10, STATUS='OLD',
     +  FILE='/home/egeo17/arc/glac/lins/lin.gen')

      COUNT=1

C Beginning of grid calculation loop
C Read a lineation from old generate file LIN.GEN


30    READ (10, *, ERR = 20, END = 20) ID

      READ (10, *, ERR = 20, END = 20) LX1, LY1

      READ (10, *, ERR = 20, END = 20) LX2, LY2

      READ (10, '(A)',ERR = 20, END = 20) E

      COUNT = COUNT+1

C ZERO X AND Y

      X = 0
      Y = 0
      Z = 0

C calculate which grid square lineation is in. Assign X & Y


              CALL WHGC (LX1, LY1, LX2, LY2, X, Y,
     +          GXO, GYO, DG)

C calculate direction and direction band.  Assign Z

              CALL CALDIRB (DIR, Z, LX1, LY1, LX2, LY2)

C count number of lineations for grid cell  X,Y in direction Z

              V(X,Y,Z) = V(X,Y,Z) + 1

C return to start of loop and read next line from LIN.GEN

          GOTO 30
```

```
C end of file, no more points to read continue from here

20      CLOSE (10)

C-------------------------------------------------------------------
C  R1
C-------------------------------------------------------------------

        IF (R1 .EQ. 0) THEN
                GOTO 100
        END IF

C Open new generate file for output of rose diagrams

        OPEN (UNIT=11, STATUS='NEW',
     +    FILE='/home/egeo17/arc/glac/lins/rose/ros1/r1.gen')

        ID = 1

C Do loops for calculating coordinates for rose diagrams
C and writing generate file for them using V(X,Y,Z)

        DO X = 1, XN
            DO Y= 1, YN
                DO Z= 1, ZN

C check if there is any data for this grid cell and direction

                    IF (V(X,Y,Z) .NE. 0) then

C Calculate GCX,GCY coordinate of grid centres

                    CALL GRIDCEN (GXO, GYO, DG, GCX, GCY, X, Y)

C Calculate RX and RY coordinates for rose diagrams

                    CALL ROSE (PR1, V, X, Y, Z, GCX, GCY, RX, RY,
     +                REX, REY, NX, NY, NZ)

C Increment ID by one

                    ID = ID + 1

C Write ID, GCX, GCY, RX, RY to R1.GEN

                    CALL WRITEGEN (ID, GCX, GCY,
     +                RX, RY, REX, REY)

                    END IF

                END DO
            END DO
        END DO
                        WRITE(11,'(A)')'END'
                        CLOSE(11)

C------------------------------------------------------------------------
C   R2
C------------------------------------------------------------------------

100     IF (R2 .EQ. 0) THEN
                GOTO 200
        END IF

c  open new generate file r2.gen

        FNAME = '/home/egeo17/arc/glac/lins/rose/ros2/r2.gen'
        OPEN (UNIT = 11, STATUS = 'NEW', FILE = FNAME)


        CALL ZERO3D (PRINV, NX, NY, NZ)

        CALL ZERO2D (VMAX, NX, NY)


        CALL MAXV (V, X, Y, Z, NX, NY, NZ, XN, YN, ZN,
     +          MAXZ, VMAX, PRINV)


        ID = 1

c       do loops for calculating coordinates for rose diagrams
c       and writing generate file for them using v(x,y,z)


        DO X = 1, XN
            DO Y = 1, YN
                DO Z = 1, ZN

c       check if there is any data  for this grid cell and direction

                IF (PRINV(X,Y,Z) .NE. 0) THEN

c       calculate gcx, gcy coordinate of grid centres

                    CALL GRIDCEN (GXO, GYO, DG, GCX, GCY, X, Y)

c       create rose diagram generate file

                    CALL ROSE (PR2, PRINV, X, Y, Z, GCX, GCY,
     +             RX, RY, REX, REY, NX, NY, NZ)

c       write id,gcx,gcy,rx,ry to R2.gen

                    CALL WRITEGEN (ID, GCX, GCY, RX, RY, REX, REY)

                ENDIF

c       increment ID by I

                ID = ID + 1

                END DO
            END DO
        END DO

        WRITE (11, '(A)') 'END'
        CLOSE(11)


C-----------------------------------------------------------------------
C    R3
C-----------------------------------------------------------------------

200     IF (R3 .EQ. 0) THEN
                GOTO 300
        END IF

c       run maxv if it hasn't been run before

        IF (R2 .EQ. 0) THEN
                CALL MAXV( V, X, Y, NX, NY, NZ, XN, YN, ZN,
     +                  MAXZ, VMAX, PRINV)

        END IF


        CALL ZERO3D (SEC, NX, NY, NZ)

        CALL SECV(V, X, Y, Z, PRINV, SEC, NX, NY, NZ)

```

```
        FNAME = '/home/egeol7/arc/glac/lins/rose/ros3/r3.gen'
        OPEN (UNIT = 11, STATUS = 'NEW', FILE = FNAME)

        ID = 1

C Do loops for calculating coordinates for rose diagrams
C and writing generate file for them using SEC(X,Y,Z)


        DO X = 1, XN

                DO Y = 1, YN

                        DO Z = 1, ZN

                                IF (SEC(X, Y, Z) .NE. 0) THEN

                                        CALL GRIDCEN (GXO, GYO, DG, GCX,
     +                                          GCY, X, Y)

                                        CALL ROSE(PR3, SEC, X, Y, Z,
     +                                  GCX, GCY, RX, RY, REX, REY, NX, NY, NZ)

                                        CALL WRITEGEN (ID, GCX, GCY,
     +                                  RX, RY, REX, REY)


                                        ID = ID + 1

                                END IF
                        END DO

                END DO

        END DO

                       WRITE(11,'(A)')'END'
                        CLOSE(11)


C------------------------------------------------------------------------
C    R4
C------------------------------------------------------------------------

300     IF (R4 .EQ. 0) THEN
               GOTO 400
        END IF

        IF (R2 .EQ.0) THEN

                CALL ZERO2D (MAXV, NX, NY, NZ)

                CALL MAXV ( V, X, Y, NX, NY, NZ, XN, YN, ZN,
     +                  MAXZ, VMAX, PRINV)
        END IF

        CALL ZERO3D (VBAND, NX, NY, NZ)

C Open new generate file for output of rose diagrams

        FNAME = ('/home/egeol7/arc/glac/lins/rose/ros4/r4.gen')
        OPEN (UNIT = 11, STATUS = 'NEW', FILE = FNAME)

C set arrays of bandv to fixed values according to total number of
c lineations in each grid cell

        CALL BANDV(V, X, Y, Z, VMAX, VBAND, NX, NY, NZ, XN, YN, ZN)

                        ID = 1

        DO X = 1, XN

                DO Y = 1, YN

                        DO Z = 1, ZN

C check if there is any data for this grid cell and direction

                            IF (VBAND(X,Y,Z) .NE. 0) THEN

C Calculate GCX,GCY coordinate of grid centres

                        CALL GRIDCEN (GXO, GYO, DG, GCX, GCY, X, Y)

C Calculate RX and RY coordinates for rose diagrams

                        CALL ROSE (PR4, VBAND, X, Y, Z, GCX, GCY, RX,
     +                RY, REX, REY, NX, NY, NZ)

C Write ID, GCX, GCY, RX, RY to R1.GEN

                        CALL WRITEGEN (ID, GCX, GCY,
     +                RX, RY, REX, REY)

                        ID = ID + 1

                        END IF

                        END DO

                END DO

        END DO
                        WRITE(11,'(A)')'END'
                        CLOSE(11)


C------------------------------------------------------------------------
C    R5
C------------------------------------------------------------------------

400     IF (R5 .EQ. 0) THEN
                GOTO 500
        END IF

        CALL ZERO3D (REPV, NX, NY, NZ)


        FNAME = '/home/egeol7/arc/glac/lins/rose/ros5/r5.gen'
        OPEN (UNIT = 11, STATUS = 'NEW', FILE = FNAME)

        ID = I

        DO X = 1, XN

                DO Y = 1, YN

                        DO Z = 1, ZN

                                IF (V(X,Y,Z) .NE. 0) THEN
                                        REPV(X,Y,Z) = 1

C Calculate GCX,GCY coordinate of grid centres

                                CALL GRIDCEN (GXO, GYO, DG,
     +                                  GCX, GCY, X, Y)

C Calculate RX and RY coordinates for rose diagrams

                 CALL ROSE (PR5, REPV, X, Y, Z,
     +           GCX, GCY, RX, RY, REX, REY, NX, NY, NZ)

```

```
C Write ID, GCX, GCY, RX, RY to R1.GEN

                         CALL WRITEGEN (ID, GCX, GCY,
      +                RX, RY, REX, REY)

C Increment ID by one

                         ID = ID + 1


                     END IF

                         END DO

                END DO

        END DO

                        WRITE(11,'(A)')'END'
                        CLOSE(11)

C--------------------------------------------------------------------------
C    R6
C--------------------------------------------------------------------------


500     IF (R6 .EQ. 0) THEN
                GOTO 600
        END IF

c       run maxv if it hasn't been run before

        IF (R2 .EQ. 0) THEN
                CALL MAXV( V, X, Y, NX, NY, NZ, XN, YN, ZN,
     +                  MAXZ, VMAX, PRINV)

        END IF

        FNAME = '/home/egeo17/arc/glac/lins/rose/ros6/r6.gen'
        OPEN (UNIT = 11, STATUS = 'NEW', FILE = FNAME)

        ID = 1

        DO X = 1, XN

                DO Y = 1, YN

                        DO Z = 1, ZN

                                IF (PRINV(X,Y,Z) .NE. 0) THEN
                                        PRINREPV(X,Y,Z) = 1
                                ELSE
                                        PRINREPV(X,Y,Z) = 0
                                END IF

                        ID = ID + 1

                        IF (PRINREPV(X,Y,Z) .NE. 0) THEN

C Calculate GCX,GCY coordinate of grid centres

                           CALL GRIDCEN (GXO, GYO, DG, GCX, GCY, X, Y)

C Calculate RX and RY coordinates for rose diagrams

                           CALL ROSE (PR6, PRINREPV, X, Y, Z, GCX,
     +                          GCY, RX, RY, REX, REY, NX, NY, NZ)

C Write ID, GCX, GCY, RX, RY to R1.GEN

                           CALL WRITEGEN (ID, GCX, GCY,
     +                        RX, RY, REX, REY)

C Increment ID by one

                            ID = ID + 1

                        END IF

                END DO

             END DO

        END DO

                        WRITE(11,'(A)')'END'
                        CLOSE(11)


600     RESULT=1
        WRITE(0,*) RESULT
        CALL EXIT(0)
        END
```

```
      SUBROUTINE BANDV(V, X, Y, Z, VMAX, VBAND, NX, NY, NZ, XN, YN, ZN)

C
C SUBROUTINE to calculate band values for proportional rose diagram
C plots
C

      IMPLICIT NONE

      INTEGER V, VMAX, VBAND, X, Y, Z, VBAND1, VBAND2, VBAND3,
     +        VBAND4, NX, NY, NZ, XN, YN, ZN
      INTEGER V(NX, NY, NZ), VMAX(NX, NY), VBAND(NX,NY,NZ)


       DO X = 1, XN

              DO Y = 1, YN

                     VBAND1 = 0.25 * VMAX(X,Y)
                     VBAND2 = 0.5 * VMAX(X,Y)
                     VBAND3 = 0.75 * VMAX(X,Y)
                     VBAND4 = VMAX(X,Y)

                     DO Z = 1, ZN

                            IF (V(x,y,z) .eq. 0) then
                                   VBAND(X, Y, Z) = 0
                                   GOTO 10
                            END IF

                            IF (V(X,Y,Z) .LT. VBAND1) THEN
                                   VBAND(X,Y,Z) = 1
                            ELSE IF (V(X,Y,Z) .LT. VBAND2) THEN
                                   VBAND(X,Y,Z) = 2
                            ELSE IF (V(X,Y,Z) .LT. VBAND3) THEN
                                   VBAND(X,Y,Z) = 3
                            ELSE
                                   VBAND(X,Y,Z) = 4
                            END IF

10                          CONTINUE


                     END DO

              END DO

      END DO

      RETURN

      END
```

```
      SUBROUTINE CALDIRB(DIR, Z, LX1, LY1, LX2, LY2)

C Program to calculate the direction of lineation and the direction
C band to which it should be assigned
c
c 0-4.999 deg => z=1, 5-9.999 deg => z=2, ... ,
c 85.0-89.999 deg => z=18, 90-94.999 deg => z=19, 175-179.999 => z=36
c
c       calculation formula is:  Z = zdir/5 + 1 (where Z is an integer)
c
        IMPLICIT NONE

        REAL*8 DIR, LX1, LY1, LX2, LY2, DX, DY, PI, RADIR, FDIR
        PARAMETER (PI = 3.1415927)
        INTEGER Z


        DX = ABS(LX2-LX1)

        DY = ABS(LY2-LY1)

        IF (((LX1 .LT. LX2) .AND. (LY1 .GT. LY2))
     +     .OR. ((LX1 .GT. LX2) .AND. (LY1 .LT. LY2))) THEN

               RADIR = ATAN(DX/DY)

               FDIR = RADIR*(180/PI)

               DIR = 180 - FDIR

               Z = (DIR/5) + 1

        ELSE IF (LY1 .EQ. LY2) THEN

               DIR = 90

               Z = (DIR/5) + 1
       ELSE IF (LX1 .EQ. LX2) THEN

               Z = 1

        ELSE
               RADIR = ATAN(DX/DY)

               DIR = RADIR*(180/PI)

               Z = (DIR/5) + 1

        ENDIF

        RETURN

        END
```

```
      SUBROUTINE GRIDCEN(GXO, GYO, DG, GCX, GCY, X, Y)

C to work out the centre coordinates (GCX, GCY) of each grid cell for
C given X and Y (X=rows, Y=columns)

      IMPLICIT NONE

      REAL*8 GXO, GYO, DG, GCX, GCY
      INTEGER X, Y


      GCX = GXO + (X*DG - 0.5*DG)


      GCY = GYO + (Y*DG - 0.5*DG)


      RETURN
      END
```

```
      SUBROUTINE GRIDOR(DG, GXO, GYO, XN, YN)

C Calculates the grid origin and number of grid cells in the X and Y
C directions

      IMPLICIT NONE

      INTEGER XN, YN
      REAL*8 DG, GXO, GYO, GXMAX, GXMIN, GYMAX, GYMIN

C Find maximum and minimum values from generate file

      CALL MAXMINLIN(GXMAX, GXMIN, GYMAX, GYMIN)

C Work out number of cells in X and Y directions


      XN = ((GXMAX - GXMIN)/DG)+1

      YN = ((GYMAX - GYMIN)/DG)+1

C Assign values for grid origin

      GXO = GXMIN

      GYO = GYMIN

      RETURN

      END
```

```
      SUBROUTINE MAXMINLIN(GXMAX, GXMIN, GYMAX, GYMIN)
C
C finds max and min coords of area for grid creation
C

      IMPLICIT NONE

      REAL*8 GXMIN, GXMAX, GYMIN, GYMAX, lx, ly
      CHARACTER E
      INTEGER COUNT, ID, MCOUNT, FCOUNT
      PARAMETER (MCOUNT = 500 000)
      REAL*8 LCX(MCOUNT), LCY(MCOUNT)

C
C Open up I/O files
C
      GXMIN = 99E32
      GYMIN = 99E32
      GXMAX = -99E32
      GYMAX = -99E32

      OPEN (10, STATUS='OLD',
     +  FILE='/home/egeo17/arc/glac/lins/lin.gen',
     +          ERR=9999)

      COUNT = 1


30    READ (10, *, ERR = 20, END = 20) ID

      READ (10, *, ERR = 20, END = 20) LCX(COUNT), LCY(COUNT)

      READ (10, *, ERR = 20, END = 20) LCY(COUNT + 1), LCY(COUNT+1)

      READ (10, '(A)',ERR = 20, END = 20) E

      COUNT=COUNT+2
      FCOUNT = COUNT
      GOTO 30

20    CONTINUE

      COUNT = 0

      FCOUNT = FCOUNT - 1

100   CONTINUE

      IF (COUNT .EQ. FCOUNT) THEN
              GOTO 200
      END IF

      COUNT = COUNT + 1

      LX = LCX(COUNT)
      LY = LCY(COUNT)

      IF (LX .GT. GXMAX) THEN
          GXMAX = LX
      ENDIF

      IF (LX .LE. GXMIN) THEN
          GXMIN = LX
      ENDIF

      IF (LY .GT. GYMAX) THEN
          GYMAX = LY
      ENDIF

      IF (LY .LE. GYMIN) THEN
          GYMIN = LY
      ENDIF

      GOTO 100

200   CONTINUE

9999  CLOSE (10)

      CONTINUE
      RETURN
      END

```

```
        SUBROUTINE MAXV (V, X, Y, Z, NX, NY, NZ, XN, YN, ZN,
     +          MAXZ, VMAX, PRINV)


C Calculates maximum number of lineations in a particular gridcell
C and creates a 2-d array vmax(x,y) of these maximum values for each
C grid cell and a 3-d array prinv(x,y) of principle directions and maximum
C values for each grid cell.

        IMPLICIT NONE

        INTEGER NX, NY, NZ, X, Y, Z, XN, YN, ZN
        INTEGER VMAX, MAXZ, PRINV, V
        INTEGER PRINV(NX, NY, NZ), VMAX(NX, NY), V(NX, NY, NZ)

        DO X = 1, XN

                DO Y = 1, YN

                        DO Z = 1, ZN

                                IF (Z .EQ. 1) THEN

                                        VMAX(X,Y) = 0
                                        MAXZ = 1

                                END IF



                                IF (V(X,Y,Z) .GT. VMAX(X,Y)) THEN

                                        VMAX(X,Y) = V(X,Y,Z)
                                        MAXZ = Z

                                ENDIF


                                IF (Z .NE. ZN) THEN
                                        GOTO 10
                                ELSE
                                        PRINV(X,Y,MAXZ) = V(X,Y,MAXZ)
                                END IF

10                              CONTINUE


                        END DO

                END DO

        END DO


        RETURN

        END
```

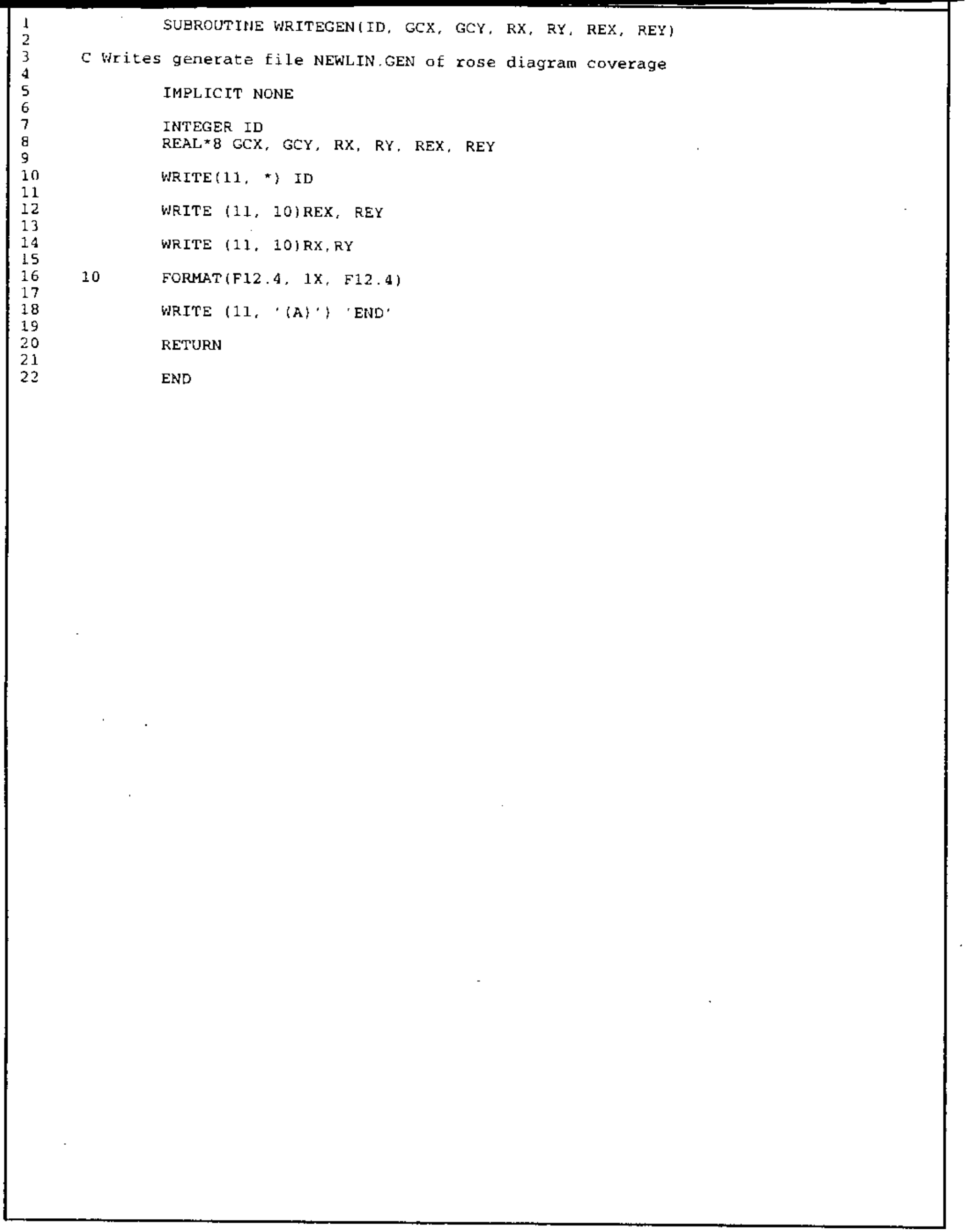
```
        SUBROUTINE PRINLIN(V, X, Y, Z, XN, YN, ZN, GXO, GYO, DG)
c
c
c       This subroutine selects the principle lineations and creates a
c       generate file of these lineations which plot as rose diagrams
c       It calls subroutine rose to create the rose diagram generate file
c       and zero3d to zero the 3 dimensional array of principle directions

        IMPLICIT NONE

        REAL*8 GCX, GCY, RX, RY, REX, REY, GXO, GYO, DG
        INTEGER X, Y, Z, XN, YN, ZN, ID, VMAX, V, PRINV,
     +          NX, NY, NZ
        PARAMETER (NX = 200, NY = 200, NZ = 36)
        INTEGER V(NX, NY, NZ), PRINV(NX, NY, NZ), VMAX(NX, NY)
        CHARACTER*80 FNAME

c       calculate principle directions for each grid cell X,Y

c       zero all prinv(x,y,z)

        CALL ZERO3D(PRINV, NX, NY, NZ)

        DO X = 1, NX

                VMAX(X,Y) = 0

           DO Y = 1, NY

                VMAX(X,Y) = 0

                DO Z = 1, NZ

                IF (V(X,Y,Z) .GT. VMAX(X,Y)) THEN
                        GOTO 10
                END IF

        GOTO 20

10      VMAX(X,Y) = V(X,Y,Z)

        PRINV(X,Y,Z) = V(X,Y,Z)

20      CONTINUE

                END DO
           END DO
        END DO

c       write coordinates to lineation generate file prin.gen

        FNAME = '/home/egeol7/arc/glac/lins/rose/prin.gen'
        OPEN (11, STATUS = 'NEW', FILE = FNAME)

        ID = 1

c       do loops for calculating coordinates for rose diagrams
c       and writing generate file for them using v(x,y,z)

        DO X = 1, XN
                DO Y = 1, YN
                        DO Z = 1, ZN

c       check if there is any data  for this grid cell and direction

        IF (PRINV(X,Y,Z) .NE. 0) THEN

c       calculate gcx, gcy coordinate of grid centres

        CALL GRIDCEN (GXO, GYO, DG, GCX, GCY, X, Y)

c       create rose diagram generate file

        CALL ROSE(PRINV, X, Y, Z, GCX, GCY,
     +  RX, RY, REX, REY, NX, NY, NZ)

c       increment ID by 1

        ID = ID + 1

c       write id,gcx,gcy,rx,ry to prin.gen

        CALL WRITEGEN (ID, GCX, GCY, RX, RY, REX, REY)

                    END IF
                END DO
            END DO
        END DO

        WRITE (11, '(A)') 'END'
        CLOSE (11)

        RETURN

        END
```

```
      SUBROUTINE ROSE (p, V, X, Y, Z, GCX, GCY,
     +  RX, RY, REX, REY, NX, NY, NZ)

C To calculate the coordinates for the end of the line for each part
C of the rose diagram for given X and Y (X=columns, Y=rows)
C P is the unit length of the line for one lineation in a particular
C direction on the rose diagram

      IMPLICIT NONE

      REAL*8 RDIR, GCX, GCY, P, ZDIR, DRX, DRY, RX, RY,
     +   PI, REX, REY
      INTEGER X, Y, Z, NX, NY, NZ
      PARAMETER (ZDIR = 5.0, PI = 3.1415927)
      INTEGER V(NX, NY, NZ)

C Convert Z value to an angle RDIR

      RDIR = ZDIR*Z - 2.5


C Calculate distance in X and Y (DRX, DRY) from centre of grid cell
C and end coordinates RX and RY of lines for rose diagram
C and to work out other end of rose diagrams rex and rey


         IF (Z .LT. 19) THEN

            DRX = P*V(X,Y,Z)*SIN((PI/180)*RDIR)
            DRY = P*V(X,Y,Z)*COS((PI/180)*RDIR)


            RX = GCX + DRX
            RY = GCY + DRY

            REX = GCX - DRX
            REY = GCY - DRY

         ELSE

            RDIR = RDIR - 90


            DRX = P*V(X,Y,Z)*COS((PI/180)*RDIR)
            DRY = P*V(X,Y,Z)*sin((PI/180)*RDIR)

            RX = GCX + DRX
            RY = GCY - DRY

            REX = GCX - DRX
            REY = GCY + DRY

         ENDIF


      RETURN

      END
```

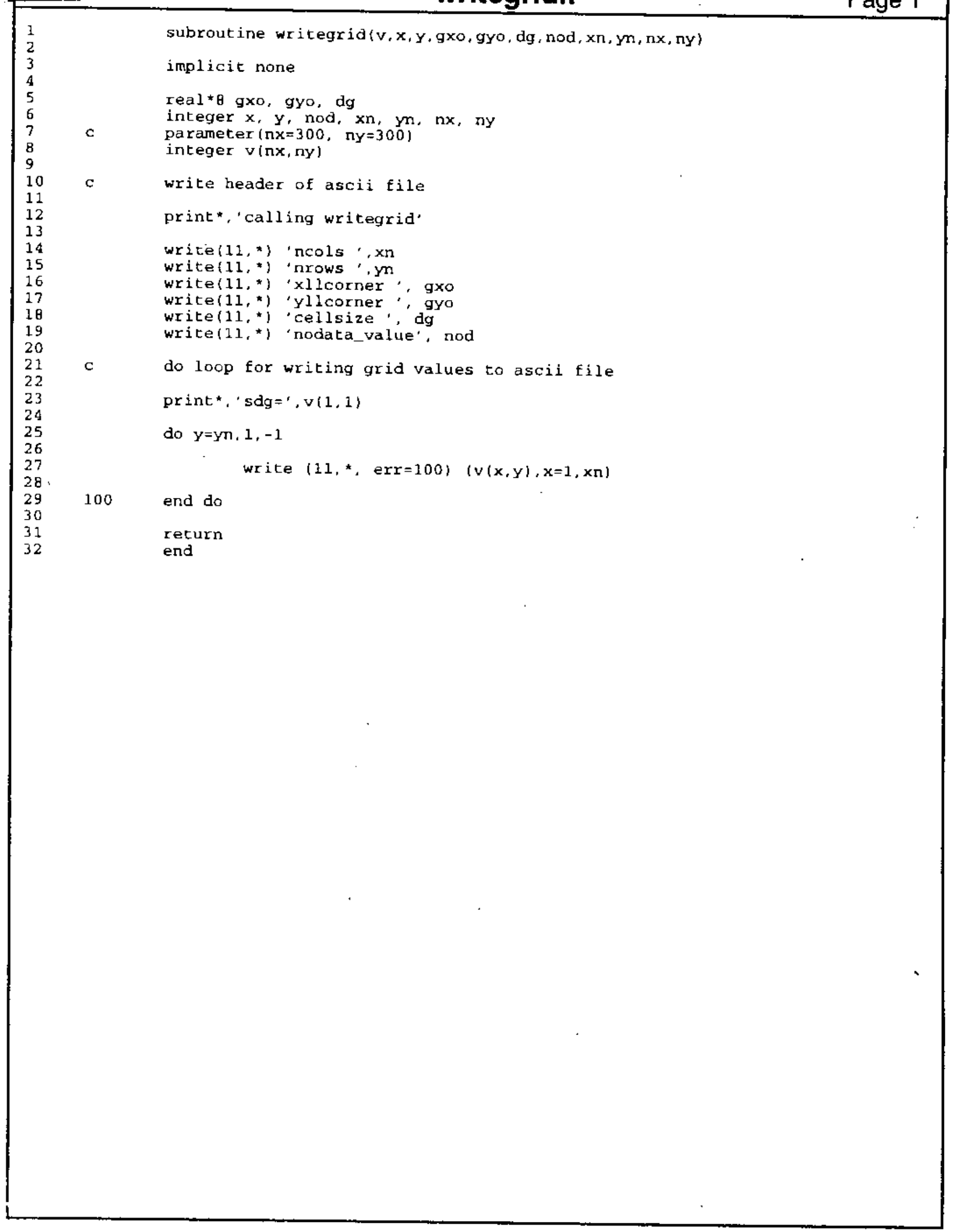
```
      SUBROUTINE SECV(V, X, Y, Z, PRINV, SEC, nx, ny, nz)
C
C Sets all secv(x,y,z) = non-zero prinv(x,y,z) to zero
C and all prinv(x,y,z+/-1) non-zero to zero
C
C thus only recording the secondary directions outside 5 degrees of the
C principal component.
C
C


      IMPLICIT NONE

      INTEGER X, Y, Z, NX, NY, NZ, V, PRINV, SEC
      INTEGER V(NX, NY, NZ), PRINV(NX, NY, NZ), SEC(NX, NY, NZ)

      DO X = 1, NX

            DO Y = 1, NY

                  DO Z = 1, NZ

                        SEC(X,Y,Z) = V(X,Y,Z)

                        IF (PRINV(X,Y,Z) .NE. 0) THEN
                              SEC(X,Y,Z) = 0
                        END IF

                        IF (Z .NE. 1) THEN
                              IF (PRINV(X,Y,Z-1) .NE. 0) THEN
                                    SEC(X,Y,Z) = 0
                              END IF
                        END IF

                        IF (Z .NE. 36) THEN
                              IF (PRINV(X,Y,Z+1) .NE. 0) THEN
                                    SEC(X,Y,Z) = 0
                                    SEC(X,Y,Z) = 0
                              END IF
                        END IF

                  END DO

            END DO

      END DO

      RETURN

      END
```

```
          PROGRAM WEED

c         this program weeds out the extra coordinates from file olin.gen
c         the generate file produced by ungenerating the lineations
c         coverages.  The reason for this program is that the rose diagram
c         program will only accept pairs of coordinates to create rose
c         diagrams.

c         this program reads from generate format file OLIN.GEN
c         and writes out weeded file LIN.GEN which is accepted by
c         the rose diagram program roslin.f


          implicit none
          real*8 lx1, lx2, bx1, bx2, bx3, bx4, ly1, ly2,
     +    by2, by1, by3, by4
          integer ID
          character*80 fname, nfname

c         open generate format file olin.gen

          fname='/home/egeo17/arc/glac/lins/olin.gen'
          open(unit=10,file=fname, status='old', err=997)

c         open new file to write weeded coords to

          nfname='/home/egeo17/arc/glac/lins/lin.gen'
          open(unit=11,file=nfname,status='new', err=999)

c         beginning of loop for reading olin.gen and writing coords
c         to file lin.gen such that each line has only one pair of
c         coordinates

c         read ID

 10       read(10,*,end=995,err=995) ID

c         read coordinates up to 5 pairs until reach END flag

          read(10,*,err=20) lx1, ly1
          read(10,*,err=20) lx2, ly2
          read(10,*,err=20) bx1, by1
          read(10,*,err=20) bx2, by2
          read(10,*,err=20) bx3, by3
          read(10,*,err=20) bx4, by4

c         write ID and only one pair of coordinates and END flag
c         to new file

 20       write(11,*) ID
          write(11,*) lx1, ly1
          write(11,*) lx2, ly2
          write(11,'(a)') 'END'

          goto 10

c         error lines

 995      write(11,'(a)') 'END'
          goto 999
 997      print*,'Could not open file olin.gen'
          goto 999
 998      print*,'Could not open file lin.gen'

 999      continue

          end
```

```
        SUBROUTINE WHGC(LX1, LY1, LX2, LY2, X, Y, GXO, GYO, DG)

C subroutine to calculate which grid square a lineation is in
C and assign X and Y values accordingly

        IMPLICIT NONE

        REAL*8 LX1, LY1, LX2, LY2, GXO, GYO,
     +   LCX, LCY, DG, DLCX, DLCY
        INTEGER X, Y

c       print*, 'wlx1=',lx1,'wlx2=',lx2


C Calculate mid-point of line LCX, LCY

        DLCX = ABS((LX1 - LX2)/2)

        DLCY = ABS((LY1 - LY2)/2)

C Calculate X and Y values (X=columns, Y=rows)

        IF (LX1 .GE. LX2) THEN

           LCX = (LX1 - DLCX)

        ELSE

           LCX = (LX1 + DLCX)

        ENDIF

        IF (LY1 .GE. LY2) THEN

           LCY = (LY1 - DLCY)

        ELSE

           LCY = (LY1 + DLCY)

        ENDIF

        X = ABS((LCX - GXO)/DG) + 1

        Y = ABS((LCY - GYO)/DG) + 1

c       print*, 'x=',x,'y=',y

        RETURN

        END
```



```
      SUBROUTINE WRITEGEN(ID, GCX, GCY, RX, RY, REX, REY)

C Writes generate file NEWLIN.GEN of rose diagram coverage

      IMPLICIT NONE

      INTEGER ID
      REAL*8 GCX, GCY, RX, RY, REX, REY

      WRITE(11, *) ID

      WRITE (11, 10)REX, REY

      WRITE (11, 10)RX,RY

10    FORMAT(F12.4, 1X, F12.4)

      WRITE (11, '(A)') 'END'

      RETURN

      END
```



writegrid Page 1

```
      subroutine writegrid(v,x,y,gxo,gyo,dg,nod,xn,yn,nx,ny)

      implicit none

      real*8 gxo, gyo, dg
      integer x, y, nod, xn, yn, nx, ny
c     parameter(nx=300, ny=300)
      integer v(nx,ny)

c     write header of ascii file

      print*,'calling writegrid'

      write(11,*) 'ncols ',xn
      write(11,*) 'nrows ',yn
      write(11,*) 'xllcorner ', gxo
      write(11,*) 'yllcorner ', gyo
      write(11,*) 'cellsize ', dg
      write(11,*) 'nodata_value', nod

c     do loop for writing grid values to ascii file

      print*,'sdg=',v(1,1)

      do y=yn,1,-1

            write (11,*, err=100) (v(x,y),x=1,xn)

100   end do

      return
      end
```

```
      SUBROUTINE ZERO2D(V, NX, NY)

C Sets all V(X,Y) to zero

      IMPLICIT NONE

      INTEGER X, Y
      INTEGER NX, NY
      INTEGER V(NX,NY)

      DO X=1,NX
          DO Y=1,NY

              V(X,Y)=0

              END DO
          END DO

      RETURN
      END
```

```
      SUBROUTINE ZERO3D(V, NX, NY, NZ)

C Sets all V(X,Y,Z) to zero

      IMPLICIT NONE

      INTEGER X, Y, Z
      INTEGER NX, NY, NZ
      INTEGER V(NX,NY,NZ)

      DO X=1,NX
          DO Y=1,NY
              DO Z=1,NZ

              V(X,Y,Z)=0

              END DO
          END DO
      END DO

      RETURN
      END
```

```
        program linden
c
c       this program calculates lineation density plots and writes the
c       results to a file for input into ARC/INFO GRID in ASCII format
c       the input is created by ungenerating a coverage to a lin.gen
c       file and the output file linden.gen is then read into ARC/INFO
c       output file: /home/egeo17/arc/glac/lins/linden/linden.gen

        implicit none
        real*8 dg, gxo, gyo, lx1, lx2, ly1, ly2
        integer nx, ny, nod, result
        parameter (nx=300, ny=300)
        integer v(nx,ny), x, y, xn, yn, id, count
        character e


c       get grid cell size for calculation

c       write(*,'(a)')' Grid cell size?'
c       read (*,*) dg
c       print*, 'dg=',dg

        read (5,*) dg

c       set all v(x,y) to zero

        call zero2d(v, nx, ny)

c       calculate grid origin

        call gridor(dg,gxo,gyo,xn,yn)
c       print*,'dg',dg,'gxo=',gxo,'gyo=',gyo,'xn=',xn,'yn=',yn
c       open old lineations file

        open (unit=10, status='old',
     +  file='/home/egeo17/arc/glac/lins/lin.gen')

        count=1

c       beginning of loop to calculate number of lineations in
c       each grid cell

c       read a lineation from old generate file linden.gen

30      READ (10, *, err=20, end=20) id
        READ (10, *, err=20, end=20) lx1, ly1
        READ (10, *, err=20, end=20) lx2, ly2
        READ (10, *, err=20, end=20) e
c       write(*,*) lx1, ly1
        count=count+1
c       print*,'count=',count
c       calculate which grid cell a lineation is in
c       assign X, Y values of V

        call whgc(lx1, ly1, lx2, ly2, x, y,
     +  gxo, gyo, dg)
c       print*,'x=',x,'y=',y
c       add to number of lineations for that grid cell

        v(x,y) = v(x,y) + 1

        goto 30

20      close (10)

c       open new generate file for output of rose diagrams

        open (unit=11, status='new',
     +  file='/home/egeo17/arc/glac/lins/linden/linden.asc')

c       write asciigrid file


        nod=0

        call writegrid(v,x,y,gxo,gyo,dg,nod,xn,yn,nx,ny)

        close(11)

        result=1
        write(0,*) result
        call exit(0)
        end
```

APPENDIX III

The User Interface for Sea Level Calculations

This interface is written using the ARC Macro Language (AML) which calls FORTRAN programmes to undertake the relative sea level suface and isostatic surface calculations. The analysis is described below in the stages represented by the boxes in Figure 5.8.

1. The program is initiated using a shell script which calls the program SL.AML. The user is asked whether they wish to analyse the sea level curves, or merely view the data and the results of previous analyses. If they elect to undertake analysis the AML prompts for a time between 0 and 1000 years BP. The program checks that the user has entered a valid response, and continues to prompt for a valid time until one is entered.

2. The user is then asked whether they wish to calculate an isostatic surface by subtracting a eustatic value from the relative sea level heights for each location. If they elect to do this, they are given a menu of possible eustatic estimates from which they can select the eustatic curve which they prefer.

3. The time variable is then passed to a FORTRAN programme which accesses the sea level curve files which are stored as a set of height, time strings. A subroutine searches through the strings for the two points which are either side of the time which has been entered (i.e. the two numbers which are closest to the required value on each curve). For some curves a null value may be returned because there is no data for the required time slice. If the user chose to calculate an isostatic surface, the height value on the eustatic curve is also calculated.

4. A further subroutine then uses a straight line interpolation between these two points to calculate the height value for the time slice selected for each curve. These points are read into an array for use later. If the user chose to calculate isostasy the eustatic value is then subtracted from each element in the relative sea level array to create a second array of isostatic height values.

5. These arrays are then used in a set of UNIRAS subroutines which interpolate the points for each location to calculate a regular grid of points which can be used to generate a surface within ARC/INFO. The routines generate a two dimensional array of height values.

6. The array of points is then written to a system file in grid lattice format, control is passed back to ARC and the surfaces are generated in the GRID module and contoured within ARC/INFO.

7. The user can then view these surfaces, and the points used to generate them using AMLs within the GRID module.

8. Finally the user has the option to exit, or to perform further analyses.

```
/*
/* 22/11/94
/*
/* called from arc with arc command SEA
/* or from system with shell script lins
/* starts analysis and plotting of sea level programs
/* runs sl.aml
/*
&amlpath /home/egeo17/arc/sea/aml
&terminal 9999
&thread &create sea &r sl.aml
&thread &delete &self

```

```
/* 22/11/94
/*
/* SL.AML
/*
/* Controlling AML for creation of relative and isostatic sea level surfaces
/* according to user defined time slices.  Isostatic surfaces created using
/* user-defined eustatic curve.  Also creates plotfiles of surfaces.
/*
/*

&amlpath /home/egeo17/arc/sea/aml

&r setpaths.aml

&terminal 9999

&sv ansel = [query 'Do you wish to do some analysis Y/N']

&if ^ %ansel% &then
  &goto sview

&label begin

/*&if [variable ] &then
/*  &dv

/* ask for time slice x

&label tslice

&setvar .x [response 'Enter time slice (Years BP) for surface creation']


&if [null %.x%] &then
  &goto tslice

&if [type %.x%] ne -1 &then
  &do
   &if [type %.x%] ne -2 &then
     &goto tslice
  &end

/* check that time slice is not too big or negative

&if %.x% gt 14000 &then
  &do
    &type 'WARNING: Out of range time slice, Maximum = 14 000''
    &goto tslice
  &end

&if %.x% lt 0 &then
  &do
   &type 'WARNING: Time slice must be a positive number'
   &goto tslice
  &end

/* create isostatic surfaces?

&s eus = [query 'Create isostatic surfaces']
&if %eus% &then

/* ask which eustatic sea level curve to use

&label eustcurve

&if %eus% &then
  &do
    &sv .eus = 1
    &type '  1.   Morner'''s 1984 curve
    &type ''
    &type '  2.   Fairbanks 1989 curve'
    &type ''
    &s eusfile = [response ' Select number for eustatic curve to use']

&if %eusfile% ne 1 &then
  &do
   &if %eusfile% ne 2 &then
     &do
       &type ' WARNING: appropriate numeric response expected'
       &goto eustcurve
     &end
  &end

&if %eusfile% eq 1 &then
  &s .eusfile = eustasy

/*  should really have another curve digitised but don't!

&if %eusfile% eq 2 &then
/*  &s .eusfile = %.eslpath%/eustasy
  &s .eusfile = eustasy

/* look up curves for that time slice and produce:
/*       relative sea level grid
/*       (isostatic surfaces grid)
/*       info data file(s) of heights for input into INFO

/* delete previous ascii.grid/sl.dat/info.dat files

&r killfile.aml

&r killcovs.aml %eusfile%

/* create irregular point, grid and info files
/* create grid of surface(s)
/* create contour coverage of surface(s)

&r slcgrid.aml %eusfile%

/* create point coverage with height values

&r htinfo.aml %eusfile%

&label sview

/* display surface(s)

&r sview.aml %eusfile%

/* hardcopy of surface(s)

/*&r splot.aml
```

```
/* HTINFO.AML  1/12/94
/*
/* inputs height information into INFO copying the locations coverage
/* and adding height values
/*
/*

&args eusfile

&amlpath /home/egeo17/arc/sea/aml
copy %.slocpath%/slloc_lcc %.rslocpath%/slloc_lcc

arcedit
create %.rslocpath%/H%.x%_LCC.DAT INFO %.rslocpath%/HTTEMPL.DAT
quit

&workspace %.rslocpath%

&data ARC INFO
  ARC
  SELECT H%.X%_LCC.DAT
  ADD SLLOC_LCC-ID,Z FROM %.rinfopath%/relinfo.dat
  Q STOP
&end

JOINITEM SLLOC_LCC.PAT H%.X%_LCC.DAT SLLOC_LCC.PAT SLLOC_LCC-ID SLLOC_LCC#

&data ARC INFO
  ARC
  SELECT H%.X%_LCC.DAT
  DELETE H%.X%_LCC.DAT
  Y
  Q STOP
&end

copy slloc_lcc h%.x%_lcc
kill slloc_lcc

&workspace %.islocpath%/isl%eusfile%

&if %.eus% eq 1 &then

&do
  copy %.slocpath%/slloc_lcc %.islocpath%/isl%eusfile%/slloc_lcc

  arcedit
  create HI%.x%_LCC.DAT INFO %.islocpath%/HTTEMPL.DAT
  quit

  &data ARC INFO
    ARC
    SELECT HI%.X%_LCC.DAT
    ADD SLLOC_LCC-ID,Z FROM %.iinfopath%/isoinfo.dat
    Q STOP
  &end

  JOINITEM SLLOC_LCC.PAT HI%.X%_LCC.DAT SLLOC_LCC.PAT SLLOC_LCC-ID SLLOC_LCC#

&data ARC INFO
  ARC
  SELECT HI%.X%_LCC.DAT
  DELETE HI%.X%_LCC.DAT
  Y
  Q STOP
&end

COPY slloc_lcc hi%.x%_lcc
kill slloc_lcc

&end

&RETURN
```

```
/*
/*  KILLCOVS.AML
/*
/* AML to check whether grid and contour coverages already exist and
/* if they do kill them for new ones to be created
/*


&args eusfile
&type %eusfile%

&if [exists %.rslocpath%/slloc_lcc -cover] &then
  kill %.rslocpath%/slloc_lcc

&if [exists %.islocpath%/isl%eusfile%/slloc_lcc -cover] &then
  kill %.islocpath%/isl%eusfile%/slloc_lcc

&if [exists %.rslocpath%/h%.x%_lcc -cover] &then
  kill %.rslocpath%/h%.x%_lcc

&if [exists %.islocpath%/isl%eusfile%/hi%.x%_lcc -cover] &then
  kill %.islocpath%/isl%eusfile%/hi%.x%_lcc


&if [exists %.rsurfpath%/rsl_%.x% -grid] &then
  kill %.rsurfpath%/rsl_%.x%

&if [exists %.isurfpath%/isl%eusfile%/isl_%.x% -grid] &then
  kill %.isurfpath%/isl%eusfile%/isl_%.x%

&if [exists %.rsurfpath%/rslt_%.x% -tin] &then
  kill %.rsurfpath%/rslt_%.x%

&if [exists %.isurfpath%/isl%eusfile%/islt_%.x% -tin] &then
  kill %.isurfpath%/isl%eusfile%/islt_%.x%


&if [exists %.rsurfpath%/crsl_%.x% -cover] &then
  kill %.rsurfpath%/crsl_%.x%

&if [exists %.isurfpath%/isl%eusfile%/cisl_%.x% -cover] &then
  kill %.isurfpath%/isl%eusfile%/cisl_%.x%


&return
```

```
/*
/* KILLFILE.AML
/*
/*  kills files produced by fortran program before a second run
/*

/* delete relative and isostatic irregular point files (x,y,z)

&if [exists %.rslirrpath%/rsl.dat -file] &then
   &sys rm  %.rslirrpath%/rsl.dat

&if [exists %.islirrpath%/isl.dat -file] &then
  &sys rm %.islirrpath%/isl.dat

/* delete relative and isostatic info files

&if [exists %.rinfopath%/relinfo.dat -file] &then
  &sys rm %.rinfopath%/relinfo.dat

&if [exists %.iinfopath%/isoinfo.dat -file] &then
  &sys rm %.iinfopath%/isoinfo.dat

/* delete relative and isostatic ascii grid files

&if [exists %.rascpath%/rsl.grid -file] &then
  &sys rm %.rascpath%/rsl.grid

&if [exists %.iascpath%/isl.grid -file] &then
  &sys rm %.iascpath%/isl.grid


&return
```

```
/* setpaths.aml
/*
/* sets all the path names for the coverages, programs and files
/* any changes to path names for relocation of output or input should
/* be made here

&amlpath /home/egeol7/arc/sea/aml

/* set path name for sea level locations coverages

&sv .slocpath = /home/egeol7/arc/sea
&sv .rslocpath = /home/egeol7/arc/sea/rel
&sv .islocpath = /home/egeol7/arc/sea/isos
/* set path names for the fortran programs

&sv .forpath = /home/egeol7/arc/sea/progs/new

/* set path names for sealevel curves

&sv .slcpath = /home/egeol7/arc/sea/slc
&sv .eslpath = /home/egeol7/arc/sea/eslc

/* set path name for new irregular sea level points (x,y,z)

&sv .rslirrpath = /home/egeol7/arc/sea/work
&sv .islirrpath = /home/egeol7/arc/sea/work

/* set path names for the new info data files

&sv .rinfopath = /home/egeol7/arc/sea/work
&sv .iinfopath = /home/egeol7/arc/sea/work

/* set path names for asciigrid files

&sv .rascpath = /home/egeol7/arc/sea/rel
&sv .iascpath = /home/egeol7/arc/sea/isos

/* set path names for contour coverages and surfaces

&sv .rsurfpath = /home/egeol7/arc/sea/rel
&sv .isurfpath = /home/egeol7/arc/sea/isos
```

```
/*
/* SLCGRID.AML
/*
/* creates surfaces and contour coverages of grid files
/*

&args eusfile

/* create irregular point, info and asciigrid files

&sv y = [task %.forpath%/sl [quote %.x% %.eus% %.eusfile%]]

/* create grids

asciigrid %.rascpath%/rsl.grid %.rsurfpath%/rsl_%.x% float

&if %.eus% eq 1 &then
  asciigrid %.iascpath%/isl.grid %.isurfpath%/isl%eusfile%/isl_%.x% float

/* create contour coverages

latticecontour %.rsurfpath%/rsl_%.x% %.rsurfpath%/crsl_%.x% 2.0

&s .rccov = %.rsurfpath%/crsl_%.x%

&if %.eus% eq 1 &then

  latticecontour %.isurfpath%/isl%eusfile%/isl_%.x% ~
%.isurfpath%/isl%eusfile%/cisl_%.x% 2.0

&s .iccov = %.isurfpath%/isl%eusfile%/cisl_%.x%

/* create surfaces

latticetin %.rsurfpath%/rsl_%.x% %.rsurfpath%/rslt_%.x% # # 10000


&if %.eus% eq 1 &then

   latticetin %.isurfpath%/isl%eusfile%/isl_%.x% ~
%.isurfpath%/isl%eusfile%/islt_%.x% # # 10000


&return
```

```
/*
/* SVIEW.AML
/*
/* program to view surfaces with contour and coastline drapes
/*
/*
/*

&args eusfile

arcplot

disp 9999 2

/* view contour coverage and base map


mapex %.rccov%
linecolor 2
arcs %.rccov%
textsize 0.08
textcolor 2
overflow off
arctext %.rccov% contour line blank

linecolor 1
arcs /home/egeo17/b/ceurc_lcc

markercolor 3
markersize 0.25
textcolor 3
points %.rslocpath%/h%.x%_lcc
reselect %.rslocpath%/h%.x%_lcc points z ne -999.999
pointtext %.rslocpath%/h%.x%_lcc z 11

&pause

clear
textcolor 2
mapex %.iccov%
linecolor 2
arcs %.iccov%
textsize 0.08
overflow off
arctext %.iccov% contour line blank

linecolor 1
arcs /home/egeo17/b/ceurc_lcc

textcolor 3
points %.islocpath%/isl%eusfile%/hi%.x%_lcc
reselect %.islocpath%/isl%eusfile%/hi%.x%_lcc points z ne -999.999
reselect %.rslocpath%/h%.x%_lcc points z ne -999.999

pointtext %.islocpath%/isl%eusfile%/hi%.x%_lcc z 11
&pause

clear

/* view surfaces

quit

&return
```

```
      PROGRAM SEALEVEL

      IMPLICIT NONE

      CHARACTER EFNAME*80
      INTEGER ES, RESULT
      REAL X
      CHARACTER*80 INFNAME, OUTFNAME

      READ (5,*) X, ES, EFNAME

      write (efname, fmt='(a)') efname
      EFNAME = '/home/egeo17/arc/sea/eslc/'//EFNAME//'.dat'
c     print*,'efname=',efname
      CALL FESLINTER(X, ES, EFNAME)

      INFNAME = '/home/egeo17/arc/sea/work/rsl.dat'
      OUTFNAME = '/home/egeo17/arc/sea/rel/rsl.grid'

      CALL FISOINTERPOL(INFNAME, OUTFNAME)


      IF (ES .EQ. 1) THEN

              INFNAME = '/home/egeo17/arc/sea/work/isl.dat'
              OUTFNAME = '/home/egeo17/arc/sea/isos/isl.grid'
c             print*, 'calling fiointerpol again'
              CALL FISOINTERPOL (INFNAME, OUTFNAME)

      END IF


      RESULT=1
      WRITE(0,*) RESULT
      CALL EXIT(0)


      END
```

```
      subroutine dataload (xx, yy, nmax, success,
     +  good, location, lat, lon, cn, n, jlo)


      implicit none
      integer   i, j, cn, nmax, n, jlo
      dimension  good(nmax), xx(nmax), yy(nmax)
      dimension lat(52), lon(52), location(52)
      character  nchr*2, fname*80, record*80, good*1,location*80
      logical success
      real lat, lon, xx, yy

c
c-- Open file fname of form "sl**.dat"
c


      write (nchr,fmt='(i2.2)') cN


      fname = '/home/egeol7/arc/sea/slc/sl'//nchr//'.dat'


      open (11, file=fname, err=200, status='old')


c -- file found

      success = .true.


c -- read header first lines

      read (11, fmt='(a)') location(cn)
      read (11, *)
      read (11, fmt=10) lat(cn), lon(cn)
      read (11, *)

10    format (f6.2,2x,f6.2,1x)

c -- some traps for blank lines

      i=0
100   continue
      i=i+1
      read (11,fmt='(a)', end=800) record
      if (record .eq. ' ') goto 100
      read (record, *, err=100) xx(i), yy(i)

c -- search for Y or N putting U if niether found

      good(i)='U'
      do j=1,80
      if (record(j:j) .eq. 'Y'  .or.
     +  record(j:j) .eq. 'y') good(i)='Y'
      if (record(j:j) .eq. 'N'  .or.
     +  record(j:j) .eq. 'n') good(i)='N'
      end do
      goto 100

800   n = i-1
      if (cn .eq. 1) then
         jlo=1
      endif

      goto 999


200   success = .false.

999   continue


      return

      end
```

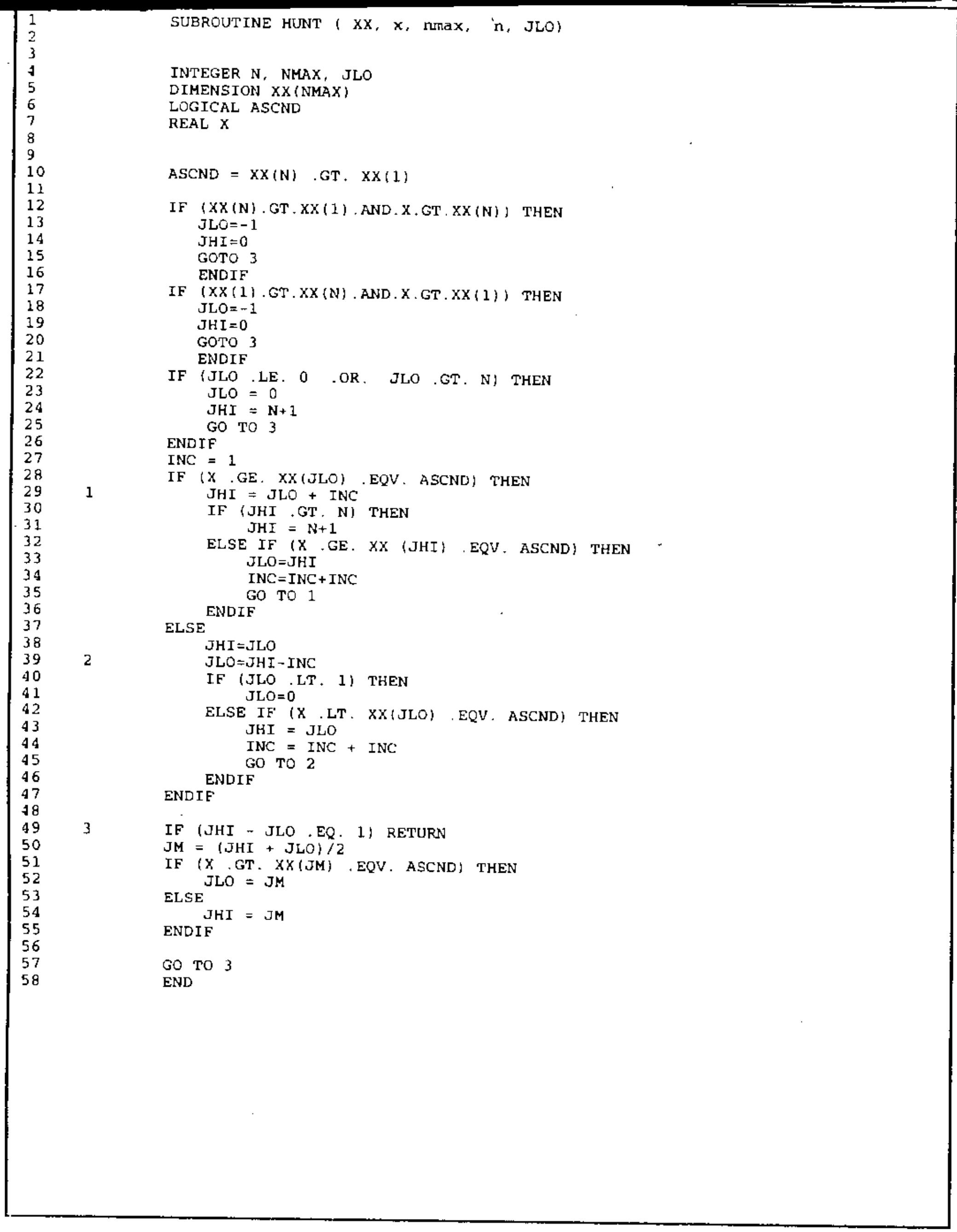
```
      SUBROUTINE EUS (EFNAME, X, E)
c
c--
c
      IMPLICIT NONE

      CHARACTER EFNAME*80, LOCATION*80, GOOD*1
      REAL XX, YY, X, LAT, LON, H, E, NULL
      INTEGER NMAX, CN, JLO, N
      PARAMETER (NMAX = 300)
      DIMENSION XX(NMAX), YY(NMAX), LOCATION (52), GOOD(NMAX)
      DIMENSION LAT (51), LON(51)
      LOGICAL SUCCESS

      NULL  = -999.999
      success = .false.
c -- load data from eustatic curve fname
c     print*, 'calling eusload'
c     print*, 'success=',success,'efname=',efname
      CALL EUSLOAD (XX, YY, NMAX, SUCCESS,
     +  GOOD, LOCATION, LAT, LON, CN, N, JLO, EFNAME)

c -- file slcn.dat found?

      IF (SUCCESS) THEN

c -- look for points xx(jlo) xx(jlo+1) on either side of desired x

         CALL HUNT (XX, X, NMAX, N, JLO)

      IF ((XX(JLO) .EQ. 0) .AND. (YY(JLO) .EQ. 0)) THEN
            E = NULL
            GOTO 10
      END IF

c -- write file number, location and coords x,y,z to file slpts.dat

         H = (YY(JLO+1) - YY(JLO)) * X / (XX(JLO+1) - XX(JLO)) + YY(JLO) -
     +        (YY(JLO+1) - YY(JLO)) * XX(JLO) / (XX(JLO+1) - XX(JLO))

         E = H / 1000
c     print*,'e=',e
      ENDIF


 10   RETURN

      END
```

```
      SUBROUTINE EUSLOAD (XX, YY, NMAX, SUCCESS,
     +   GOOD, LOCATION, LAT, LON, CN, N, JLO, EFNAME)


      IMPLICIT NONE
      INTEGER I, CN, NMAX, N, JLO
      DIMENSION GOOD(NMAX), XX(NMAX), YY(NMAX)
      DIMENSION LAT(52), LON(52), LOCATION(52)
      CHARACTER EFNAME*80, RECORD*80, GOOD*1, LOCATION*80
      LOGICAL SUCCESS
      REAL LAT, LON, XX, YY

c-- Open file fname of form "eustasy.dat"
c     efname = '/home/egeo17/arc/sea/eslc/eustasy.dat'
      OPEN (11, FILE = EFNAME, ERR = 200, STATUS = 'OLD')
c     print*, 'efname=',efname
c -- file found

      SUCCESS = .TRUE.
c     print*,'success=',success
c -- read header first lines

      READ (11, FMT = '(A)')

 10   FORMAT (F6.2, 2X, F6.2, 1X)

c -- some traps for blank lines

      I = 0

 100  CONTINUE

      I = I + 1

      READ (11, FMT = '(A)', END = 800) RECORD

      IF (RECORD .EQ. ' ') GOTO 100

      READ (RECORD, *, ERR = 100) XX(I), YY(I)

 800  N = I - 1

      IF (CN .EQ. 1) THEN
        JLO = 1
      ENDIF

      GOTO 999


 200  SUCCESS = .FALSE.


 999  RETURN

      END
```

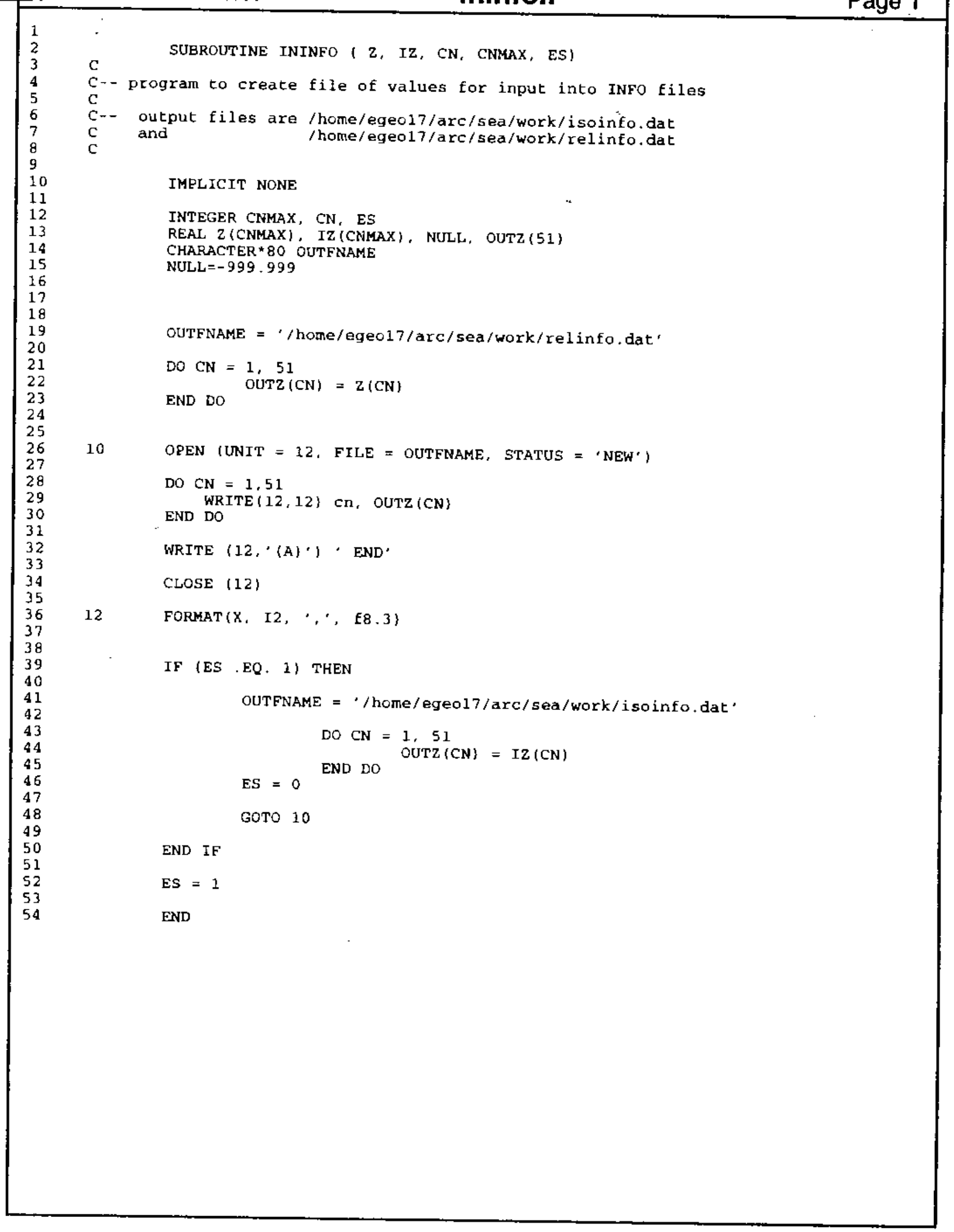
```
       SUBROUTINE FESLINTER(X, ES, EFNAME)
c
c
c-- 17/11/94
c-- this program interpolates using simple straight line interpolation
c-- from files of two columns of numbers with the location name and date
c-- contained in the first and third lines respectively at the top of the
c-- file the second and fourth lines being blank.  Filenames of the form
c-- SL**.dat up to 51 which can be extended to 99 .  It uses the
c-- subroutine HUNT to search for the two numbers XX(JLO), XX(JLO+1)
c-- surrounding the required date X and if the first coords are found to
c-- be zero the program assumes that there is a data gap - can also cope with
c-- a data gap at the end of files.
c
c-- it also calls subroutines EUS and EUSLOADand eustatic component
c-- is subtracted from the relative sea which also produces file isl.dat

      IMPLICIT NONE

      CHARACTER EFNAME*80, LOCATION*80, GOOD*80
      REAL XX, YY, X, LAT, LON, H, NULL, E, Z, IZ
      INTEGER NMAX, CN, JLO, N, INT, ES, CNMAX
      PARAMETER (NMAX = 300, CNMAX = 51)
      DIMENSION XX(NMAX), YY(NMAX), LOCATION(CNMAX), GOOD(NMAX)
      DIMENSION LAT(CNMAX), LON(CNMAX), Z(CNMAX), IZ(CNMAX)
      LOGICAL SUCCESS
      NULL = -999.999
c
c -- do for files numbering 1 to 51
c

c     print*,'efname=',efname
      DO CN = 1, 51

c -- load data

      CALL DATALOAD (XX, YY, NMAX, SUCCESS,
     +  GOOD, LOCATION, LAT, LON, CN, N, JLO)

C -- File slcn.dat found?

      IF (SUCCESS) THEN

c -- look for points xx(jlo) xx(jlo+1) on either side of desired x

         CALL HUNT(XX, X, NMAX, N, JLO)

c -- if first x and y coords assume data gap and print no within range


         IF ((XX(JLO) .EQ. 0) .AND.
     +         (YY(JLO) .EQ. 0 )) THEN
           Z(CN) = NULL
           GOTO 70
         ELSE
           GOTO 40
         ENDIF

c -- write file number, location and coords x,y,z to file slpts.dat

40    H = (YY(JLO+1) - YY(JLO)) * X / (XX(JLO+1) - XX(JLO)) + YY(JLO) -
     +  (YY(JLO+1) - YY(JLO)) * XX(JLO) / (XX(JLO+1) - XX(JLO))

         Z(CN) = H / 1000

      ENDIF


70    END DO


       INT = X
c
c -- subtract eustasy?
c

       IF (ES .EQ. 1) THEN
c      print*, 'so far so good - calling eus'
          CALL EUS (EFNAME, X, E)

          IF (E .EQ. NULL) THEN
               ES = 0
               GOTO 50
          END IF

c
c-- subtract eustatic value e from relative sealevel values z(cn)
c
          DO CN = 1, 51
c              print*, 'e=',e

               IF (Z(CN) .EQ. NULL) THEN
                  IZ(CN) = NULL
                  GOTO 12
               ENDIF

              IZ(CN) = Z(CN) - E
c              print*, 'iz=',iz(cn)
c              print*, 'z=',z(cn)


12        CONTINUE

          END DO


      ELSE

          GOTO 999

      END IF
c
c-- if only relative sealevel is required write values to rsl.dat
c-- otherwise write values to rsl.dat *and* isl.dat
c

50    CALL WRITEPOINTS(Z, IZ, CN, CNMAX, ES)

      CALL ININFO (Z, IZ, CN, CNMAX, ES)

999   CONTINUE

      RETURN
      END
```

```
      SUBROUTINE FISOINTERPOL (INFNAME, OUTFNAME)
c
***** to do limited area interpolation of sl points
c

      IMPLICIT  NONE
      INTEGER C, R, ROWS, COLS
      PARAMETER (ROWS = 215, COLS = 167)
      REAL XIRR(51), YIRR(51), ZIRR(51)
      REAL GRID(COLS, ROWS), BUFFER(COLS)
      INTEGER*2, ROWSOUT, COLSOUT
      REAL CELLSIZE, XLLCORNER, YLLCORNER, NODATA_VALUE
      CHARACTER*80 INFNAME, OUTFNAME

***** read points

      OPEN (UNIT = 12, FILE = INFNAME, STATUS = 'OLD')

      DO C = 1, 51
         READ (12, *), XIRR(C), YIRR(C), ZIRR(C)
         XIRR(C) = XIRR(C) / 1000
         YIRR(C) = YIRR(C) / 1000
10    END DO

      CLOSE (12)

      CALL GROUTE ('S HPOSTA4;E ')

      CALL GOPEN
c       print*, 'gopen opened'
***** do interpolation

c     set limits of rectangular grid and max,min(z) of input data pts
c     glimit(xmin,xmax,ymin,ymax,zmin,zmax)

      CALL GLIMIT (-703.415011,1112.233944,-816.060105,1401.920152,
     +  999.999,999.999)
      XLLCORNER = -703.415011
      YLLCORNER = -816.060105
c       print*, 'glimit opened'
c     specify gridding interval in user units

      CALL GBLKSI (10.316187,10.316187,0.0)
c       print*, 'gblksi opened'
      CELLSIZE = 10.316187

c     if no data found within radius value to be inserted as the
c     undefined value specified: gundef(value, colour)

      CALL GUNDEF (-999.999,0)
      NODATA_VALUE = -999.999
c       print*, 'gundef opened'
c     where radius=search area given in user units
c     default = diagonal length of display area

      CALL GRADUS(500.0)

c     interpolates from a set of irreg distrib data points to reg grid

      CALL GINTPF (XIRR, YIRR, ZIRR, 51, GRID, COLS, ROWS)
c      print *, 'gintpf opened'
      OPEN (UNIT = 13, STATUS = 'NEW',
     +  FILE = OUTFNAME)

      ROWSOUT = ROWS
      COLSOUT = COLS

      WRITE (13, *) 'NCOLS', COLS
      WRITE (13, *) 'NROWS', ROWS
        XLLCORNER = XLLCORNER * 1000
      WRITE (13, *) 'XLLCORNER', XLLCORNER
```

```
        YLLCORNER = YLLCORNER * 1000
      WRITE (13, *) 'YLLCORNER', YLLCORNER
        CELLSIZE = CELLSIZE * 1000
      WRITE (13, *) 'CELLSIZE', CELLSIZE
      WRITE (13, *) 'NODATA_VALUE', NODATA_VALUE

c       print*, 'file written'
      DO R = 1, ROWS

         DO C = 1, COLS
           BUFFER(C) = GRID(C,R)
         END DO

         WRITE (13,*) BUFFER

      END DO

      CLOSE (13)

      CALL GCLOSE

      RETURN
      END
```



```
      SUBROUTINE HUNT ( XX, x, nmax, n, JLO)


      INTEGER N, NMAX, JLO
      DIMENSION XX(NMAX)
      LOGICAL ASCND
      REAL X


      ASCND = XX(N) .GT. XX(1)

      IF (XX(N).GT.XX(1).AND.X.GT.XX(N)) THEN
         JLO=-1
         JHI=0
         GOTO 3
         ENDIF
      IF (XX(1).GT.XX(N).AND.X.GT.XX(1)) THEN
         JLO=-1
         JHI=0
         GOTO 3
         ENDIF
      IF (JLO .LE. 0  .OR.  JLO .GT. N) THEN
          JLO = 0
          JHI = N+1
          GO TO 3
      ENDIF
      INC = 1
      IF (X .GE. XX(JLO) .EQV. ASCND) THEN
1         JHI = JLO + INC
          IF (JHI .GT. N) THEN
              JHI = N+1
          ELSE IF (X .GE. XX (JHI) .EQV. ASCND) THEN
              JLO=JHI
              INC=INC+INC
              GO TO 1
          ENDIF
      ELSE
          JHI=JLO
2         JLO=JHI-INC
          IF (JLO .LT. 1) THEN
              JLO=0
          ELSE IF (X .LT. XX(JLO) .EQV. ASCND) THEN
              JHI = JLO
              INC = INC + INC
              GO TO 2
          ENDIF
      ENDIF

3     IF (JHI - JLO .EQ. 1) RETURN
      JM = (JHI + JLO)/2
      IF (X .GT. XX(JM) .EQV. ASCND) THEN
          JLO = JM
      ELSE
          JHI = JM
      ENDIF

      GO TO 3
      END
```



Page 1

```

      SUBROUTINE ININFO ( Z, IZ, CN, CNMAX, ES)
C
C-- program to create file of values for input into INFO files
C
C--  output files are /home/egeo17/arc/sea/work/isoinfo.dat
C    and              /home/egeo17/arc/sea/work/relinfo.dat
C

      IMPLICIT NONE

      INTEGER CNMAX, CN, ES
      REAL Z(CNMAX), IZ(CNMAX), NULL, OUTZ(51)
      CHARACTER*80 OUTFNAME
      NULL=-999.999



      OUTFNAME = '/home/egeo17/arc/sea/work/relinfo.dat'

      DO CN = 1, 51
            OUTZ(CN) = Z(CN)
      END DO


10    OPEN (UNIT = 12, FILE = OUTFNAME, STATUS = 'NEW')

      DO CN = 1,51
         WRITE(12,12) cn, OUTZ(CN)
      END DO

      WRITE (12,'(A)') ' END'

      CLOSE (12)

12    FORMAT(X, I2, ',', f8.3)


      IF (ES .EQ. 1) THEN

            OUTFNAME = '/home/egeo17/arc/sea/work/isoinfo.dat'

                  DO CN = 1, 51
                        OUTZ(CN) = IZ(CN)
                  END DO
            ES = 0

            GOTO 10

      END IF

      ES = 1

      END
```

```
      SUBROUTINE WRITEPOINTS(Z, IZ, CN, CNMAX, ES)
c
c-- this program reads projected locations from file slll_lcc.dat
c-- and from each of file z.dat and puts each of the values together
c

      IMPLICIT NONE

      INTEGER CN, CNMAX, ES
      REAL Y(51),X(51),Z(CNMAX), IZ(CNMAX)
      CHARACTER*80 FNAME


      FNAME = '/home/egeo17/arc/sea/work/slll_lcc.dat'

      OPEN(UNIT=11, FILE = FNAME, STATUS='OLD')

      DO CN=1,51
         READ(11,*)Y(CN),X(CN)
      END DO

      CLOSE (11)


      OPEN(UNIT=13,FILE='/home/egeo17/arc/sea/work/rsl.dat'
     +,STATUS='NEW')

      DO CN=1,51
         WRITE(13,12) X(CN),Y(CN),Z(CN)
      END DO

      CLOSE (13)


      IF (ES .EQ. 1) THEN

              FNAME = '/home/egeo17/arc/sea/work/isl.dat'

              OPEN (UNIT = 12, FILE = FNAME, STATUS = 'NEW')

              DO CN=1,51
                 WRITE(12,12) X(CN),Y(CN),IZ(CN)
              END DO

              CLOSE (12)

      END IF

12    FORMAT(X,F13.4,1X,F13.4,1X,F8.3)

999   CONTINUE

      END
```

APPENDIX IV

A SIGNIFICANT CHALLENGE : PREDICTION OF ENVIRONMENTAL CHANGES USING A TEMPORAL GIS

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Abstract

Prediction of environmental change requires an understanding of the principal mechanisms implicated in long-term large scale climatic variation. Uncovering these mechanisms can only be achieved by the analysis of past environment states as well as the recognition of patterns of change through time. These controlling factors and their causes are not fully understood and scientists are only beginning to centralise the related large data sets in national databases.

A temporal GIS seems to be the key to handling distributed data sets at different scales for environmental change in terms of space and time. A wider scope of analysis will be offered by providing rules to maintain updating changes coherent with the former stored environment states. Moreover, the description of a lineage of data will produce historical information which will enable one to recognise patterns of environmental change in a more realistic way. Temporal Geographical Information Systems are as yet unavailable and only in the early stages of development.

Inherent challenges are involved in predicting environmental change using a temporal GIS. These challenges are mainly concerned with the availability of spatio-temporal tools for optimising our understanding of the data, synthesising data from different sources and updating large data sets more efficiently. This paper is concerned with the principles and problems involved in the development of a temporal GIS to meet these challenges.

INTRODUCTION

With the growing acceptance that GIS is capable of managing primary environmental data sets, a vast amount of interdisciplinary research is being carried out into how GIS can be integrated with environmental modelling. The term "environmental modelling" covers a huge spectrum of different sorts of modelling. It can be used for qualitative interpretative descriptions of environmental states, for qualitative and also empirical descriptions of processes operating in the environment and also for numerical models which describe physical processes in a mathematical sense and can be used with input parameters as predictive dynamic models. Numerical modelling lends itself very well to linking with or incorporation within GISs, but not so the descriptive manually interpolative modelling process which is more often used and extremely valuable to environmental scientists. This process is the result of scientific intuition, background knowledge and experience which would be extraordinarily difficult, if not impossible, to emulate on an information system.

Recently, a "3-pronged approach" has been recognised by the forthcoming Second International Conference Workshop on Integrating GIS and Environmental Modelling [1993], as follows:

- environmental database and mapping
- environmental modelling linked to GIS
- building environmental models within GIS

These three main approaches reflect concerns about the integration of GIS with environmental modelling. The available environmental databases have been implemented by local, regional, national and international organisations which have collected a diversity of spatio-temporal environmental data. Most of the environmental databases contain large data sets at many different scales, levels of accuracy, different times of acquisition and in different formats (Townshend 1991). These characteristics are very common for environmental data sets, therefore the establishment of more efficient mapping techniques are required for integrating environmental databases and current GIS. Among the most important is the development of improved methods of data capture and data visualisation. These methods should deal with the creation of space-time series for storing and portraying changes through time.

In the Agenda 21 document from the UN Conference on Environment and Development, Din [1993] highlights some areas of environmental processes and future policy changes which are of particular relevance to GIS research. Data integration, dynamic modelling and spatial decision support systems are suggested as major priorities in GIS research for the implementation and development of concepts for sustainable living, long-term policy planning and management solutions.

At present most environmental GISs concentrate on present day to near-recent data (e.g. hydrological, remote sensing, vegetation, landslide hazard etc.) with short-term aims and modelling of present day processes (climatic General Circulation Models, valley glaciers in Norway Jacobsen). Long-term climate change has largely been left out, due possibly to the problems involved in getting data into such a system and the time involved in implementation. Current GISs are unsuitable when handling the spatial and temporal problems inherent in palaeoclimatic data. The problems include the management of large complex data sets which are poorly distributed in space and time.

One project worth citing at this point (since it involves one of the authors), which would benefit from the employment of a temporal GIS, is an EEC Project presently running which is looking into the long-term safety of nuclear waste repositories in Salt Domes in parts of North West Europe. This project involves the use of many spatial data sets pertaining to the last three glaciations including pollen (giving information about past vegetational conditions), glacial landforms (which can be interpreted to reveal something of how the Scandinavian glacier evolved through time), sea level (which is extremely important when considering groundwater flow and gives an indication of land uplift changes), and many others. Added to these palaeoenvironmental data sets is some present day data and two models, one for the Scandinavian glaciation and the other for the hydrological system in the area. Aspects of the glacial model are changed and tested according to past reconstructions of the environmental conditions which existed in NW Europe during past glaciations and then the model is run for the present situation to determine, amongst other things, the hydrological conditions which may exist in the future. Using the hydrological model the safety of nuclear waste in salt domes can then be assessed.

Only by looking at long-term climatic oscillations (especially the glacial/interglacial cycles of the past) can the present estimates, forecasts and concerns about such topics as global warming be put into perspective. Is man affecting the climate to the extent that he is perturbing the natural oscillations to an alarming extent or is the climatic system merely following a pattern determined by much more fundamental processes? Indeed is the climate system robust enough to accommodate changes caused by man?

WHY TEMPORAL GIS

Since current research tends to focus on short-term changes, it is important to remember that factors which influence climate in the short-term are not necessarily those which determine the climate in the long-term. There have been periods in the past during which climatic extremes of both very hot and very cold temperatures have persisted for long periods. Recently, much of the effort put into looking at long-term climatic changes has been focused on the Milankovitch theory which searches for evidence of the earth's orbital oscillations in records from palaeoenvironmental indicators from the past 800,000 years (Figure 1). Records such as the δO18 Specmap curve, which is an indicator of global ice volumes, reveal the same frequencies as the orbital variations cited by Milankovitch. Identification of such oscillatory sequences and patterns is fundamental in aiding our understanding of the processes affecting long-term climate change. Many of the problems involved in converting such work to a GIS lie in representing and tracking changes through time and cross correlating different sequences and different data types. A temporal GIS is an extremely important development which can greatly enhance the manipulation of paleoenvironmental data sets in terms of creating a more suitable tool for dealing with temporal uncertainties and correlation of events. There are often large temporal errors associated with this data and also large gaps which need to be filled by methods of interpolation in both spatial and temporal dimensions. A GIS with a temporal element which could handle these factors in a satisfactory way, would hugely improve our understanding of the data sets. A temporal GIS would support a multi-state data analysis capability and facilitate improved understanding of the relevant spatio-temporal information.

Langran [1992] cites that by knowing:

- where and when change occurred
- what types of change occurred
- the rate of change
- the periodicity of change

a temporal GIS would assess:

- whether temporal patterns exist
- what trends are apparent
- what processes underlie the change

Although temporal GISs are in the early stages of development, these embedded aspects of space and time (discussed below) enhance the role of temporal GIS as a fundamental requirement for dealing with the elusive subject of environmental change prediction.

First of all, there is an overwhelming acceptance that the basic aspects of time and space are both conceptualised in a more natural way through the dimensional representation. However, at the implementation level, there has been no consensus as to how to implement the concepts themselves into the different data structures of existing GISs. Implementing hypermedia co-ordination as well as multimedia functions will enable temporal GISs to handle the dynamics of environmental changes in a more realistic manner with animated maps, images and special effects.

Secondly, there is the unique value of a temporal GIS for generating hypotheses concerning cause and effect, through operation in both spatial and temporal dimensions. An effect manifested in the past time can be analysed using a temporal GIS to discover whether a possible cause exists or not. There is an enormous research scope for advancement of such a temporal GIS, mainly by incorporating it with knowledge-based research.

Finally, there is a need for a temporal GIS with a capability to dynamically control very large data sets. The primary aspect here is recognising possible patterns in large data sets and facilitating their correlations since it is unrealistic to expect previous knowledge of environmental patterns and associations of potential interest to be readily available. This requires further research in new data capture mechanisms as well as the development of parallel processors.

A CONCEPTUAL BASIS FOR HANDLING PALEOENVIRONMENTAL DATA WITHIN A TEMPORAL GIS

Temporal GIS forms a wide scope within non-traditional applications especially because it offers the opportunity to manipulate environmental data sets available from different sources, epochs, resolution and of different qualities. The outstanding aspect of space and time in temporal GISs is the possibility of exploring their similarities in such a way that time is conceptualised along a linear dimension to provide a sense of past, present and future, while space is conceptualised along three linear dimensions (Figure 2).

Therefore, space and time can be embedded within the semantics of **objects** and **events**. Temporal GISs would enable the capture of past environmental changes and projections to future states by exploring the derivation of events from the object states and vice versa due to their temporal interdependence. Events occur at specific points or intervals in time, although events that occurred in a pre-historic past cannot be dated as precisely as events that occur in the present.

Events are used to describe the environmental changes (the change from one object state to another) and can be categorised in two ways:

- **effect**: an environmental change which can be detected by experience or observation of the environment
- **cause**: the circumstances acting over a period of time which produce an environmental change

Objects and their interrelationships exist over time. An object composes two main parts which are denominated by descriptive (or interpretative) and geometric attributes. They represent three kinds of features:

- discrete points, for example, height and date measurements at ancient sea level locations
- definite features, such as eskers
- indefinite features, such as end moraines

The same event can affect one object or several objects at the same time, for example, two locations (discrete points) may be affected by the same sea level drop. By modelling time using the semantics of event, some main advantages can be highlighted:

- events can have any duration
- events can take place without necessarily invoking geometric attribute or significant descriptive attribute changes,
- events can occur simultaneously

Basically, in order to capture a history of changes to an object, the evolving states of that object would be described as conforming to the following:

- an object cannot be in two places at once
- an object can be in one place at two different times
- two objects cannot be in the same place at the same time
- two objects can be in the same place at different times

These statements are critical for a temporal GIS because of their significant role in incorporating temporality in an information system. A temporal GIS might be able to differentiate between events which occur at different times affecting different objects. A temporal GIS would require the data management of two events which affect the same object at different times. For example, a global sea level change (due to a change in ocean volume) and a localised seismic event (earthquake) will affect the position of a beach with respect to a datum level.

THE TIME DIMENSION

The time dimension can assume two main forms of representation. These are database time and world time. A user-defined time may also be included if required.. All are important in a temporal GIS. The database time is the time at which the event was stored in the database, the world time is the time the event occurred in reality and user-defined time is a date denominated attribute data type which may be useful as a reference.

The database time is mainly relevant to system domain developments for concurrency control and recovery to re-establish a consistent database state during a multi-user access or after a system failure. World time is used to capture the history of an object through time. Returning to the sea level change example, the database time would be the time at which the information was entered into the database, the world time would be the time at which the beach was at sea level (e.g. 8000 years before the present day) and the user-defined time might be the date on which this information was collected or published.

It is important to note that for these sorts of ancient data, the most important time used for environmental analysis, reconstruction and prediction is the world time, and the database and user-defined times would be for reference only, although these are also very important. Improvements in radiocarbon methods for example would often call for an adjustment to the world time of pre-improvement dated material which would affect subsequent interpretations.

OBJECT AND EVENT RELATIONS

Three main classes of object and event relationships can be identified:

Conditional relationships act as a set of conditions which must exist in order for the event to occur. Conditional relationships are not necessarily directly responsible for the changes in the object states. This relationship is useful for future prediction in terms of an environmental GIS.

Indirect relationships alter the resultant object state but there is no direct relationship.

Direct relationships are the events which directly contribute to the resultant object state.

Whenever an event becomes associated with a particular object change, it becomes a candidate for a particular type of relationship. Temporal GISs would be able to determine the probability of a relationship between an object and an event. A recursive analysis from event to event is necessary to determine the significance of a potential relationship between an event and an object, and thus the possibility of whether a relationship exists or not.

This is particularly exciting in terms of environmental data as it provides a temporal framework which can facilitate, more readily than a conventional GIS, the identification and interpolation of events linked with climatic change. In the sea level change example inferences can be made about sea level variation for areas where there is little or no data. This can be done by using knowledge of factors such as global sea level change and variation of sea level at neighbouring locations.

DATA ACQUISITION AND CAPTURE

It is important to distinguish between data acquisition which is the collection of data and data capture which is the entry of the data into the system. Development of data capture mechanisms in temporal GIS are dependent upon the data acquisition which are outwith the control of the GIS developer and depend on the type of data being collected. Data acquisition can be categorised as shown below:

- periodic data acquisition, in which data is collected uniformly at regular intervals
- aperiodic data acquisition, in which the data is collected on an irregular basis
- random data acquisition, in which the data is collected in a disorder manner

Random data capture is the major process at work in an environmental GIS. Ancient environmental data have a variable distribution in space and time and will not enter the GIS in chronological order since discoveries of records for any time in the past could occur in the present or at any time in the future. For example, when considering recordings of relative sea level positions in the past, a raised beach may be discovered in Northern Norway and dated at 7000 BP (Before Present) at a height of 5m above MSL (present day mean sea level). Subsequently another raised beach is discovered in that area at a height of 20m above MSL and dated at 10,000 BP. These are entered as two states linked by an event which is a sea level fall of 15m. Then another beach is found dating around 8000 BP at a height 2 metres above MSL. Thus the change between states is now a two event process with a sea level fall followed by a sea level rise (Figure 3).

Careful examination and understanding of data acquisition are of particular importance when developing a temporal GIS. This acquisition presents a huge problem for a temporal GIS because a fully dynamic update procedure is required. The temporal GIS will need to be flexible enough to allow an efficient data capture without conflicting with the data acquisition.

PREDICTION - ENVIRONMENTAL MODELS AND PATTERN RECOGNITION

There are two methods which can be used together to predict environmental change. The recognition of patterns of change such as cyclical repeats in the past means that, by knowing the pattern, it can be extended and projected into the future. Linked to this is the investigation into processes which affect climate change, and in attempting to understand these processes better, modelling them in an attempt to establish how influential they really are on climate. Pattern recognition can often lead to process modelling, as for example, similarities in frequency patterns will lead to the identification of the process causing the pattern (e.g. Milankovitch cycle). These patterns and processes operate in space and through time. Once a process has been identified, successfully modelled and found to be a significant factor in environmental change, then a model can be run for various times to produce scenarios of environmental conditions in the future. By knowing past patterns of change, parameter variations can be projected into the future and along with present conditions as start point used as model input.

Environmental modelling, using ancient data, is a three stage modelling process. Often understanding processes, and producing environmental reconstructions never gets beyond stage one because of the complexity of the data and the interplay of many different parameters. These stages are summarised below:

Descriptive Modelling is an attempt to reconstruct past environments using the fragmentary data to develop relationships between features and the processes which are altering them through time. It is necessary to have a temporal GIS to create these relationships for further pattern recognition and correlation..

Empirical Modelling is a qualitative description of the reconstructed environment and the parameters of the environment processes operating. In this case, a temporal GIS will be a tool for manipulating the relationships between features and processes as they interact through time.

Dynamic Numerical Modelling where the processes operating on the environment are described using physics and mathematics with variable input parameters. The models are generally tested for past scenarios where something is known about the variation of input parameters and the resulting effects, and once a satisfactory agreement has been reached, it can be used as a predictive model. A temporal GIS will help in reaching this satisfactory agreement.

On the basis of the conceptual model , some approaches can be identified as shown below:

Descriptive Modelling - a possible approach utilises the correlation on an event by event basis. By counting a certain number of events of interest and correlating them in space and time with other locations which have experienced a similar number of the events at the same time.

Empirical Modelling - in this case a correlation between event and object relations is a more suitable approach.

Dynamic Numerical Modelling - the past patterns of variation and quantities of the parameters can then be used for model input and the past reconstructions for testing the good behaviour of the model for past environments.

CONCLUSIONS

The emphasis has been put on describing the concepts of time and space using the semantics of event and object in order to develop a temporal GIS for prediction of environmental changes.

However, there is one major fundamental question which needs to be answered. How the necessary links could be implemented between events and object states in a temporal GIS? Should the links be created during the development of the user application or would it be possible to have a temporal GIS capable of creating those links automatically probably requiring the use of knowledge-based tools. The answer to these questions involves significant challenges to be conquered in the development of temporal GIS.

ACKNOWLEDGEMENTS

We would like to thank Richard Healey, Chris Place and Christoph Corves for their comments on the manuscript and their support.

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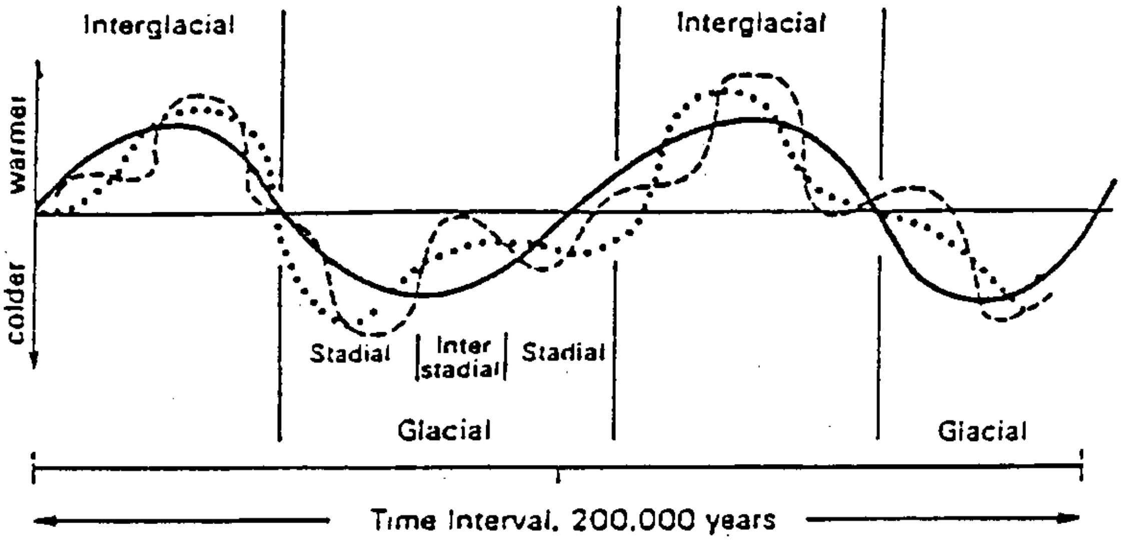


Figure 1
Schematic representation of possible Quaternary mean temperature variations according to 300,000 (solid line), 43,000 (dotted line), and 24,000 (dashed line) year cycles of Hays *et al.* (1976)

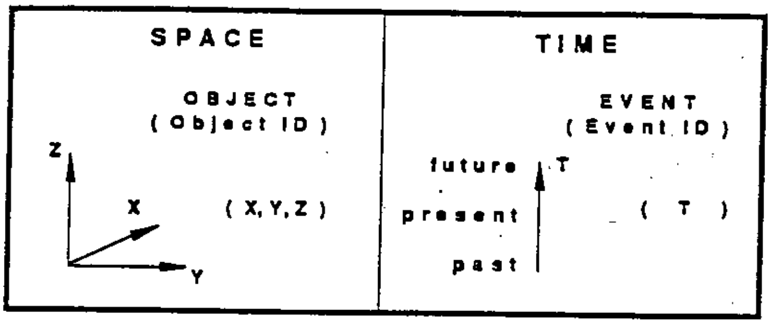


Figure 2

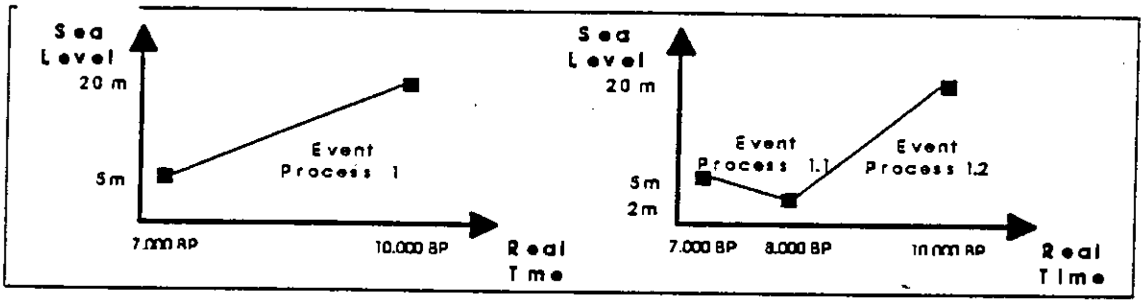
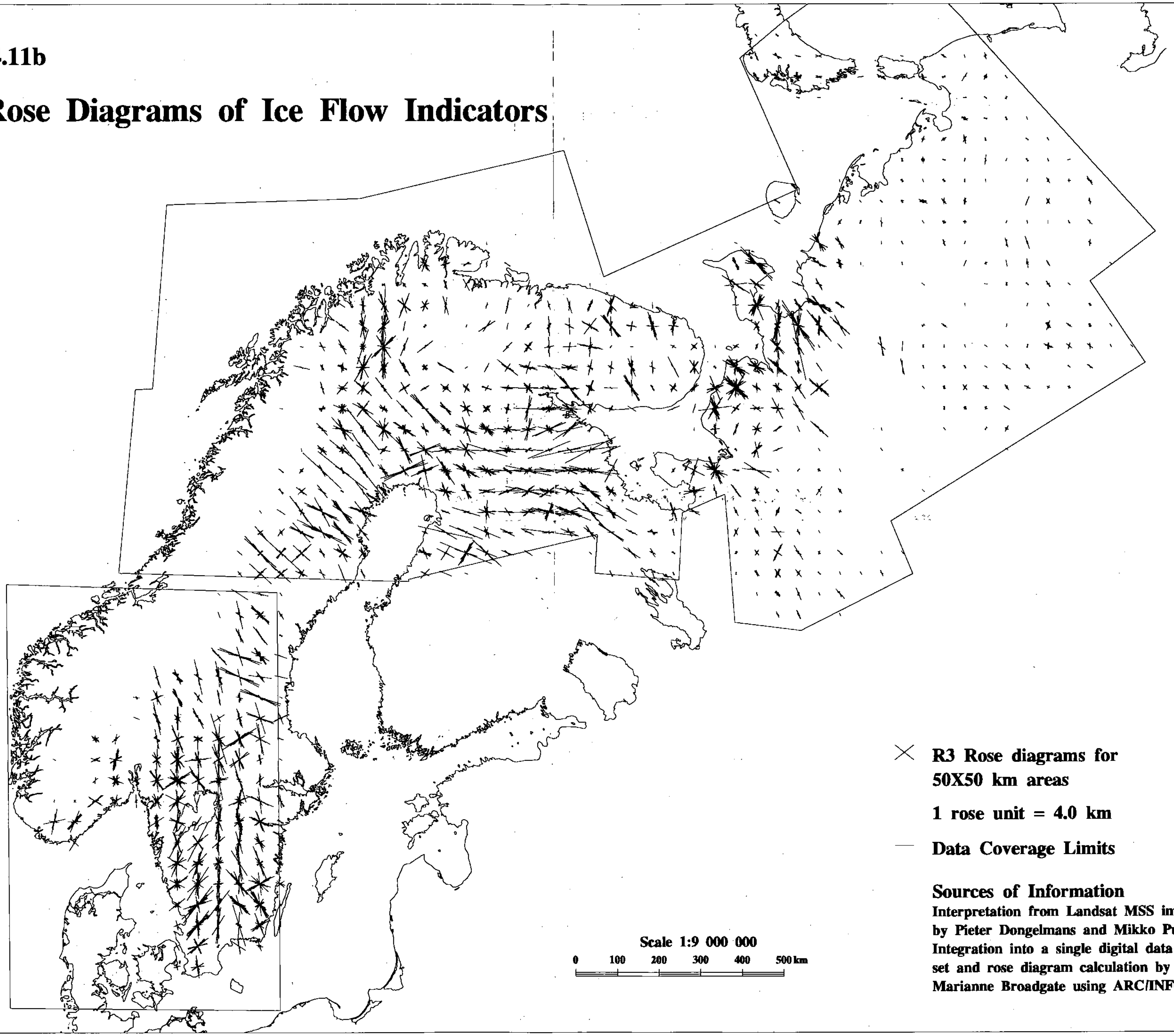


Figure 3

Map 4.11b

R3 Rose Diagrams of Ice Flow Indicators



╳ **R3 Rose diagrams for 50X50 km areas**

1 rose unit = 4.0 km

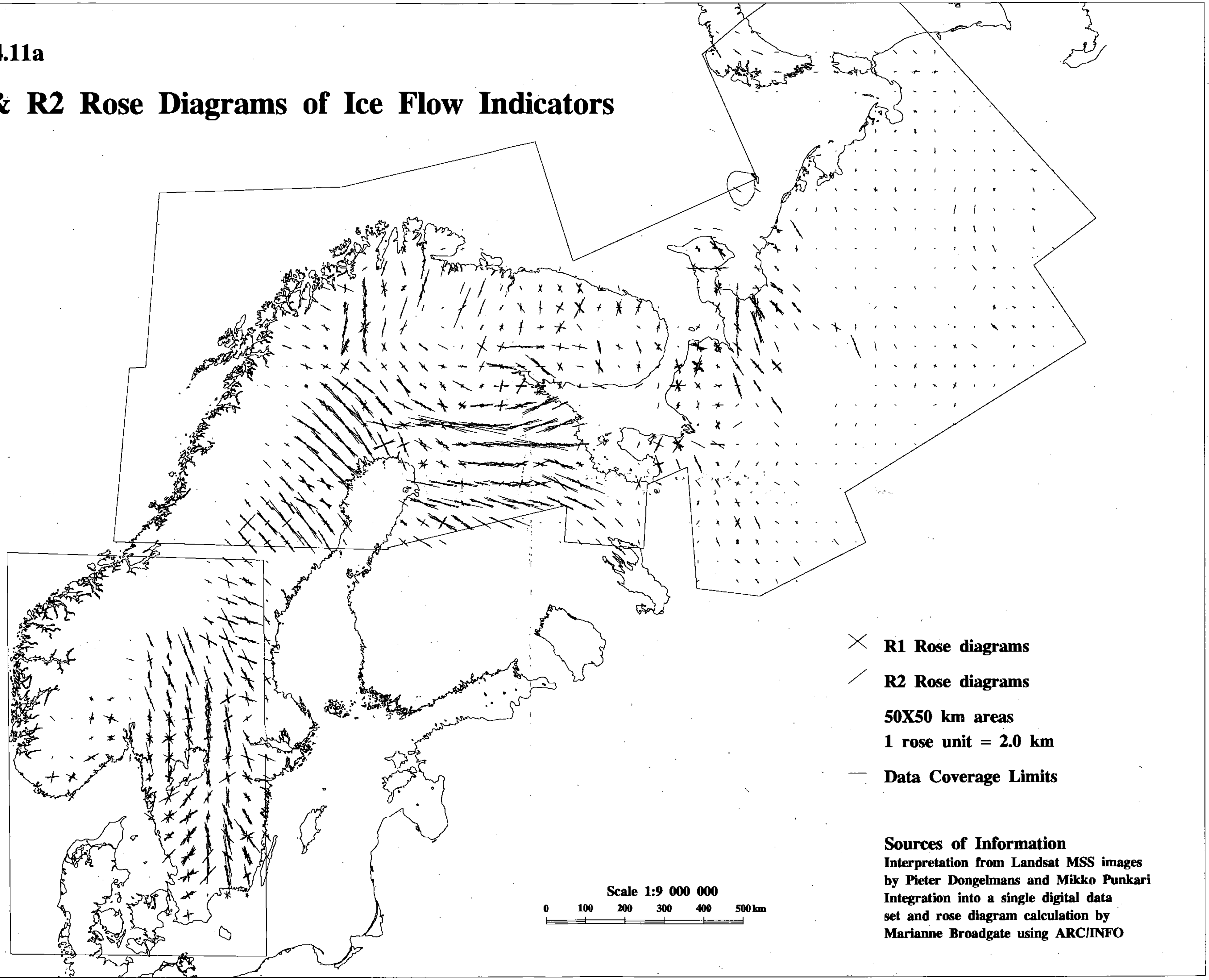
— **Data Coverage Limits**

Sources of Information

Interpretation from Landsat MSS images by Pieter Dongelmans and Mikko Punkari
Integration into a single digital data set and rose diagram calculation by Marianne Broadgate using ARC/INFO

Map 4.11a

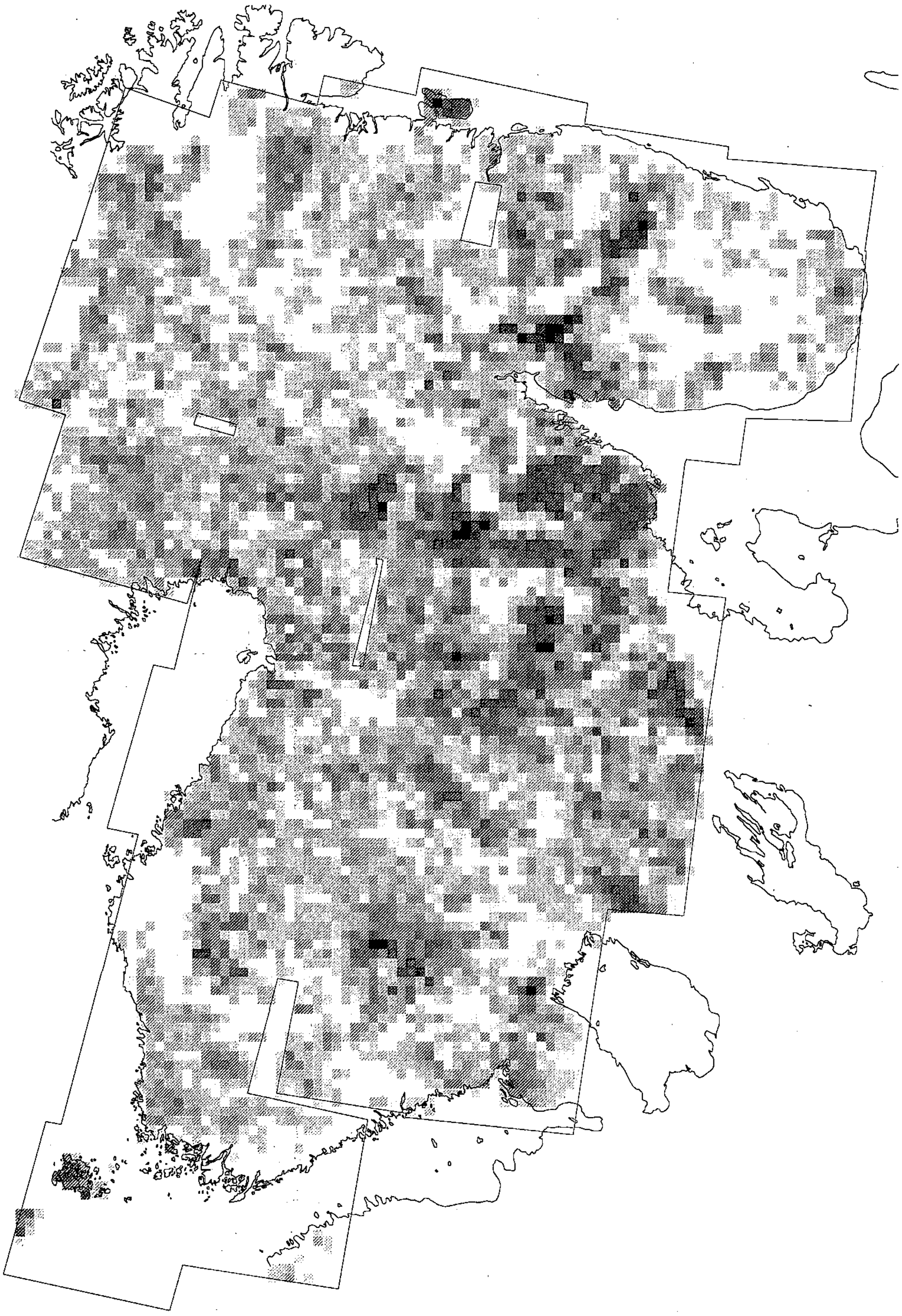
R1 & R2 Rose Diagrams of Ice Flow Indicators



Sources of Information

Interpretation from Landsat MSS images by Pieter Dongelmans and Mikko Punkari
Integration into a single digital data set and rose diagram calculation by Marianne Broadgate using ARC/INFO

Map 4.12a
Lineation Densities



— Data Coverage Limits

Lineation Density

Grid Cell Size: 10X10 km

□ 0
▨ 5
▨ 10
▨ 15
▨ 20
▨ 25
▨ 30
▨ 35
■ 40
■ 45
■ 50

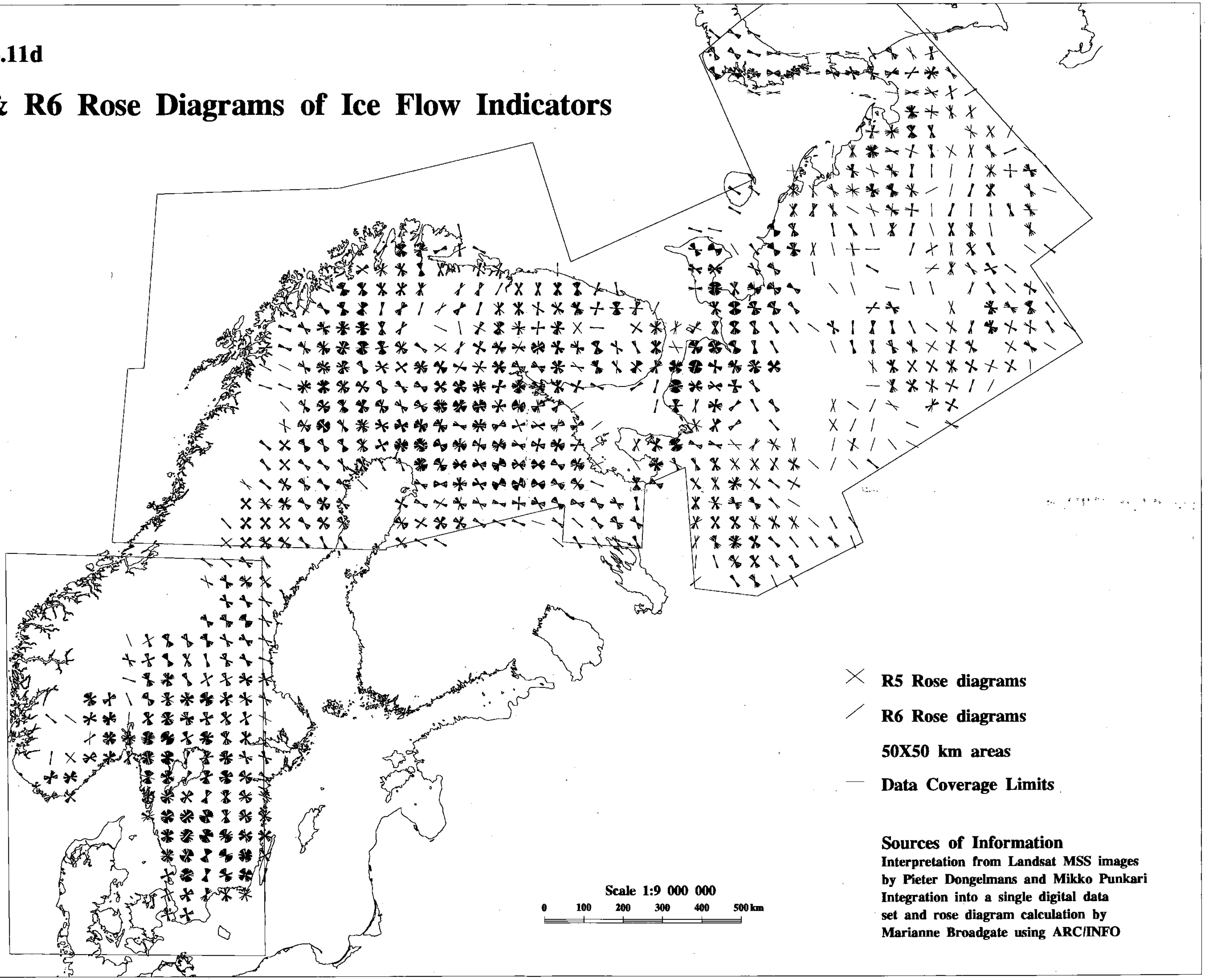
Sources of Information

Interpretations from Landsat MSS
images by Pieter Dongelmans
Integration into a single digital
dataset and lineation density calculation
by Marianne Broadgate using ARC/INFO

Scale 1:5 000 000
0 50 100 150 200 250 km

Map 4.11d

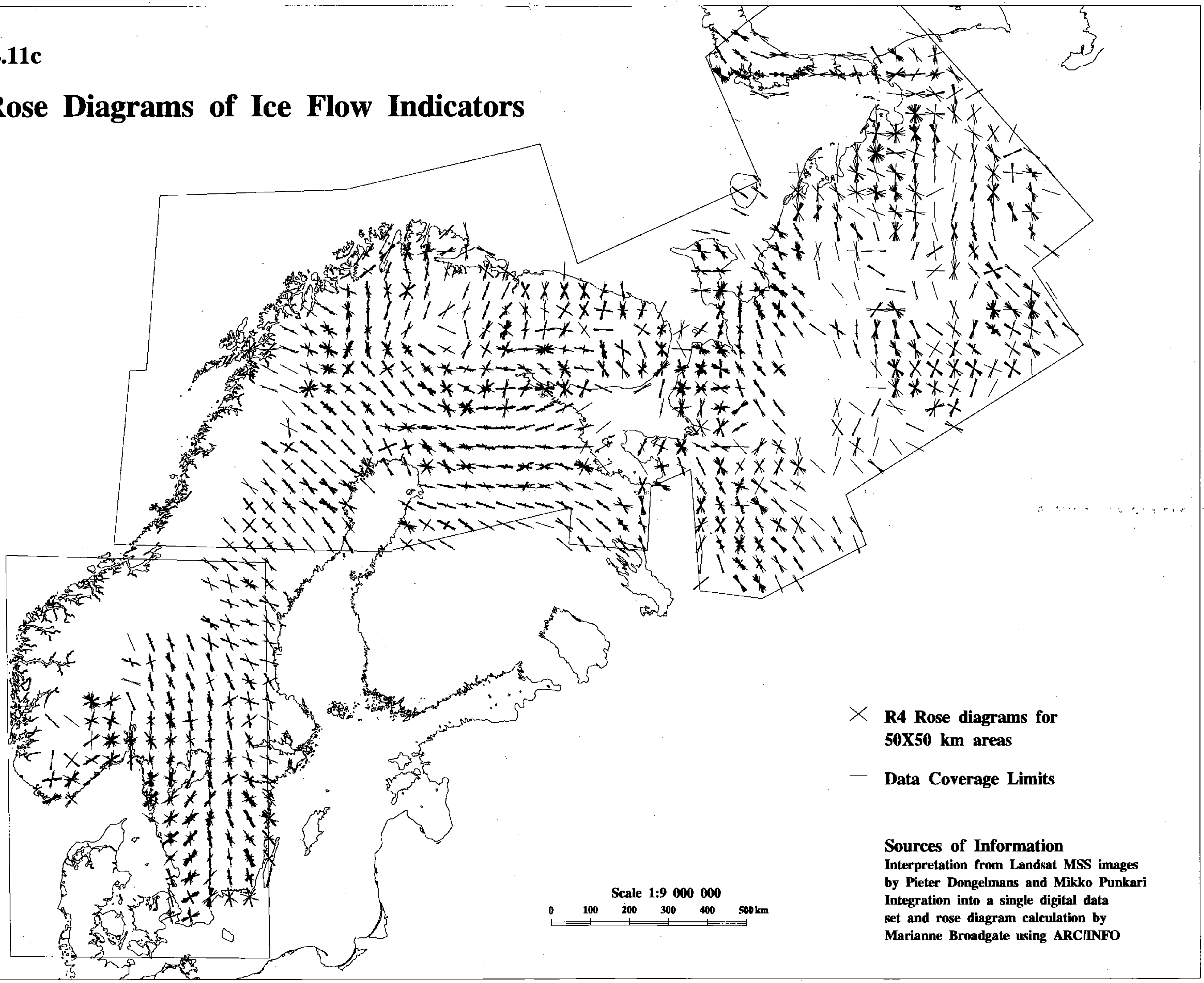
R5 & R6 Rose Diagrams of Ice Flow Indicators



Sources of Information
Interpretation from Landsat MSS images
by Pieter Dongelmans and Mikko Punkari
Integration into a single digital data
set and rose diagram calculation by
Marianne Broadgate using ARC/INFO

Map 4.11c

R4 Rose Diagrams of Ice Flow Indicators



╳ R4 Rose diagrams for 50X50 km areas

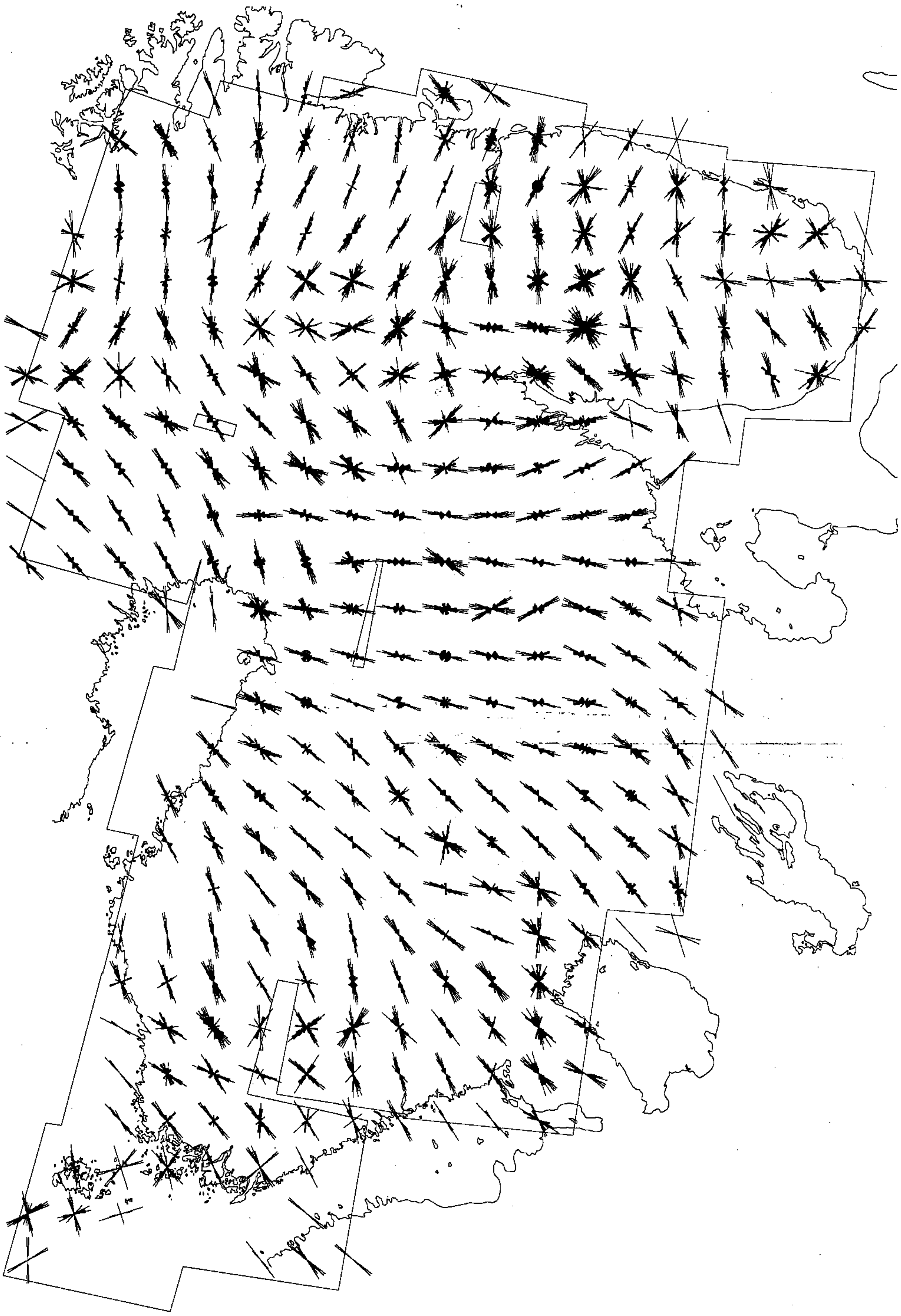
— Data Coverage Limits

Sources of Information

Interpretation from Landsat MSS images by Pieter Dongelmans and Mikko Punkari
Integration into a single digital data set and rose diagram calculation by Marianne Broadgate using ARC/INFO

Map 4.10c

R4 Rose Diagrams of Ice Flow Indicators



× **R4 Rose Diagrams**

50X50 km areas

— **Data Coverage Limits**

Scale 1:5 000 000

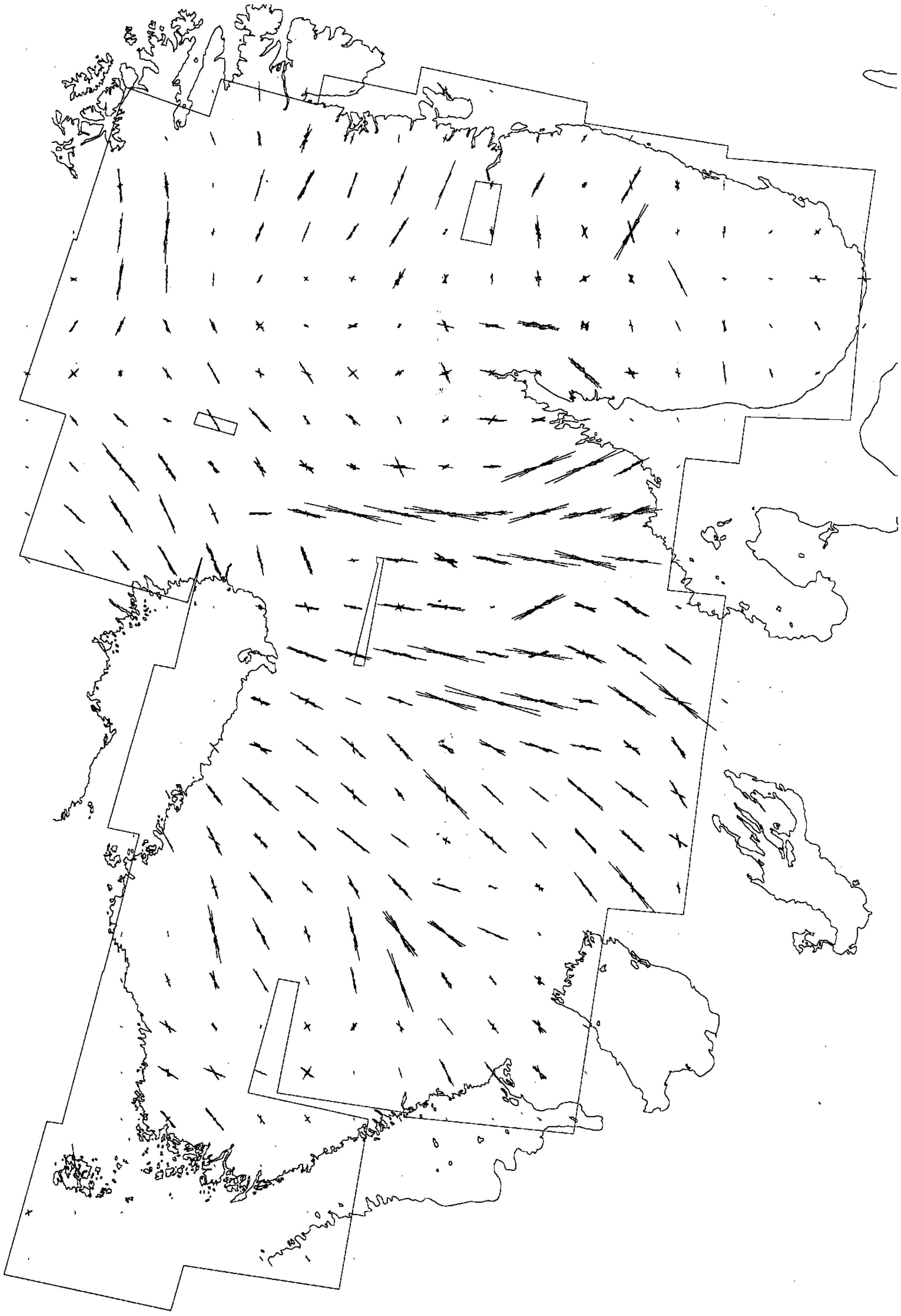
0 50 100 150 200 250 km

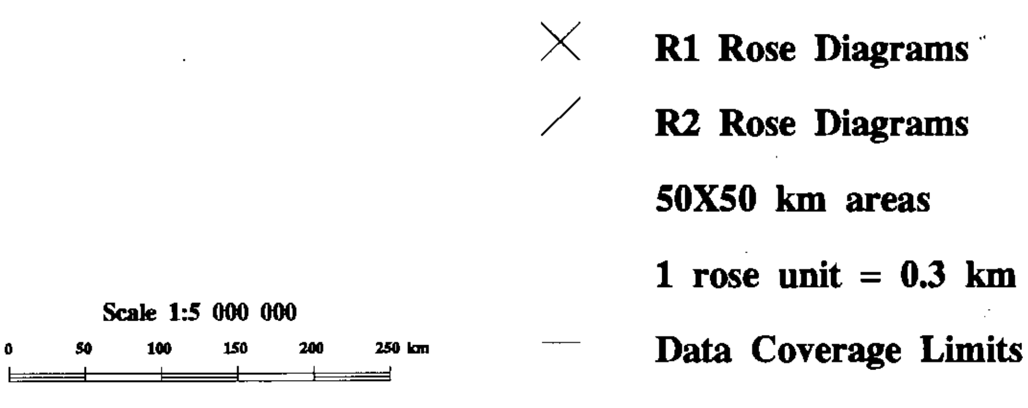
Sources of Information

Lineation interpretation from Landsat MSS images by Pieter Dongelmans Integration into a single digital data set and rose diagram calculation by Marianne Broadgate using ARC/INFO

Map 4.10a

R1 & R2 Rose Diagrams of Ice Flow Indicators





Sources of Information

Lineation interpretation from Landsat MSS images by Pieter Dongelmans Integration into a single digital data set and rose diagram calculation by Marianne Broadgate using ARC/INFO

Map 4.8f

R6 Rose Diagrams

 satellite mapped ice flow indicators

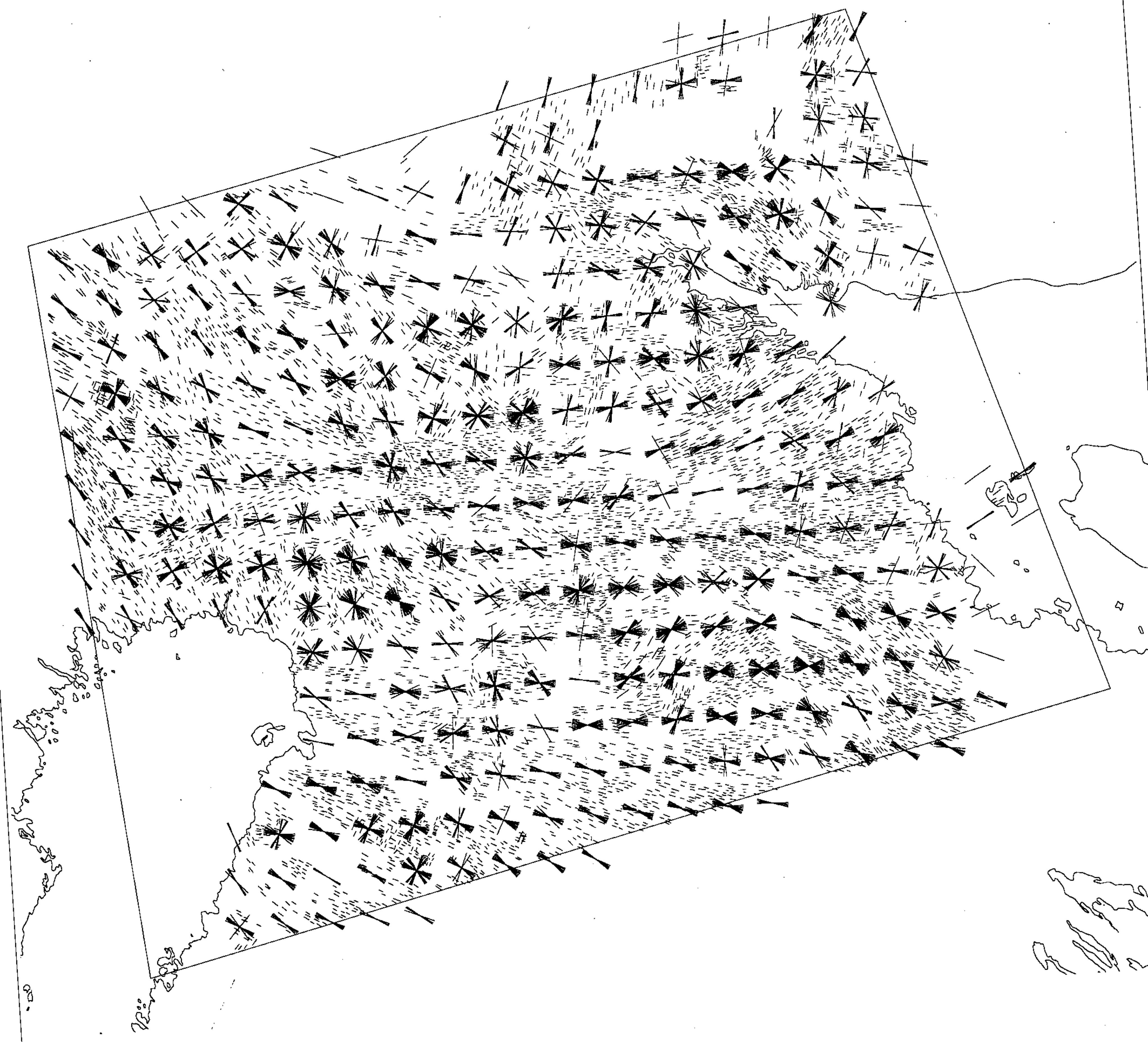
 R6 rose diagrams

30X30 km areas

— Satellite mosaic boundary

Map 4.8e

R5 Rose Diagrams



/ satellite mapped ice flow indicators

× R5 rose diagrams

30X30 km areas

— Satellite mosaic boundary

Map 4.8d

R4 Rose Diagrams

satellite mapped ice flow indicators

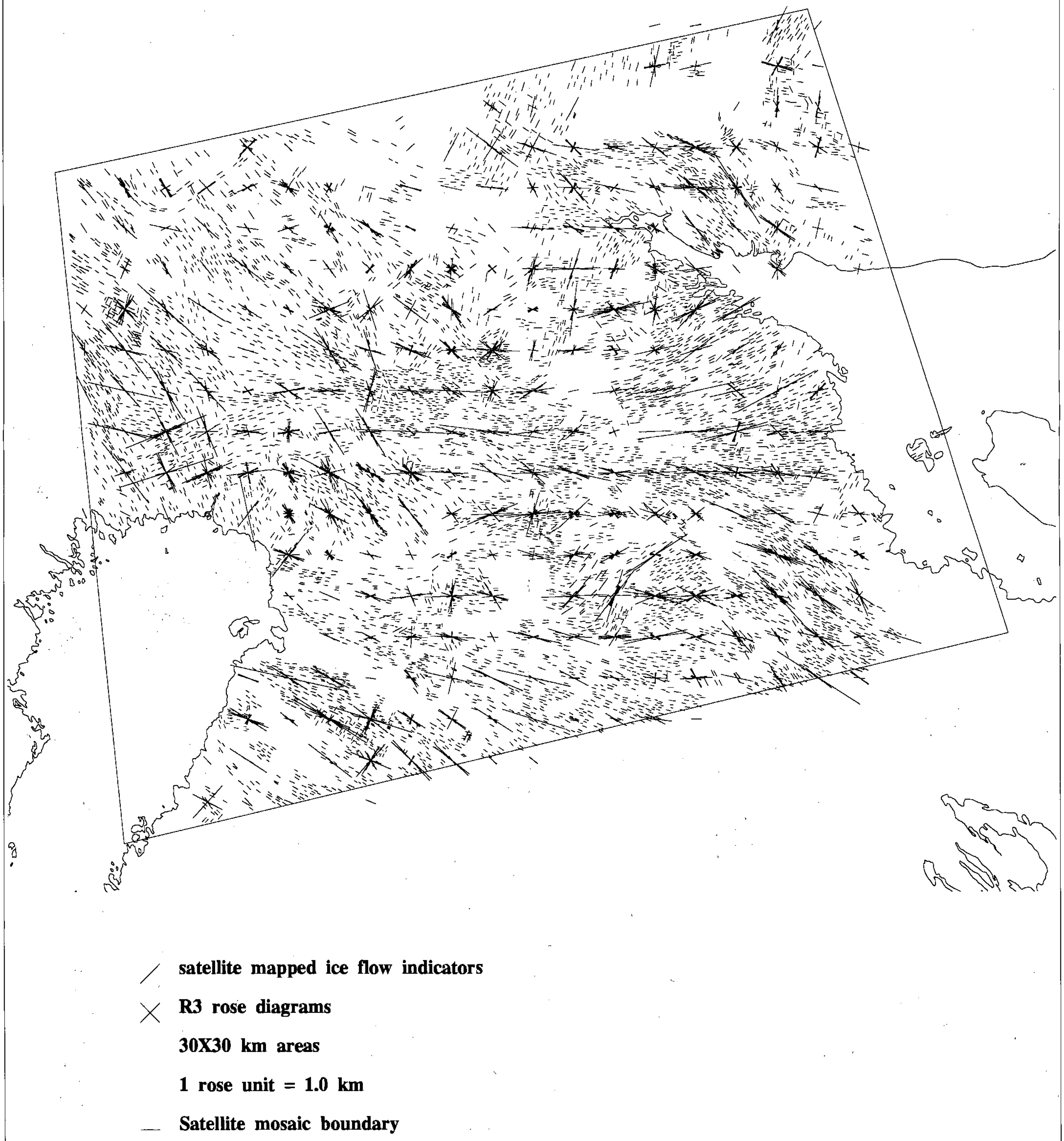
R4 rose diagrams

30X30 km areas

— Satellite mosaic boundary

Map 4.8c

R3 Rose Diagrams



Map 4.8b

R2 Rose Diagrams

╱ satellite mapped ice flow indicators

╳ R2 rose diagrams

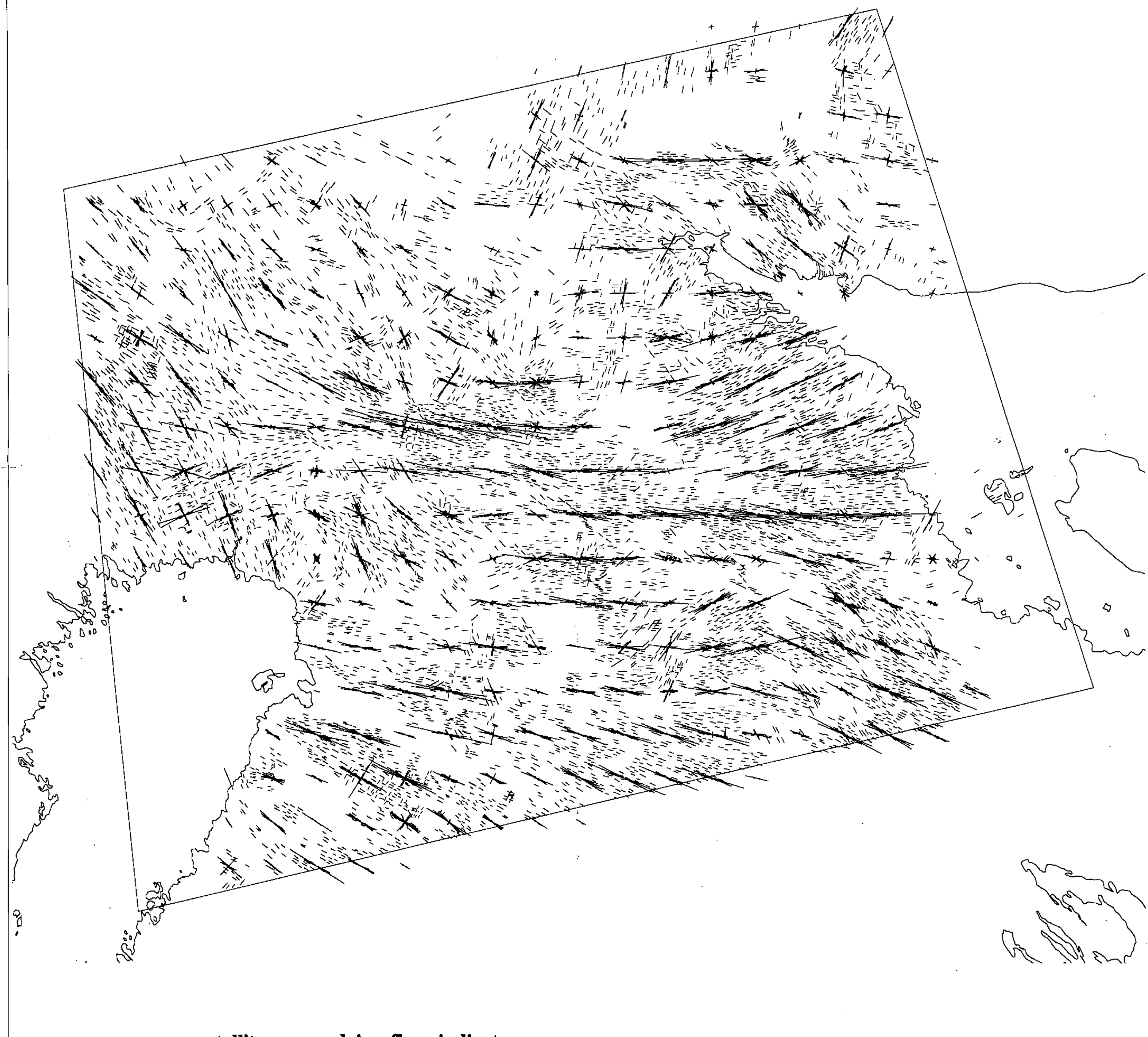
30X30 km areas

1 rose unit = 1.0 km

— Satellite mosaic boundary

Map 4.8a

R1 Rose Diagrams



╱ satellite mapped ice flow indicators

╳ R1 rose diagrams

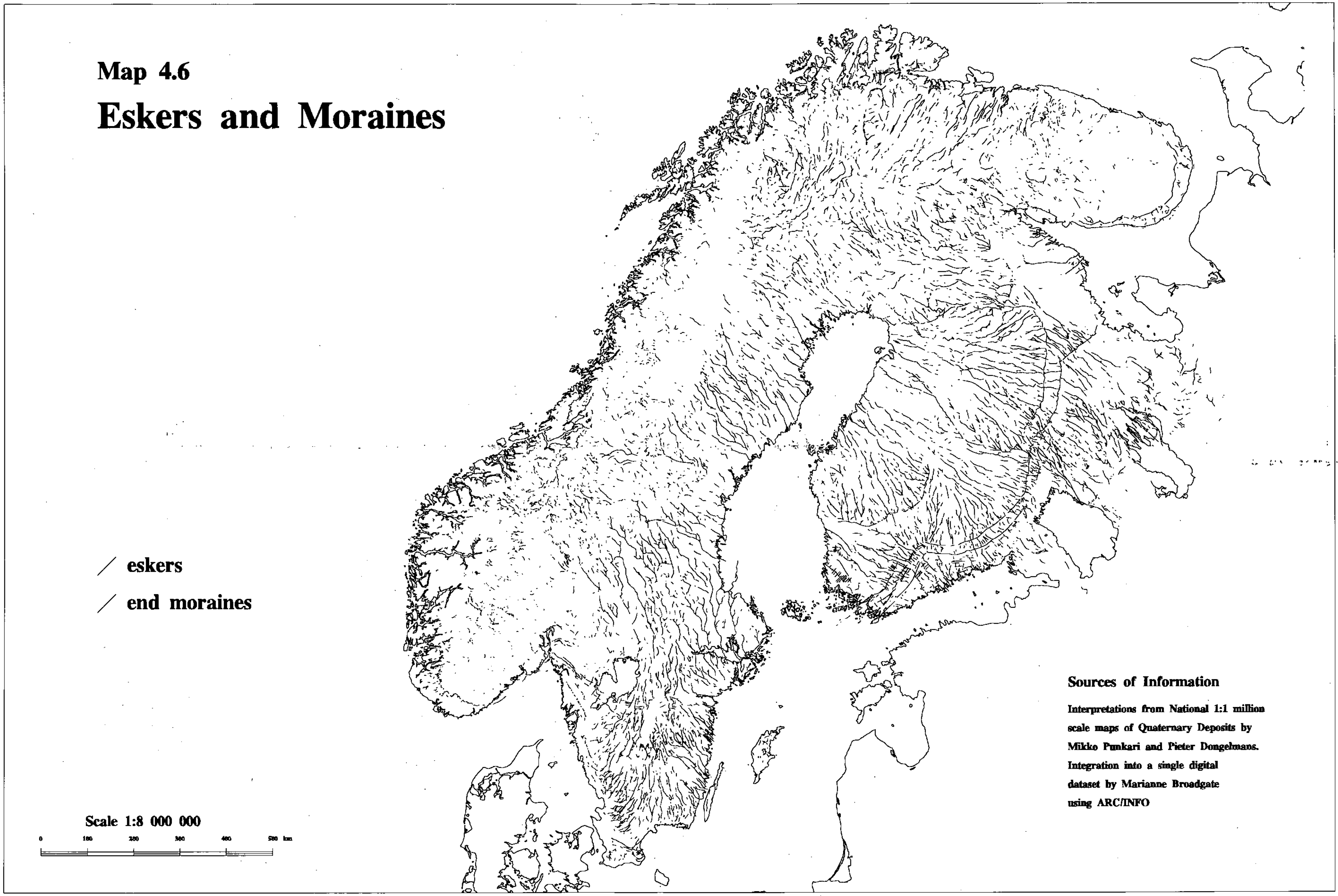
30X30 km areas

1 rose unit = 1.0 km

— Satellite mosaic boundary

Map 4.6

Eskers and Moraines

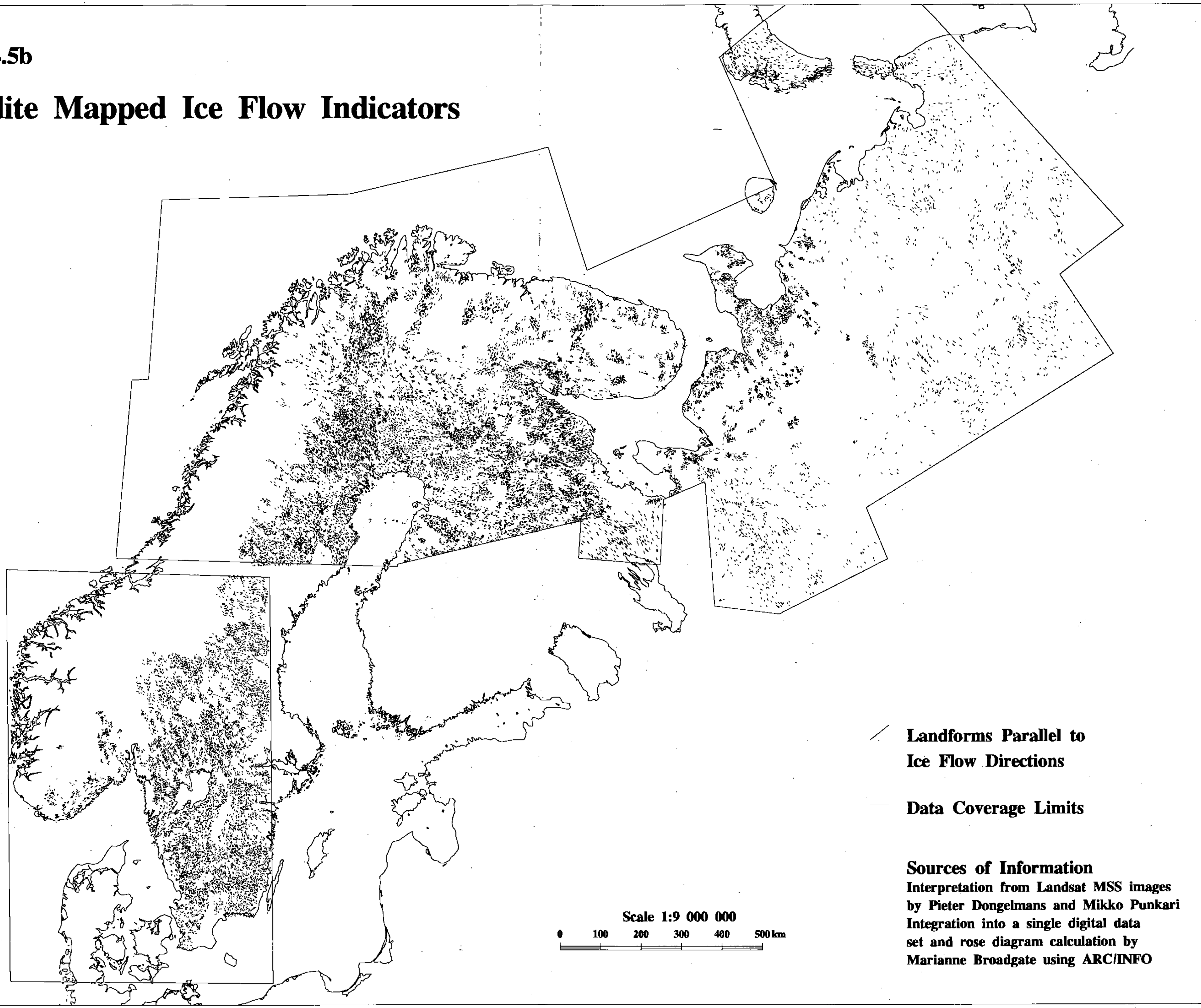


Sources of Information

Interpretations from National 1:1 million scale maps of Quaternary Deposits by Mikko Punkari and Pieter Dongelmans. Integration into a single digital dataset by Marianne Broadgate using ARC/INFO

Map 4.5b

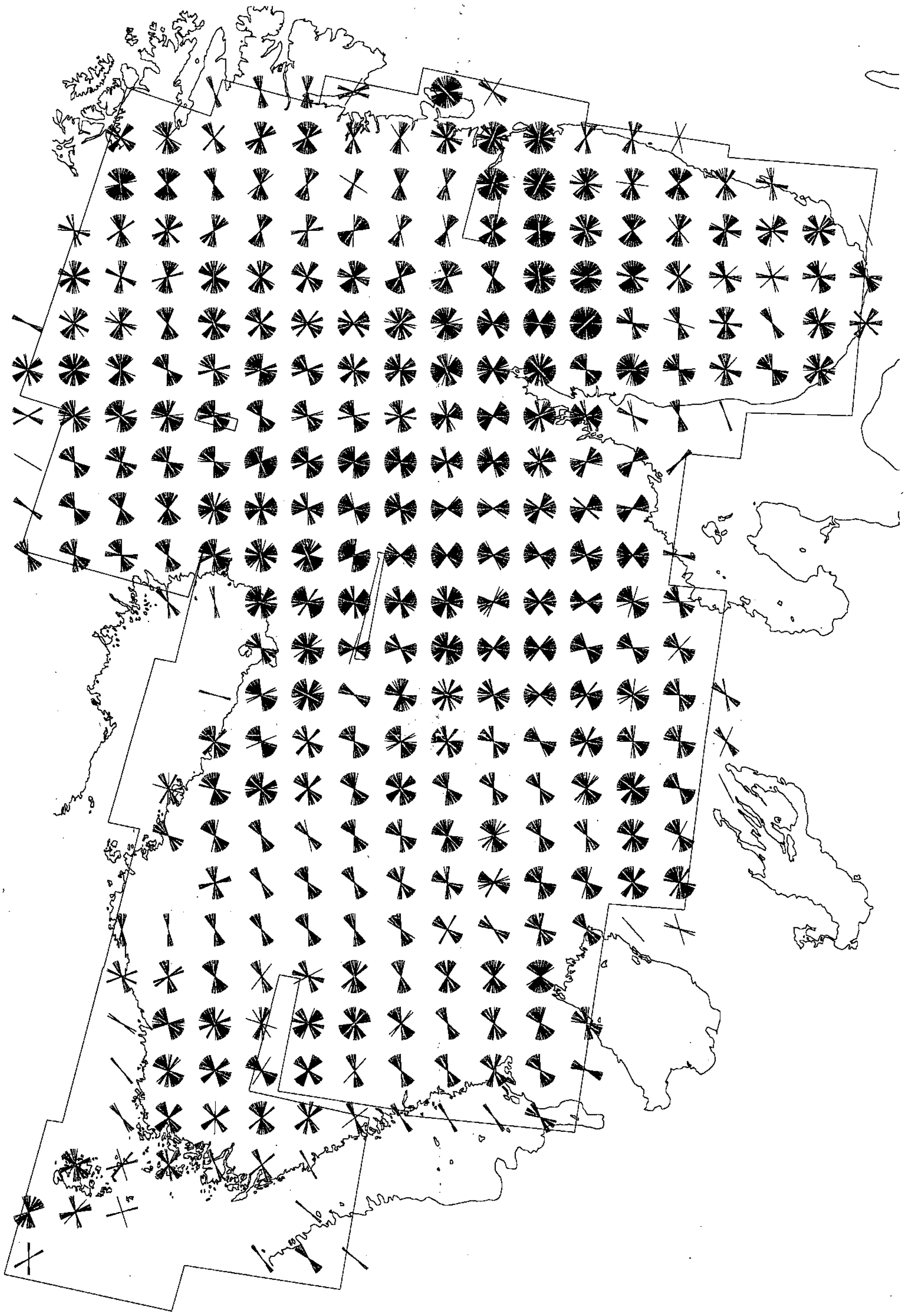
Satellite Mapped Ice Flow Indicators



Sources of Information
Interpretation from Landsat MSS images
by Pieter Dongelmans and Mikko Punkari
Integration into a single digital data
set and rose diagram calculation by
Marianne Broadgate using ARC/INFO

Map 4.10d

R5 & R6 Rose Diagrams of Ice Flow Indicators



× R5 Rose Diagrams

/ R6 Rose Diagrams

50X50 km areas

— Data Coverage Limits

Scale 1:5 000 000

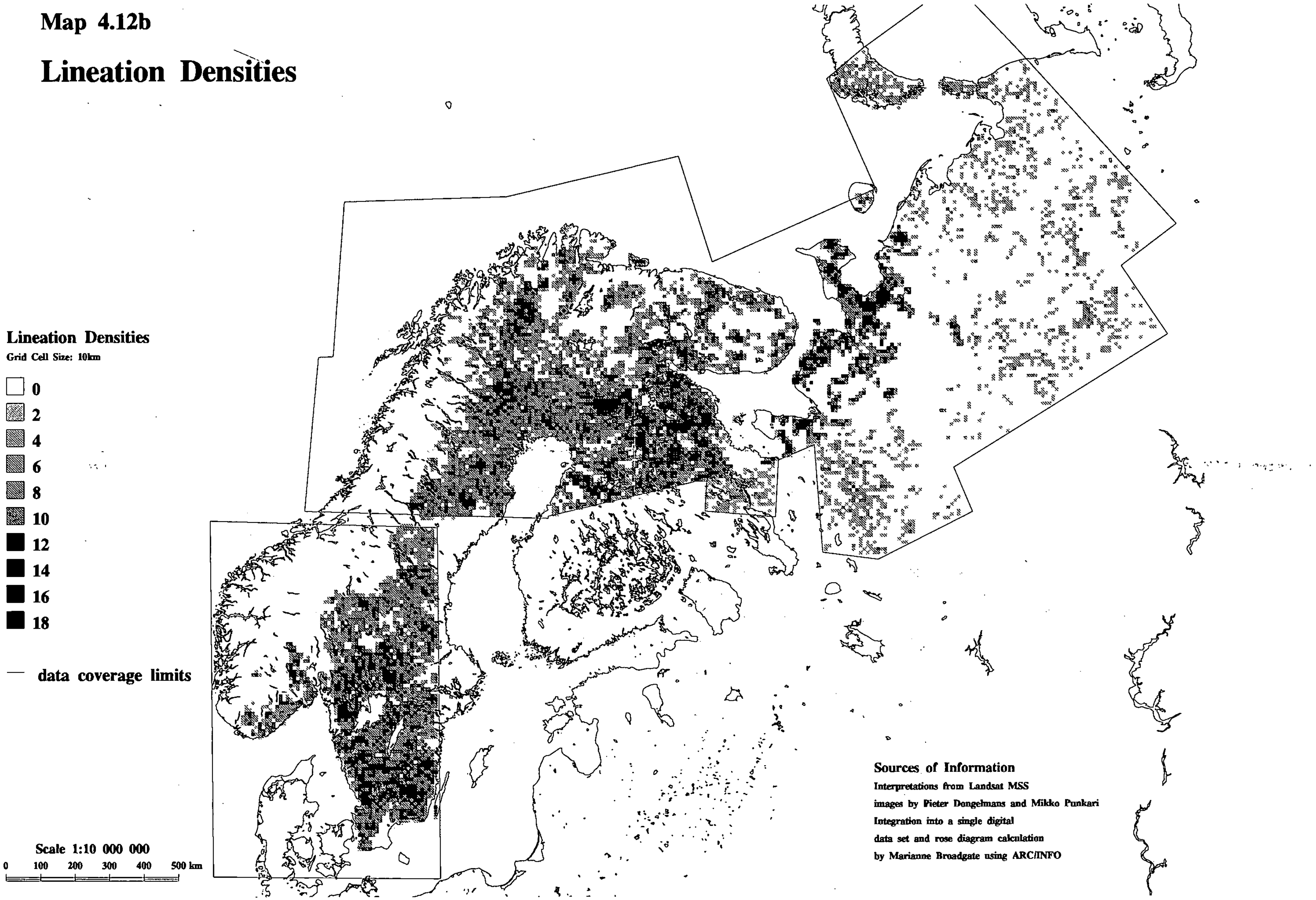
0 50 100 150 200 250 km

Sources of Information

Lineation interpretation from Landsat MSS images by Pieter Dongelmans Integration into a single digital data set and rose diagram calculation by Marianne Broadgate using ARC/INFO

Map 4.12b

Lineation Densities



Sources of Information

Interpretations from Landsat MSS
images by Pieter Dongelmans and Mikko Punkari
Integration into a single digital
data set and rose diagram calculation
by Marianne Broadgate using ARC/INFO

Map 4.10b

R3 Rose Diagrams of Ice Flow Indicators

× R3 Rose Diagrams

50X50 km areas

1 rose unit = 1.0 km

— Data Coverage Limits

Scale 1:5 000 000

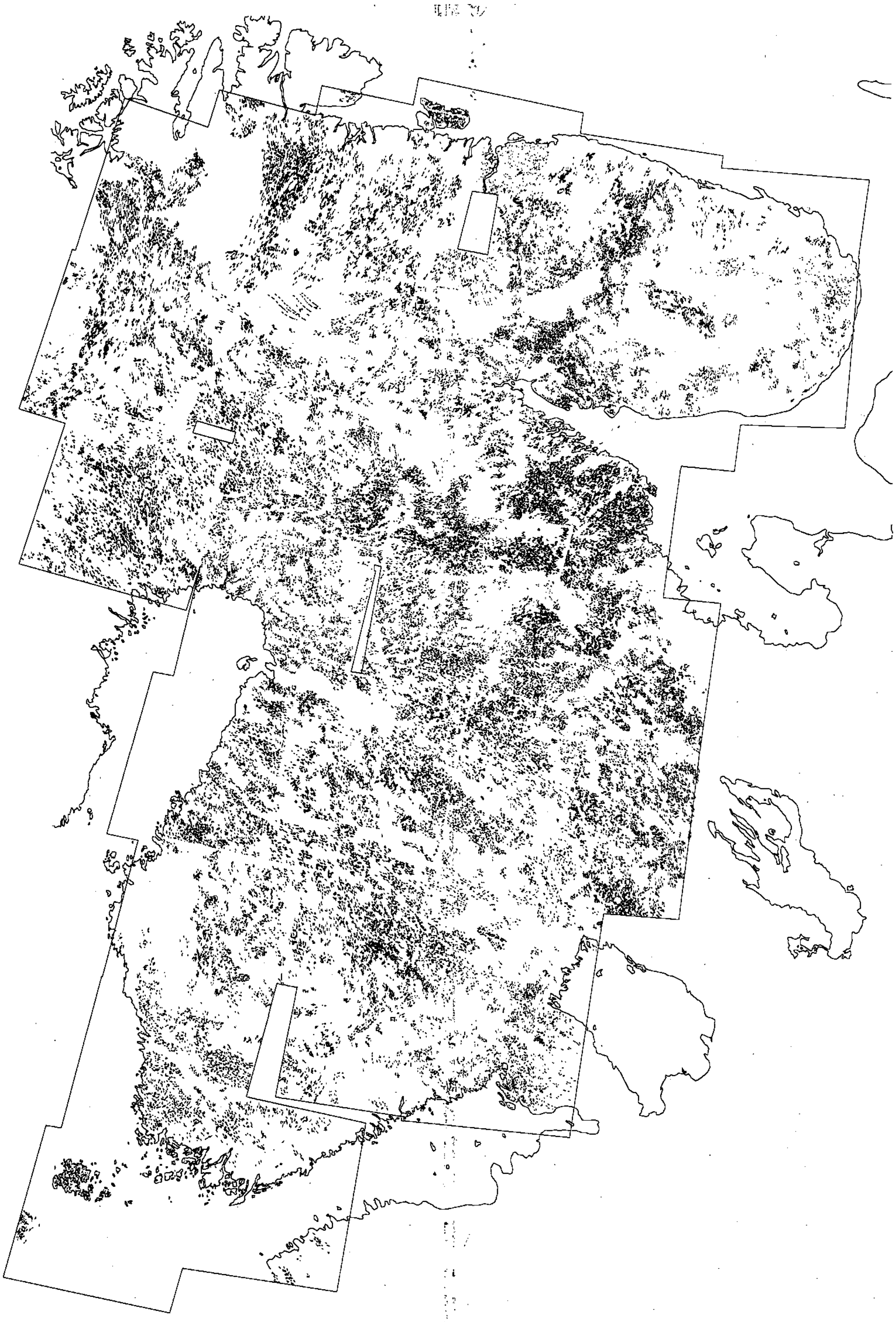
0 50 100 150 200 250 km

Sources of Information

Lineation interpretation from Landsat MSS images by Pieter Dongelmans
Integration into a single digital data set and rose diagram calculation by Marianne Broadgate using ARC/INFO

Map 4.5a

Satellite Mapped Ice Flow Indicators



— landforms parallel to ice flow directions

— extent of satellite coverage

Scale 1:5 000 000

0 50 100 150 200 250 km

Sources of Information

Interpretations from single Landsat MSS Images by Pieter Dongelmans.
Integration into a single digital data set by Marianne Broadgate using ARC/INFO