Extreme climates: a UK–North Atlantic ocean-margin perspective

Continental Shelf and Margins Programme

Draft Scientific Prospectus

Internal Report IR/04/099

BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT IR/04/099

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Key words

Climate; Cenozoic; UK–North Atlantic ocean margin.

Front cover

Debris-laden iceberg at southern margin of Vatnajökull ice sheet, Iceland (photo by M. Stoker)

Bibliographical reference

STOKER, M.S. 2004 Extreme climates: a UK–North Atlantic ocean-margin perspective. Draft Scientific Prospectus. *British Geological Survey Internal Report*, IR/04/099. 39pp.

Edinburgh British Geological Survey 2004

Foreword

A recent article in WWF News (Autumn 2003) reported that global warming would result in 'drier summers, wetter winters, dramatic reductions in snowfall, and significant increases in sea levels' for the Western and Northern Isles of Scotland (WWF 2000). It also gave a prediction that the Gulf Stream, which they state 'brings warm water to the west coast of Scotland', will lose 20% of its strength over the next 100 years. Such predictions of change, be they specific or general, are increasingly commonplace both in media and scientific publications. However, the validity of such claims remains ambiguous in the light of contradictions concerning even some of the most basic of assumptions. For example, the Gulf Stream does not reach Britain. It is heat released by North Atlantic Deep Water formation (as part of the global thermohaline circulation system, GTC) that keeps NW Europe warmer than it should be (for its latitude). Establishing the correct boundary conditions is fundamental to accurate modelling and prediction, especially as it generally agreed that 'the ocean is the key to understanding climate changes; if you don't get the ocean right, you're not going to get the atmosphere right' (a quote from Dr. Walter Muck at Scripps Institution of Oceanography in California: National Geographic, October 2000, p94). Another major fear of the popular press is that a shutdown of the GTC would block the poleward transfer of heat; but it is unclear whether or not this would initiate a sudden episode of chilling for NW Europe, as happened about 12,000 years ago, or a more gradual (decadal) change (see W.S. Broecker in GSA Today, 1999, 9, 1-6). Whilst the consequences for Human society would likely be profound, in either case, there remains an uncertainty of the nature and rate of change. As the deep-water area off NW Britain is one of the most sensitive regions in the world to changes in the GTC, past rates of change are likely preserved in the deep-water sediment record. The development of an understanding of how Earth's climate reached its present state is crucial if we are to be able to make accurate future predictions. To date, no comprehensive study of the sediments in this region has been made; thus, it must be considered that general predictive statements, such as that made in WWF News, remain incomplete.

Acknowledgements

I am grateful to the following people for their motivation and inspiration in trying to help shape a way forward for this research:

- Derek Ritchie and Howard Johnson (BGS)
- John Howe (SAMS)
- Lidia Lonergan (Imperial College)
- The STRATAGEM team

Thanks also to Eileen Gillespie for assistance with the drafting of Figures 1–4.

Contents

Summary

This report provides a draft prospectus that maps a way forward for BGS science research into climate change, with particular emphasis on the ocean-margin record. The information presented is based on core activity and research undertaken by the Continental Shelf and Margins programme (CSM), including national and international collaboration. The emphasis has been to compile an overview statement on the current status of climate-related research within the CSM, with a view to assessing its potential relevance to the emerging BGS Science Programme 2005–2010 and beyond.

The report begins with a summary of the key themes relevant to any understanding of environmental change, namely: Forcing Mechanisms (internal and external to Earth); Long-Term Climate Change; and, Short-Term Climate Change. Accurate predictions of future climate change can only be established by understanding how the climate has reached its present state. As the Earth has been an icehouse world since late Eocene time, an understanding of the Cenozoic evolution of the North Atlantic region is of paramount importance in unravelling this puzzle. The consequences of forcing mechanisms are clear on ocean margins around the North Atlantic region, where they have driven changes in sedimentary, oceanographic and glacial dynamics. However, the linkage between internal and external forces, and their relative contributions to change remain unclear. The establishment of a better event chronology for the North Atlantic region would help to resolve this issue.

From an ocean-margin perspective, the way forward should incorporate better regional correlations and syntheses, and properly co-ordinated strategic sampling, drilling and core analysis. Within the framework of the CSM, four detailed scientific objectives are proposed:

- North Atlantic Cenozoic correlations and syntheses.
- Neogene sequence stratigraphy.
- Reconstruction of Pleistocene ice limits offshore NW Britain.
- Collaborative focusing.

These objectives represent the starting point of the project, which is initially perceived as a three-year project, dependent upon the level of science budget funding. These objectives can be fully met by utilising the extensive set of legacy data and knowledge held by the BGS, and by building upon established collaborations with other research institutes and universities. These objectives have relevance to the key themes, and fall within the science priorities as defined by both NERC and the BGS science strategy team.

The current ongoing record of research outlined in Appendices 1–3, highlights the well-established collaboration with other national and international groups. These ventures are expressed as scientific papers and joint PhD projects. Appendices 4 and 5 represent concept notes on future CSM/BGS initiatives. In particular, Appendix 5 proposes a multidisciplinary approach to developing a better understanding of near-surface and surface Earth system processes, with particular respect to the late Cenozoic shaping of the UK landmass and continental margin — the ‘Peak-to-Trough (P2t) initiative.

1 Introduction

Understanding the mechanisms by which climatic extremes develop, are maintained and end is fundamental to a quantitative description of global change, and ultimately to the development of a safer and sustainable environment. Earth is currently in one of those extremes, the geologically unusual situation of bipolar glaciation. Whilst knowledge of how the Earth's system operates to maintain the current climate is relatively good, there is much debate as to how the climate reached this state.

The crucial questions of climate change are those of process and response (cause and effect). The instrumental climate record is only about 100 years long, which is insufficient for establishing whether climatic variation over this interval reflects natural rates of change or the effect of anthropogenic atmospheric input. By way of contrast, ocean sediments provide a unique record of Earth's climate fluctuations at a variety of scales: tectonic (>0.5 m.y.); orbital (20–400 kyr); oceanic/deglacial/millennial (hundreds to a few thousand years); and historical/anthropogenic (seasonal to millennial) (Fig. 1). Analysis of the recovered marine sediments provides vital information on palaeoenvironmental conditions that were significantly different from those observed today (i.e. sea-surface temperature, thermocline depths, ocean surface and deep circulation, atmospheric circulation patterns). For scientists engaged in the development of predictive models of future climate change, such information is crucial if they are to anticipate the true magnitudes, frequencies and rates of natural climatic variability. For policy makers concerned with sustainable development, this information provides both a perspective (a long view) and a focus for what are the major and underlying problems.

The climate of the UK is controlled to a large extent by oceanographic circulation in the North Atlantic Ocean. Despite its relatively high latitude, the UK enjoys a temperate climate largely through the influence of northward-flowing surface waters that flow into the North Atlantic where — between Norway and Greenland — they eventually cool, increase in density and sink to great depths forming North Atlantic Deep Water (NADW). It is heat released by NADW formation that keeps the UK (and Western Europe) warmer than it should be, and not the (incorrect) assertion that the heat is carried in the Gulf Stream, which does not reach Britain (Broecker & Denton 1990; Kershaw 2000). Deep ocean water involves the bulk of the ocean's volume, and thus controls the long-term heat distribution of the Earth via the global thermohaline circulation (GTC). As NADW flows south, away from the Norway–Greenland region, a major bathymetric ridge — the Greenland-Scotland Ridge (GSR) — forms a barrier to flow. Of particular significance to the UK, is the fact that the deepest passageway across the GSR is located between NW Britain and the Faroe Islands (Fig. 2). This has resulted in the ocean margin bordering NW Britain being one of the most sensitive areas of the NE Atlantic region with respect to the flux of the GTC and its impact on large-scale climate change. Consequently, Cenozoic sediments preserved in the deep-water basins of the Rockall Trough and Faroe-Shetland Channel represent an invaluable database for the study of climate change over all time scales.

The purpose of this prospectus is to define a science strategy that will enable the BGS to make a relevant and valuable contribution to the scientific community concerned with investigating the causes of climatic changes on all time scales. Three major themes underpin the ideas contained in this prospectus: Forcing Mechanisms; Long-Term Climate Change; and Short-Term Climate Change. Each theme will be addressed by new initiatives, which incorporate the integration of legacy data with newly acquired sample and geophysical data. The focus of this prospectus has been shaped, to some degree, by ongoing work within the Continental Shelf and Margins programme of the BGS, which includes collaboration between the CSM and other external Arctic–North Atlantic research programmes (Appendix 1). This prospectus also contains an implementation strategy, which can and will be modified as the objectives become more clearly defined, but which are designed to build upon collaboration both internal and external to the BGS (Appendices 2–4).

The ideas contained within this prospectus fall within the science priorities as defined by NERC contained in the document *Science for a Sustainable Future 2002–2007* (NERC 2002), with particular emphasis on the priority area defined as **Climate Change**. This initiative also falls within the emerging BGS geoscience strategy document that outlines the programme for 2005–2010 and beyond, including *sustainable land use* and *safer environment*. Moreover, it should form an integral component of the newly emerging *Earth System Science* discipline, also highlighted by the BGS strategy document, that requires us to understand not only the processes within the component parts, but also the interactions between them, and with human society. Further comments regarding the BGS science strategy and this initiative are presented in Appendix 5, which presents a possible way forward for Earth System Science within the BGS in terms of shaping the landmass and offshore region: the *Peak-to-Trough* (P2t) initiative.

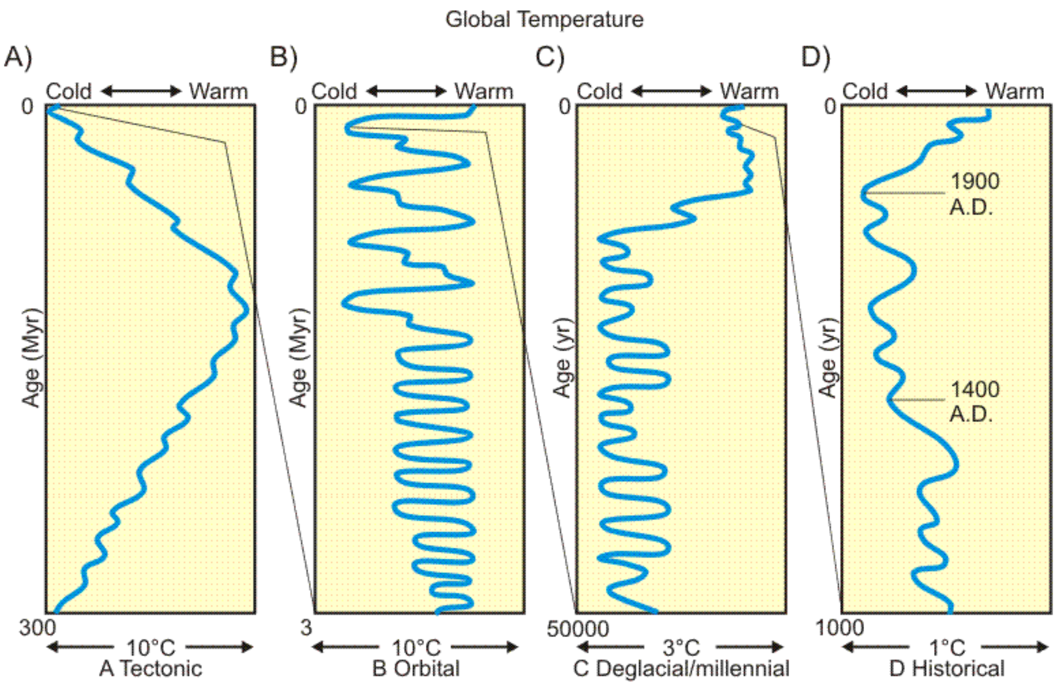

Figure 1. Timescales of climate change: (A) the last 300 million years; (B) the last 3 million years; (C) the last 50,000 years; and , (D) the last 1000 years. Redrawn after Ruddiman (2001)

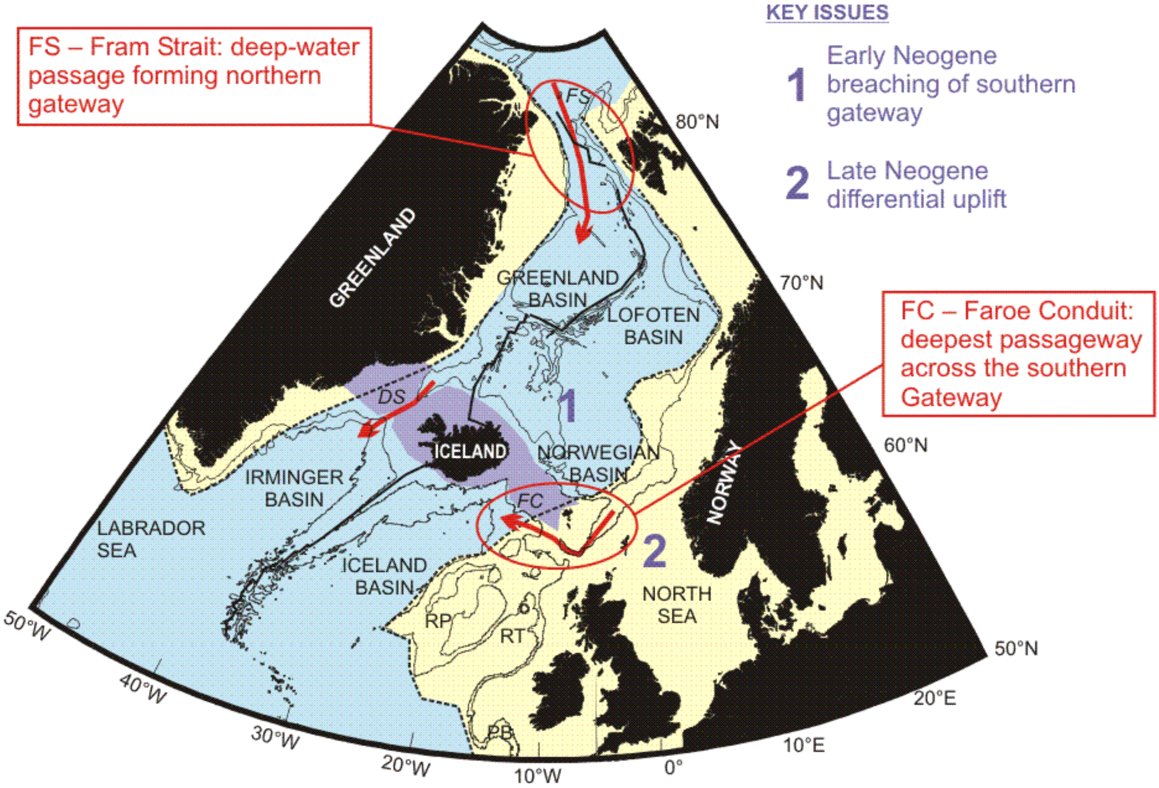

Figure 2. Simplified tectonic map of NE Atlantic region showing disposition of continental (pale yellow) and oceanic (blue) lithosphere, the anomalously shallow Greenland-Scotland Ridge (lilac), and deep-water pathways (red arrows). Abbreviations: FS, Fram Strait; DS, Denmark Strait; FC, Faroe Conduit; RT, Rockall Trough; RP, Rockall Plateau. See text for detailed explanation of key issues (1 & 2).

2 Overview of key themes

Three major themes underpin the ideas contained in this prospectus: 1) Forcing Mechanisms; 2) Long-Term Climate Change; and, 3) Short-Term Climate Change. All three themes are inexorably linked, and together they provide a template for an analysis of the climate system at its most fundamental level, i.e. in terms of forcing (cause) and response (effect). The term *forcing* refers to those processes/mechanisms that drive or cause change; *response* is the effect — the long- and short-term climate changes that occur.

In their *Initial Science Plan, 2003–2013*, the Integrated Ocean Drilling Program (IODP) stated that one of their main goals was to address the cause of environmental change on all time scales (IODP 2001). This prospectus endorses such an approach. Too many previous studies of climate change in the NE Atlantic region have tended to focus on one or two variables (e.g. ocean currents, orbital parameters), or on one scale of change (commonly hundreds to a few thousands of years). Arguably, the short-term response to changes in specific parameters, such as the shutdown of the Atlantic Ocean's conveyor circulation, is driving current research (cf. Broecker 1999). However, the present general circulation models are a legacy of a progressive change since at least mid-Miocene time (Zachos *et al*. 2001), following the creation of the Arctic–North Atlantic ocean gateways (Thiede & Myhre 1996; Stoker *et al*. In press). Thus, accurate prediction of future climate change can only be established by understanding how the climate has reached its present state.

The accurate reconstruction of past environments must be based upon a consideration of categories of processes (mechanisms) and their linkage, rather than the timing of the response. The IODP (2001) suggested three main categories of forcing mechanism:

1. Internal forcing mechanisms, i.e. those processes internal to Earth's system. This includes tectonically induced changes that affect continental assembly and breakup, elevation and erosion of mountain chains and plateaus, and the opening and closing of oceanic gateways, as well as magmatism, which may affect concentrations of CO_2 and other greenhouse gases in the atmosphere.
2. External forcing mechanism, i.e. those processes that are external to Earth's climate system. This includes the interaction of the climate system with orbital forcing, reflected by the variation in the relative strength of different orbital parameters (i.e. eccentricity, tilt and precession) (Maslin *et al*. 1998).
3. Interaction of internal and external forcing mechanisms. This is probably the most important category as it prompts the exploration both of the temporal and spatial distribution of climatic shifts and oscillations, as well as the processes, feedbacks and forcing mechanisms that lead to altered climatic states. This may be expressed by intervals of rapid climatic fluctuation superimposed on a longer-term trend, or may explain the breaching of a particular threshold and the resulting environmental changes.

Consequently, issues related to forcing of environmental change include those of the forcing mechanism (the timing and initiation of change), feedbacks that may amplify or reduce the effects of both small and large events, and response (which components of the Earth system are most sensitive and why).

The consequences of forcing mechanisms are clear where they have driven changes in sedimentary, oceanographic and glacial dynamics (Fig. 3). Such changes are commonly preserved in ocean-margin settings, where expanded sediment sections reflect the denudational history of the adjacent hinterland and shelf (prograding sediment wedges), and the effects of deep-ocean currents (contourite drifts) (Fig. 4). Prograding wedges and sediment drifts both provide proxy indicators of environmental change at a variety of timescales. The long-term record of climate change (tectonic to orbital timescale: Fig. 1) may be expressed by changing styles of deposition, manifest by regional unconformities or stratal architecture depicted on seismic reflection profiles, which require long borehole records for calibration. In contrast, short-term climate change (seasonal to a few thousand years) can be studied on relatively short cores acquired from areas of rapidly accumulating sediment. However, their location is more critical. Rapidly accumulating sediments may occur locally on sediment drifts: deltas and fjords provide alternative repositories of high-resolution ocean-margin records.

These underlying themes are addressed by several scientific objectives detailed in section 4, which primarily utilise the sedimentary record as a proxy for environmental change. Tectonic movements, ocean currents and climate all influence the style and geometry of the ocean-margin record. Thus, the ocean-margin succession potentially provides a valuable tool for establishing the nature and timing of environmental change. On this basis, the NE Atlantic region is an ideal area to undertake such research. The Cenozoic plate tectonic development of the region has facilitated the breakup of continents, post-rift vertical tectonic movements, formation of oceanic gateways and climate change, the consequences of which are preserved in the ocean margin succession.

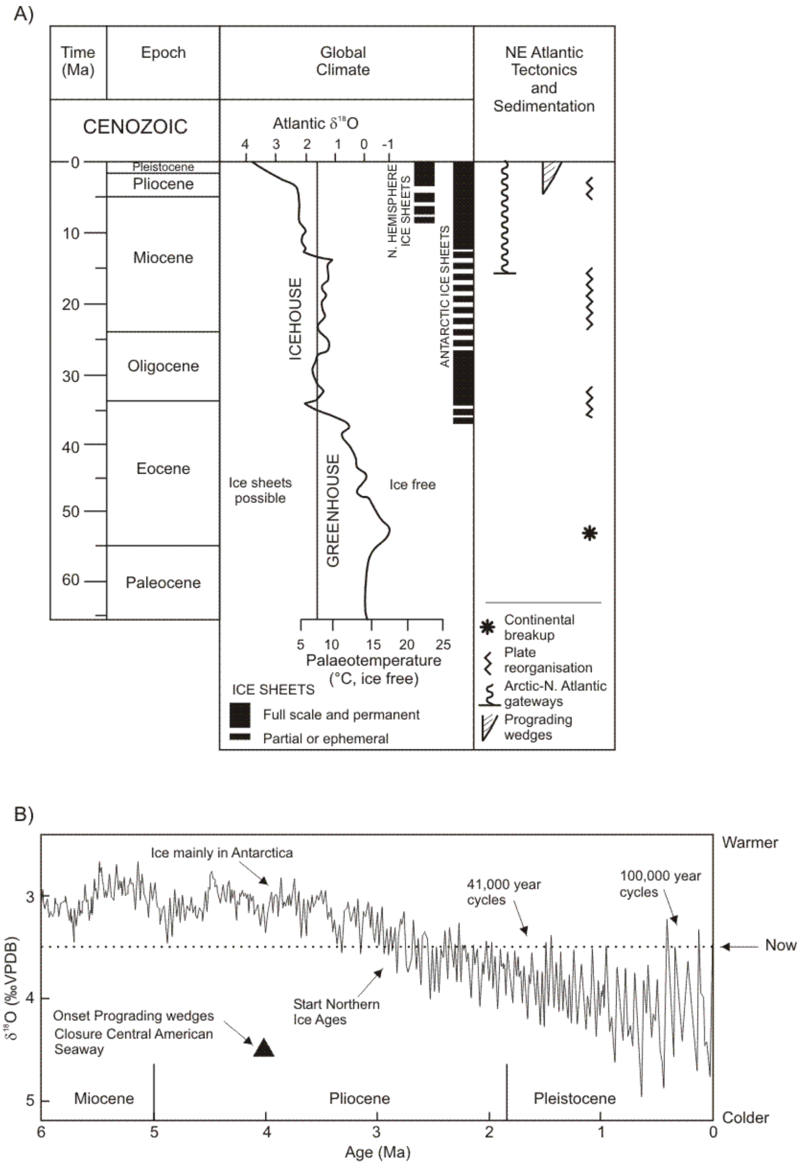

Figure 3. Forcing mechanisms and environmental change: (A) potential linkage between plate tectonic evolution of NE Atlantic region and environmental change; (B) Tectonic movements and change in oceanographic circulation at 4 Ma precedes widespread northern hemisphere glaciation. See text for details. Modified after IODP (2001) and Stoker *et al*. (In press a, b).

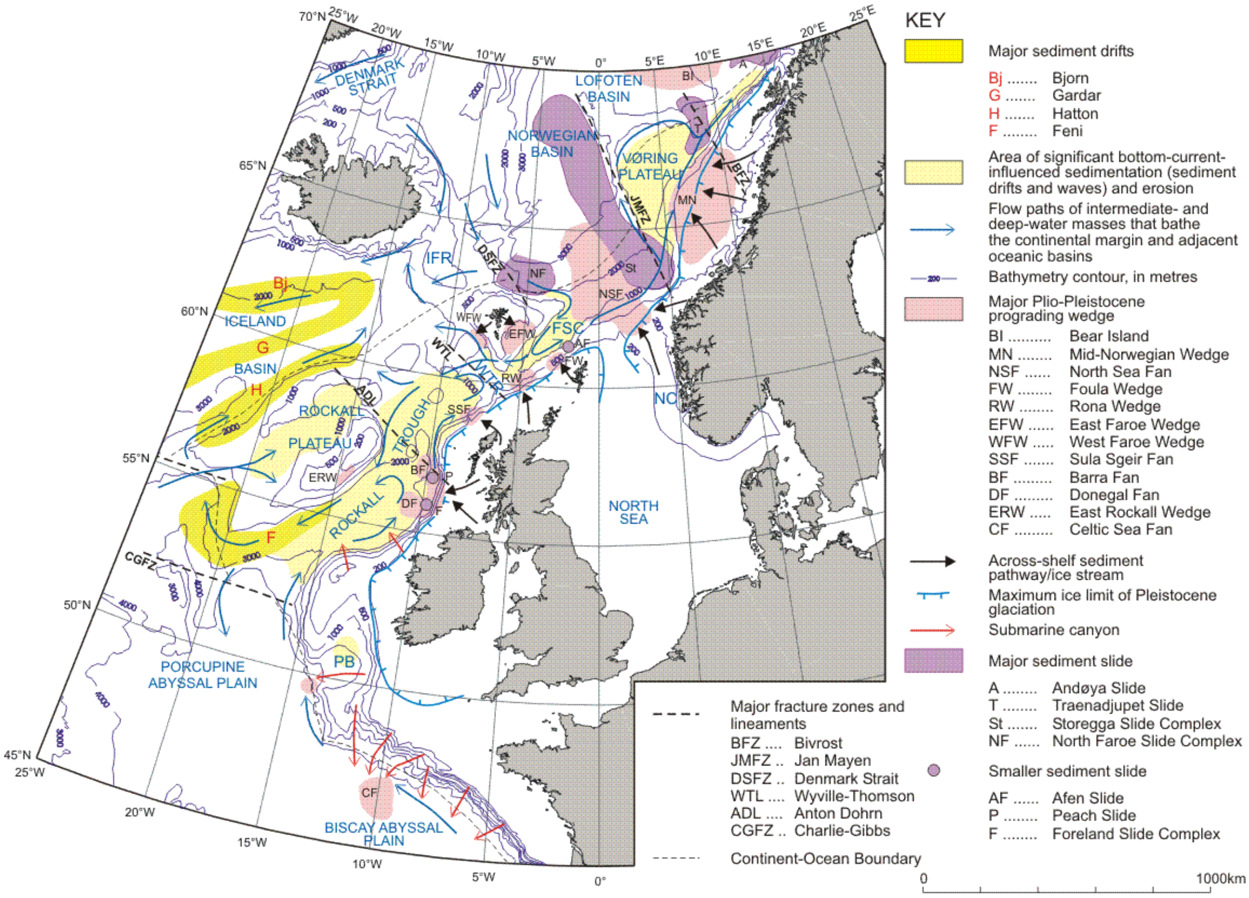

Figure 4. Bathymetric setting of NW European margin showing main tectonic elements, oceanographic circulation pattern, and summary of large-scale sedimentary processes that have contributed to the late Cenozoic shaping of the ocean margin. Abbreviations; NC, Norwegian Channel; FSC, Faroe-Shetland Channel; IFR, Iceland-Faroe Ridge; WTR, Wyville-Thomson Ridge; PB, Porcupine Basin. Modified from Stoker *et al*. (In press b)

3 UK–North Atlantic ocean-margin setting

The Cenozoic post-rift development of the NE Atlantic margins (Fig 1) is generally classed as passive (tectonically inert), subsequent to the rifting and volcanism that led to continental break-up between Europe and Greenland in the early Eocene (Doré *et al.*, 1999; Skogseid *et al*. 2000). However, both compressional and regional epeirogenic movements have affected these margins during the mid- to late Cenozoic interval (Cloetingh *et al.* 1990; Clift 1996; Brekke 2000; Lundin & Doré, 2002), indicating an evolution that has been anything but passive. The causes of these tectonic movements remain uncertain (see Doré *et al.* 2002), but have been attributed to two main types of model, driven by forces related either to horizontal plate motions (e.g. Cloetingh *et al*. 1990) or to mantle convective motions associated with the Iceland plume (e.g. Vågnes & Amundsen 1993; Clift 1996; Rohrman & van der Beek 1996). The consequences of the movements are clear on the NW European Atlantic margin, where they have driven changes in sedimentary and oceanographic dynamics (Fig. 3a) that, in turn, have found expression in regionally significant ocean-margin stratigraphic sequences bound by correlative unconformity surfaces (Stoker 1997; Jordt *et al*. 2000; Eidvin *et al*. 2000; Stoker *et al*. 2001, In press; Faleide *et al*. 2002). The cumulative effects of tectonism on sediment supply and deep-ocean current circulation have latterly been joined by those of Quaternary climate change, to create a physiographically complex and physically dynamic sedimentary environment dominated by the interaction of downslope and alongslope processes (Fig. 4).

The complex bathymetry of the margin between the Lofoten Islands and SW Ireland (Fig. 4) is ultimately a reflection of the crustal thickness variations resulting from rifting and magmatism during the northward propagation of seafloor spreading in the late Mesozoic to early Cenozoic (e.g. Doré *et al.* 1999). Continental extension resulted in a margin as wide as 800 km (west of Britain and Ireland), containing deep-water troughs, banks and plateaux that correspond to sedimentary basins and structural highs (Fig. 4). Enhanced igneous activity associated with the Iceland hotspot resulted in the thickened crust of the Greenland-Scotland Ridge (GSR), which has contributed, along with oceanic fracture zones, to a marked segmentation of the margin (Figs 2 & 4). The configuration of the margin has been further modified during the Cenozoic post-rift period by three main tectonic episodes: i) in the late Eocene–Oligocene, strongly differential subsidence in the Faroe–Rockall region outstripped sedimentation to drive a km-scale deepening, which created the present configuration of underfilled deep-water troughs (Boldreel & Andersen, 1995; Vanneste *et al*. 1995; Stoker 1997; Stoker *et al.* 2001); ii) in the late Oligocene–mid-Miocene, compressive tectonism resulted in the formation of inversion structures both on the Vøring Plateau and in the Faroe–Shetland and North Rockall regions, including the Wyville-Thomson Ridge Complex (WTRC) (Boldreel & Andersen 1995; Doré & Lundin 1996; Lundin & Doré 2002; Ritchie *et al*. In press; Hoult *et al*. In press); and, iii) in the early Pliocene, accelerated subsidence of offshore basins was accompanied by km-scale uplift and erosion of basin margins and continental hinterlands (Cloetingh *et al*. 1990; Brekke, 2000; Kyrkjebø *et al*. 2000; Japsen & Chalmers, 2000; Stoker, 2002). Significantly, these tectonic phases correspond to major North Atlantic plate tectonic reorganisations (Stoker *et al*. In press a, b) (Fig. 3a).

The regional to local variations in subsidence and sediment supply associated with these tectonic movements, acting on and modifying the variable relief of the continental margin, have had a pronounced effect on the patterns both of shelf-margin and deep-water sedimentation patterns and of palaeoceanographic circulation. Arguably, the late Eocene–Oligocene deepening in the Faroe–Shetland and Rockall–Porcupine regions triggered the most dramatic change in basin configurations, manifest by the creation of a late Eocene regional unconformity that is prominently onlapped by the Neogene succession along the ocean margin. The associated onset of deep-water circulation in the Rockall and Porcupine basins (Stoker 1997; McDonnell & Shannon 2001; Stoker *et al*. 2001) (Fig. 3a) established the context for later events, for which two outstanding issues are of importance to understanding the late Cenozoic evolution of the margin:

1. The Greenland-Scotland Ridge (Fig. 1) has had a critical influence on deep-water circulation in the Arctic–Atlantic region, and on the properties of the world ocean, by acting as a barrier to the exchange of deep-water masses between the Northern and Southern hemispheres. This barrier was breached sometime following the Eocene and the deepest passageway (800–1200 m) — channelled between the SE margin of the GSR and the anticlinal folds of the WTRC and Faroe Bank — is currently the Faroe Bank Channel, which together with the Faroe-Shetland Channel is herein termed the Faroe Conduit (Fig. 3). It remains uncertain as to whether the onset of flow of Norwegian Sea Deep Water (NSDW) across this gateway occurred during the late Eocene–early Oligocene (Miller & Tucholke 1983; Davies *et al*. 2001) or the early Neogene (mid-Miocene) (Blanc *et al*. 1980; Bohrmann *et al*. 1990; Eldholm 1990). However, isotopic, taxonomic and revised seismic-stratigraphic data from across the North Atlantic region favour an early Neogene expansion of water mass exchange (Stoker *et al*. In press a). Significantly, this approximately coincides with the opening of the Fram Strait, between Svalbard and NE Greenland (Eldholm 1990; Jansen & Raymo 1996). The coeval formation of the northern and southern gateways (Fig. 1) is arguably the major factor in the creation of the Arctic–Atlantic thermohaline circulation pattern (Jansen & Raymo 1996). It was probably only in the latter part of the Oligocene and the early Miocene that temperate to cool water began to develop north of the GSR (Thiede & Myhre 1996). With the development of this oceanic circulation pattern there was a progressive cooling on northern hemisphere climate from the mid-Miocene linked to the development of the northern and southern gateways (Zachos *et al*. 2001).
2. The late Neogene (Plio-Pleistocene) differential uplift of the North Atlantic continental margins had a major impact on the changes in global climate that ultimately led to northern hemisphere glaciation (e.g. Japsen & Chalmers 2000). There is evidence that the onset of these movements coincided with an early Pliocene plate reorganisation (Cloetingh *et al*. 1990) that affected oceanic circulation patterns throughout the Atlantic Ocean (e.g. formation of the Isthmus of Panama) (Haug & Tiedemann 1998; Lear *et al*. 2003) (Fig. 3). However, uncertainty has surrounded the relationship of onshore uplift to the observed large-scale progradation of the shelf-margin sediment wedges along the margin (Figs 3 & 4), the initiation of which has been suggested either to be a consequence of northern hemisphere glaciation (e.g. Eidvin *et al*. 2000; Faleide *et al*. 2002) or to pre-date glaciation and be a response to tectonically driven change (Japsen & Chalmers 2000; Stoker 2002; Praeg *et al*. In press). The resolution of this issue was addressed by the recent STRATAGEM project, which suggested that the prograding sediment wedges were probably instigated at about 4 Ma, at least 1 Ma prior to the expansion of northern hemisphere glaciation (Stoker 2002; STRATAGEM Partners 2002, 2003; Stoker *et al*. In press a, b) (Fig. 3b). Although there is no doubting that glacially-derived sediments form a significant component of most of the sediment wedges, glaciation (together with isostatic rebound) may have been a sustaining, rather than initiating, factor in late Neogene uplift. Thus, it could be argued that tectonic changes may have brought global climate to a critical threshold. This hypothesis remains to be fully tested by offshore sampling.

The resolution of these issues has been inhibited by uncertainty over the timing of late Cenozoic events in the NE Atlantic region, which has also prevented a proper evaluation of the cause of the environmental changes. Working towards an understanding of such fundamental issues is the purpose of this initiative.

4 Detailed scientific objectives

The way forward for any *Extreme Climate* initiative is an Earth System Science programme that is truly generic, underpinning and cross-cutting. From an ocean-margin perspective, this should incorporate:

- Better regional correlations and syntheses, and;
- Properly co-ordinated strategic sampling, drilling and core analysis.

Both of these general objectives fit within the programme proposed herein, and will provide information crucial to an elucidation of the key themes. More specifically, the following key objectives are developed as the starting point for this programme, as they fully utilise the extensive set of legacy data and knowledge held by the BGS, and build upon established collaborations with other research institutes and universities.

4.1 NORTH ATLANTIC CENOZOIC CORRELATIONS & SYNTHESES

This objective would form the basis for a unified Cenozoic stratigraphy for the North Atlantic region that would enable a proper evaluation to be undertaken of forcing mechanisms driving long- and short-term climate change. Such a framework is absolutely crucial as it represents the preserved record of sedimentary response to change throughout the North Atlantic region, and forms a timescale on which to base ideas concerning the nature and causes of change. An event stratigraphy that considers all aspects of tectonic activity, ocean-current development and climatic fluctuation would help to establish potential linkages between the various forcing mechanisms. Specific tasks designed to achieve this objective are detailed below, and essentially reflect the sedimentary response to environmental change:

- Long-term change — preserved in deep-sea contourite drifts and ocean-margin prograding sediment wedges. Seismic-sequence stratigraphy calibrated by long-core data provides valuable information on the late Palaeogene–Neogene environmental history of the North Atlantic region. No regional synthesis or correlation of these data (including BGS, released commercial and DSDP/ODP sites) currently exists.
- Short-term change — predominantly the deep-water record, with a focus on the last glacial–interglacial transition in the North Atlantic region. No regional synthesis or correlation of these high-resolution data (including BGS, DSDP/ODP and other institute/university short cores) currently exists. Additionally, there is an opportunity to collaborate with the Scottish Association for Marine Science (SAMS) in the interpretation of high-resolution seismic and core data from the Svalbard margin (see Appendix 2), and from the areas flanking the Wyville-Thomson Ridge, off NW Britain.

<u>Relevance to key themes</u>

- These tasks address issues concerned with forcing mechanisms, and with both long- and short-term change.

<u>Collaboration</u>

In addition to SAMS, there is potential for collaboration with the Norwegian Geological Survey (NGU), the Geological Survey of Denmark and Greenland (GEUS), and the universities of Bergen and Tromsø. Although the proposed joint SAMS/BGS PhD project outlined in Appendix 2 did not get approved for funding, the research collaboration as outlined in the proposal remains in place. This collaboration is valued as important and would benefit both the BGS objectives and those outlined in the SAMS *Northern Seas Programme*, which includes studies of the ocean margins. An interface could also be developed with the IODP dependent upon the success of their proposed drilling programme in the Central Arctic Ocean.

Deliverables

- A unified Cenozoic stratigraphic scheme (chronological, seismic-sequence stratigraphic) for the North Atlantic region at several levels of resolution — data presented as stratigraphic-range charts.
- Work towards the selection of suitable drilling and short core sites designed to better constrain the stratigraphic framework, and records of climate change.
- Scientific papers, including high arctic contourites (collaboration with SAMS).

4.2 NEOGENE SEQUENCE STRATIGRAPHY

A major characteristic of the circum-North Atlantic continental margins is the widespread development and preservation of sedimentary sequences and morphological features that are presumed to be of glacial origin. Most striking are the prograding wedges that have built out onto the continental slope - including NW Britain - in front of cross-shelf troughs that represent the pathways of former ice streams. These deposits represent important palaeoclimate and ice-sheet monitors. A key observation in all prograding wedges is a major change in depositional style from predominantly progradational to aggradational in character. This may be related to an increase in the intensity of glaciation in the last 0.9 Ma, whereby formerly restricted ice sheets expanded onto and across the continental shelves. The main aim of this objective is to develop a regional context for late Neogene glacial evolution of the Arctic-sub-Arctic margins. Such a regional approach will provide an unprecedented appraisal of the processes that have contributed to the shaping of the NE Atlantic region, as well as the forcing mechanisms (tectonic versus climate) that have controlled those processes. Key tasks critical to the development of the late Neogene glaciated-margin model include:

- Utilising the Cenozoic stratigraphic framework (detailed in 4.1) to focus on the late Neogene development of the circum-North Atlantic–Arctic–sub-Arctic continental margins, and establish a glacial event stratigraphy that will provide the timescale for palaeoclimatic and ice-sheet change within the North Atlantic region. This task will build upon the recently completed STRATAGEM (Stratigraphic Development of the Glaciated European Margin) project (STRATAGEM Project 2002, 2003)
- The regional comparison of the sedimentary architecture of the prograding wedges.
- An improved understanding of the sedimentary processes and driving forces responsible for the development of the glaciated continental margins.

Relevance to key themes

- This objective addresses issues of forcing mechanisms and long-term climate change.

Collaboration

There is an opportunity to develop collaboration to likeminded research groups in the UK and Scandinavia, especially the NGU and University of Tromsø.

Deliverables

- Scientific paper.
- Development of an international drilling strategy to test the early sedimentary history of prograding wedges on Faroese, Norwegian and Danish (Greenland) margins.

4.3 RECONSTRUCTION OF PLEISTOCENE ICE LIMITS OFFSHORE NW BRITAIN

Ice-sheet reconstruction is one of the key parameters of natural climate variation that needs to be determined with greater accuracy than currently exists. Despite extensive research over the last 25 years, the limit of the last ice in NW Europe over currently submerged areas remains ambiguous, and a topic of some controversy. The UK and Fennoscandian ice masses are commonly displayed as a single ice sheet despite the lack of evidence for such a linkage. The use of reconstructions that are inherently uncertain does not give confidence to climate models developed for the NW European region. Consequently, a second major task involves the compilation of all information relating to the distribution of Pleistocene ice sheets in and around the NW UK. This task would run concurrently with a BGS/Imperial College UCAC PhD project (see Appendix 3) that is focused on the North Sea.

<u>Relevance to key themes</u>

- This task provides a critical parameter for climate modelling both in long- and short-term timescales.

<u>Collaboration</u>

In addition to Imperial College, there is potential for collaboration with the University of Bergen who may be undertaking an equivalent study in the Norwegian sector of the North Sea.

<u>Deliverables</u>

- A GIS reconstruction of ice-sheets around the UK for the last 0.5 Ma — most probably an ongoing deliverable for the duration of the BGS/IC PhD project.
- Scientific papers.

4.4 COLLABORATIVE FOCUSING

This objective is intended to develop linkages both internal and external to BGS. Three main tasks are envisaged:

- Promote a BGS and NERC awareness of the initiative — one possibility is through the development of a BGS-wide 'Earth System Science' programme herein referred to as *Peak to Trough (P2t)*, designed to establish a multidisciplinary approach to landscape development of the UK and its surrounding continental margin (cf. Appendix 5).
- Strengthen links both nationally and internationally to pursue the key objectives, and to further develop new programmes of work. A meeting at the University of Bergen has already been provisionally arranged for March 2004, involving BGS, Imperial College, University of Bergen and the NGU.
- Form new partnerships with other scientific disciplines to more fully advance our understanding of the Earth system.

5 Implementation strategy: programme of CSM research

The programme of research and its duration is wholly dependent upon the level of Science Budget funding that is available to the CSM. The following work plan — sketched out in October 2003 — assumes a funding level of about 20K/annum for at least the first two years, with an appropriate level of annual OR (~5K) to help focus and facilitate collaboration and the dissemination of results (e.g. conferences/thematic publications). The various tasks outlined in section 4 are tabulated below in their broadest form, i.e. within the specific objective defined in 4.1–4.4. However, objective 4.1 is subdivided into 4.1a and 4.1b, the latter representing additional work, particularly core studies, which may arise in year 2 within the limits of this objective. It is stressed that this outline only represents a possible way forward, and is as much a basis for discussion and project planning rather than a definite work programme. Abbreviations used within the table are as follows:

SAMS — Scottish Association for Marine Science
IC — Imperial College
NGU — Norwegian Geological Survey
GEUS — Geological Survey of Denmark and Greenland
UiB — University of Bergen
UiT — University of Tromsø

YEAR	TASK
2004/05	**4.1a**: Unified Cenozoic stratigraphy, including stratigraphic-range charts — compilation and QA of regional datasets (collaboration with NGU?) — and high latitude sediment drifts (collaboration with SAMS). **4.3**: Ice sheet reconstruction around the UK, including compilation and QA of datasets (collaboration with IC). **4.4**: Collaborative focusing of initiative within the BGS, and both with existing collaborators (SAMS, IC) and other potential co-workers within the UK and Scandinavia*. This also includes PhD supervision of the BGS/IC student, and participation in international conference on *Climate Change in High Latitudes*, Bergen, September 2004.
2005/06	**4.1b**: Ongoing/additional work (e.g. SAMS). **4.2**: Neogene sequence stratigraphy — ocean-margin to the deep sea (collaboration with SAMS, NGU, GEUS, UiB, UiT?). **4.3**: Update ice sheet compilation as PhD study progresses. **4.4**: Ongoing.
2006/07	**4.4**: International scientific statement, such as thematic publication and/or conference presentation.

Table 1. A potential preliminary work programme, highlighting a possible way forward through collaboration. (*A meeting has already been provisionally arranged for March 2004, to be held at the University of Bergen, Norway)

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Appendix 1 Collaboration: scientific papers and PhD theses in progress

This project would build upon existing national and international collaboration researching aspects of environmental change. In particular, the STRATAGEM project (STRATAGEM Partners 2002, 2003) has already begun the process of establishing a unified Neogene stratigraphic scheme for the Atlantic margin of NW Europe, and a number of collaborative, climate-related, papers are currently in preparation, intended for a thematic issue of Marine and Petroleum Geology (P.M. Shannon & M.S. Stoker, guest editors). Part of Stoker's time to this project (E1281S73) in 2002/03 was allotted to completing contributions to these papers. Additionally, three PhD studies are currently addressing issues related to climate change in the North Sea and the NE Atlantic; all of these are being co-supervised by M.S. Stoker. These papers and PhD studies are listed below:

PAPERS INTENDED AS PART OF MARINE AND PETROLEUM GEOLOGY SPECIAL ISSUE

Dahlgren, K.I.T., Vorren, T.O., Stoker, M.S., Nielsen, T., Nygärd, A., & Sejrup, H.P. Submitted. Late Cenozoic prograding wedges on the NW European Atlantic margin: their formation and relationship to tectonics and climate. *Marine & Petroleum Geology*.

Laberg, J.S., Stoker, M.S., Dahlgren, K.I.T., de Haas, H., Haflidason, H., Hjelstuen, B.O., Nielsen, T., Shannon, P.M., Vorren, T.O. & van Weering, T.C.E. Submitted. Cenozoic alongslope processes and sedimentation on the NW European Atlantic margin. *Marine and Petroleum Geology*.

Nielsen, T., De Santis, L., Dahlgren, K.I.T., Kuijpers, A., Laberg, J.S., Praeg, D., & Stoker, M.S. In prep. A comparison of the NW European glaciated margin with other glaciated margins. *Marine and Petroleum Geology*.

Sejrup, H.P., Hjelstuen, B.O., Dahlgren, K.I.T., Haflidason, H., Kuijpers, A., Nygärd, A., Praeg, D., Stoker, M.S. & Vorren, T.O. Submitted. Pleistocene glacial history of the NW European continental margin. *Marine and Petroleum Geology*.

Stoker, M.S., Praeg, D., Shannon, P.M., Hjelstuen, B.O., Laberg, J.S. & Nielsen, T. Submitted. Neogene mega-stratigraphy and the sedimentary and oceanographic development of the NW European Atlantic margin. *Marine and Petroleum Geology*.

COLLABORATING INSTITUTIONS:

- British Geological Survey
- Geological Survey of Denmark and Greenland
- Istituto Nazionale di Oceanografia e di Geofisica Sperimentale
- Royal Netherlands Institute for Sea Research
- University of Bergen
- University College Dublin
- University of Tromsø

PhD STUDIES

Davison, S. *Reconstructing the Pleistocene glaciated margin off NW Britain*. University of Edinburgh. (Due to be completed by late Spring 2004: Supervisors — M.S. Stoker & R. Scrutton).

Graham, A. *Reconstructing Pleistocene ice limits in the Central North sea: implications for climate change*. Imperial College. (BGS/IC UCAC project, due for completion October 2006: Supervisors — M.S. Stoker & L. Lonergan, with C.Elders and J. Collier).

Morri, C. *North Atlantic deglaciation: its impact on deep-sea depositional environments*. University of Highlands and Islands. (Due for completion spring 2004: Supervisors — M.S. Stoker and J.A. Howe).

Appendix 2 Arctic contourites: palaeo-records of high-latitude thermohaline circulation on the Western Svalbard margin, Fram Strait (74ºN–80ºN)

This research proposal was submitted to NERC in 2003 but failed to get funding approval. However, the research outlined within the proposal remains very much part of the SAMS Northern Seas programme, and the PI — Dr John Howe — intends to pursue the work. Consequently, the BGS remains very keen to participate.

CASE FOR SUPPORT: Arctic Contourites: Palaeo-records of high latitude thermohaline circulation on the western Svalbard margin, Fram Strait (74ºN-80ºN)

Part 1: Previous Research Records.

Dr. John A. Howe

Ph.D. Postgraduate Research (1991-1994): "Bottom currents, contourites and related sedimentation in the northern Rockall Trough, North Atlantic Ocean" University of Southampton.

Postdoctoral Research (1994-1998): British Antarctic Survey (BAS) research on the role of deep-ocean circulation and the distribution of sediment on the continental slope and floor of the Southern Ocean. Took part in three Antarctic science cruises, and one drilling project, The Cape Roberts Drilling Project, based on the sea ice in the Ross Sea.

Present Position (1998-Present): Lecturer in Marine Geology / Researcher. Scottish Association for Marine Science & UHI Millennium Institute. Research into bottom-current systems and contourites in the Antarctic, North Atlantic and the Arctic. Records of palaeoclimate change in fjordic systems from Scotland, Norway and the Arctic. Member of the International Association of Sedimentologists (IAS) and the Society for Sedimentary Geology (SEPM). Fellow of the Geological Society of London and member of the Marine Studies Group. Co-Editor of the Geological Society memoir 22 (2002) "*Deep-water Contourite systems: modern drift and ancient series, seismic and sedimentary characteristics*". Series Editor for the Geological Society of London.

Postgraduate Supervision (2000-2003): Supervised a postgraduate student, Ms Clara Morri through an Uhi/OU funded PhD project entitled: "North Atlantic Deglaciation: the influence of palaeocurrent pathways on Late Quaternary deep-water sedimentary environments". 2003 began supervising a postgraduate student, Ms Suzanne MacLachan through an Uhi/OU funded PhD project entitled: "Arctic paleoenvironmental change from the fjords to the deep-sea of western Svalbard."

Selected Publications

1. Howe, J.A. & Pudsey, C. J. (1999) Antarctic Circumpolar Deepwater: a Quaternary palaeoflow record from the northern Scotia Sea, south Atlantic Ocean. Journal of Sedimentary Research, 64 (4) 847-862

2. Howe, J.A., Stoker, M.S. and Woolfe, K.J. (2001) Deep-marine seabed erosion and gravel-lags in the Northwestern Rockall Trough, North Atlantic. Journal of the Geological Society, 158, 427-438.

3. Howe, J.A., Stoker, M.S., Stow, D.A.V. and Akhurst, M.C. (2002) Sediment drifts and contourite sedimentation in the northeastern Rockall Trough and Faeroe-Shetland Channel, North Atlantic Ocean. In: Deep-Water Contourite Systems: Modern Drifts and Ancient Series, Seismic and Sedimentary characteristics. Stow, D.A.V., Pudsey, C.J., Howe, J.A., Faugeres, J-C., Viana, A. (Eds) Geological Society of London, Memoirs 22, 65-72

Dr. Martyn S. Stoker

Ph.D. Postgraduate Research (1980) University of Liverpool. Thesis title: *The Geology of Eastern Ardgour, Argyllshire*.

Postdoctoral Research (1980-Present). Marine Geologist with the British Geological Survey, Edinburgh. Project Leader responsible for the integration of geological and geophysical studies on the continental margin, north and west of Britain. World-wide research collaboration with Universities, Oceanographic Institutes and other national Geological Surveys. Consultancy work for the hydrocarbon industry on continental margin studies off the UK, West Africa, Turkey and Russia. Development of R&D proposals. Management of professional staff and PhD. students. Member of the Edinburgh Geological Society, Fellow of the Geological Society of London, Committee member of the Marine Studies Group, Chartered Geologist.

Selected Publications

1. Stoker, M.S., van Weering, T.C.E. & Svaerdborg, T. (2001). A Mid-Late Cenozoic tectonostratigraphic framework for the Rockall Trough. In: Shannon, P.M., Haughton, P.D.W. & Corcoran, D. (eds) The Petroleum Exploration of Ireland's Offshore Basins. Geological Society, London, Special Publication, 188, 411-438.

2. Stoker, M.S. (2002). Late Neogene development of the UK Atlantic margin. In: Doré, A.G.D., Cartwright, J., Stoker, M.S., Turner, J.P. & White, N. (eds), Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration. Geological Society, London, Special Publications, 196, 313-329.

Dr. Rex Harland

1967: University of Sheffield, M.Sc. (Palynology)

1988: University of Sheffield, D.Sc. (Palynology)

1970-1994: British Geological Survey, Principal Scientific Officer (UG7).

1994-Present. Honorary Lecturer, University of Sheffield, Environmental and Earth Sciences Group. Independent palynological consultant trading as DinoData Services.

Selected Publication

1. Harland, R. and Pudsey, C. J. (1999). Dinoflagellate cysts from sediment traps deployed in the Bellingshausen, Weddell and Scotia seas, Antarctica. *Marine Micropaleontology*, **37**, 77-99.

Dr. Steven G. Moreton.

2000-Present Post-doctoral research assistant, NERC Radiocarbon Laboratory.

PhD (2000) C&GCHE/BAS "Quaternary tephrochonology of the Scotia and Bellingshausen seas, Antarctica"

1999-2000 PDRA, Dept. of Earth Sciences, Cardiff University,

1999 PGRA, Geoscience Division, British Antarctic Survey.

Selected Publication

1. Moreton, S.G. and Smellie, J.L. (1998) Identification and correlation of distal tephra layers in deep-sea sediment cores, Scotia Sea, Antarctica. *Annals of Glaciology* vol. 27, p285–289.

Dr. Torbjørn Dahlgren

Has extensive research experience working in the Spitsbergen fjords, and the continental shelf and slope off mid- and northern Norway. 5 papers in international journals and 33 conference contributions (abstracts). The PhD Thesis examined the Late Cenozoic evolution, sedimentary environment and processes on the mid-Norwegian continental margin, based on sedimentological/geochemical study and facies-analyses of sediment cores as well as interpretation of high-resolution seismics. The present Post Doc.-project investigates the post-Oligocene evolution, and sedimentary environment and response of the north-Norwegian/Barents Sea margin in relation to late Cenozoic vertical tectonic movements on the shelf and mainland. This project is based on >90000 km of commercial 2D seismic data, several 3D-seismic cubes as well as sediment samples from exploration wells and short cores. Two key topics in relation to his research on the Norwegian margin are glacigenic and bottom-current (contouritic) controlled sedimentation, and the interplay between them.

Selected publication

Dahlgren, K.I.T. and Vorren, T.O., 2003. Sedimentary environment and glacial history during the last 40 ka of the Vøring continental margin, mid-Norway. Marine Geology 193, 93-127.

Part 2: Proposed Research: Arctic Contourites: Palaeo-records of high latitude thermohaline circulation on the western Svalbard margin, Fram Strait (74ºN-80ºN)

Rationale

Arctic seas contain geological records that are critical to our understanding of global climatic change and its linkages to global thermohaline circulation. At timescales of millennia and longer, the marine geological record in Arctic seas provides evidence critical to our understanding of Arctic palaeoclimate, and hence can inform contemporary studies of high latitude cryospheric, atmospheric and oceanic processes through its implications for the magnitude and abruptness of past environmental change. Contourites are little studied on Arctic continental margins. They are an extremely important but neglected group of deep-water sediments (Howe et al., 1994; 2002). Being the result of persistent, alongslope thermohaline circulation their study and interpretation is vital to further our understanding of bottom-water circulation and ocean-climate link, with huge potential for providing high-resolution records of the influences climate change in the deep-sea (Howe and Pudsey, 1999). They are also important as part of the spectrum of deposits that confront the oil industry as exploration moves into progressively deep-water (Howe et al., 2001).

Several research questions, which draw upon marine geological observations and sampling, are of critical importance and build upon current NERC programmes (e.g. RAPID, SAMS Northern Seas Programme). UK scientists are well placed to make important contributions to these problems through, for example, the deployment of high-resolution seismic and long-coring tools deployed from UK Research vessels such as RRS James Clark Ross and Discovery to understand the development of major bottom-current constructed drifts and waves and associated zones of high-latitude continental margin modification, together with the chronological controls to constrain their rates of sediment build-up and their relationship to global thermohaline circulation and climate change. The following are key research questions to be addressed by this project:

a. What do contouritic sediments in Fram Strait tell us about the frequency and rate of change of Arctic and hence global, thermohaline circulation? Is there any significant evidence of very rapid instabilities or shutdown of bottom-current flow during climatic events such as glaciation?

b. When was the initiation of drift construction in Fram Strait, and how is drift formation linked to major tectonic, and climatic events such as the onset of deep-water flow and sea level change?

c. Where are the areas of major drift development on Arctic continental margins and what is the extent and frequency of recent sea-floor processes? The acquisition and dating of core material from key sites, identified from existing seismic datasets, is a crucial step in mapping the modern processes active in Fram Strait, and establishing the regional distribution of current-influenced sedimentation and its links to modern thermohaline flow.

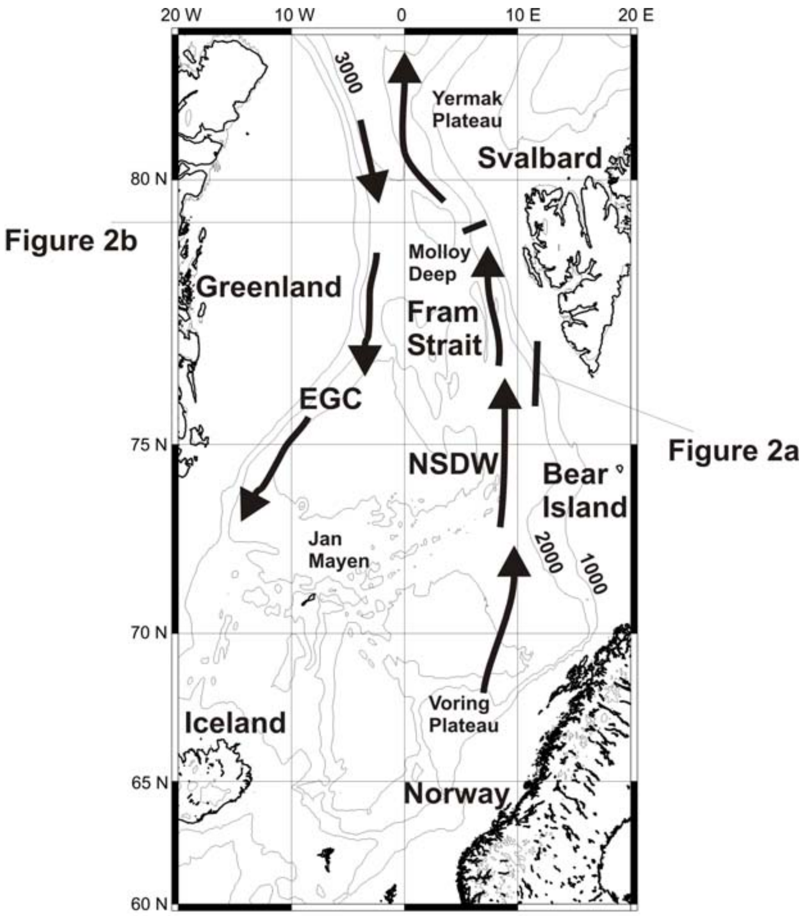
The timing and structure of the last glacial-deglacial cycle in the Arctic and the initial inflow of Atlantic water into the Arctic Ocean are not, at present well constrained (Koç et al., 2002). The glacial and palaeoceanographic conditions in the region are, in turn, linked to Quaternary climate change. Variations in ice-ocean-climate interactions on the Polar North Atlantic margins have produced a distinctive record, including drift and wave complexes, fans and deep-ocean sediments which all indicate palaeoceanographic and ice-sheet interaction. High-resolution seismic profiling and long core data will be used to investigate: contourite drift occurrence, dimensions and the timing and character of past bottom current flow; sedimentation rates and productivity. Deciphering the signal of climatic amelioration from deep-water sediments using sediment texture and geochemistry is a long-established tool of palaeoceanographers. However the precise timing and effects of deglaciation in high latitude deep-water environments remains enigmatic. Previous studies in the Polar North Atlantic have identified phases indicative of high surface water productivity interpreted as the northward advection of warm North Atlantic Water into the Polar North Atlantic. Each high productivity phase terminates in a meltwater event. Meltwater pulses would have the effect of increasing thermohaline circulation and hence reworking in deep-water. These phases can be correlated with ice sheet fluctuation on Svalbard and across the wider Fennoscandanvian Ice Sheet region (Hald et al, 2001, Phillips and Grantz, 2001). Due to the high sedimentation rates in the Polar North Atlantic (3-100 cm/ky) these abrupt climatic events can be detected at a high temporal resolution allowing the timing and onset of deglaciation and its relationship to sediment supply and productivity to be examined (Nam et al, 1995). Similar events in the mid-latitude North Atlantic have been extensively studied and meltwater and sediment pulses identified linked to the production of North Atlantic Deep Water (Vidal et al, 1997, Cortijo et al, 2000).

Fram Strait forms the only deep oceanic gateway between the Arctic and the World Ocean. The Arctic region of the northern North Atlantic plays an important role in regulating world climate through the generation of North Atlantic Deep Water, and its precursors, which are a major driving force of global thermohaline circulation (Figure 1). The thermohaline-driven ventilation of the deep-ocean at high latitude is driven by the northward advection, and subsequent cooling and sinking of the warm North Atlantic Current producing oceanic-scale thermohaline circulation (THC). Fram Strait is a key region for this process and hence the ideal study area for the interaction and influences of climate change, THC variation and the subsequent distribution and geometry of contouritic sediment. This study aims to utilise contouritic sediments as a proxy for THC variability in a climatically sensitive, high latitude oceanic gateway setting, which includes a region of known deep-water formation of global significance.

The global oceanic thermohaline circulation forms the most powerful climatic engine on Earth. It stores and redistributes heat on a global scale. From tropical latitudes Atlantic surface waters gain density due to increasingly salinity, and decreasing temperature, during the northward flow. As these waters reach the high latitude Polar North Atlantic, they sink and forming oxygen depleted, nutrient-rich deep-waters. These waters can flow as far as the Pacific before upwelling to the surface again. Any disruption to this process either through changing salinity or temperature has profound implications for global climate, in particular when occurring in the Nordic Seas (Keigwin and Lehman, 1994, Broeker 1997).

Fram Strait is dominated by two main surface currents: the West Spitsbergen Current (WSC) and the East Greenland Current (EGC) (Aagaard et al., 1997). Atlantic surface waters enter the Eastern Fram Strait and flow along the western Svalbard Margin as the WSC. The deeper water masses of the WSC consist of a number of water masses, notably Norwegian Sea Deep Water (NSDW), and further north as the Yermak Slope Current (YSC). The upper 500m of surface waters are deflected west by Coriolis Force (Haas, 2002).

Figure 1: Regional bathymetry of the continental margin from Norway-Svalbard. Deep-water circulation is indicated by the broad arrows. Northward flowing Nordic Sea Deep-Water (NSDW) and Arctic Intermediate Water (AIW) provide the strongest influence on sedimentation on eastern Fram Strait. The southward flowing East Greenland Current (EGC) dominates the western Fram Strait (Jones et al., 1995). Bathymetric contours every 1000m interval.



On-going investigations in Fram Strait are an integral component of the NERC funded SAMS Northern Seas Project (NSP), one aim of which is to elucidate the palaeoclimatic history and bottom current conditions along in a broad latitudinal transect of the European margin. A considerable amount of data already exists after the successful SAMS NSP RRS James Clark Ross Cruise in July 2002. Topas sub-bottom profiles, EM120 multibeam bathymetry and short gravity cores will all be re-examined to provide support for this study. This project aims to focus specifically on the influence of bottom-current circulation and its linkage to climatic variability in Fram Strait. Key to this aim is the collection of data (high-resolution seismic and long cores) from the forthcoming SAMS Northern Seas Programme sampling cruise to the Arctic in 2004.

Specific Objectives

The strategy adopted will build upon the on-going work conducted within the SAMS NSP and existing datasets such as the NEAPCC (North East Atlantic Paleoceanography), PONAM (Polar North Atlantic Margins) and NERC thematics such as ARCICE and RAPID results. The work also has significance and good potential for data sharing with on-going RAPID research on the contouritic Eirik Drift (Bacon and Stow), S. Greenland, and in an increase of our knowledge of high latitude contouritic systems. Cores will be subjected to an initial phase of sedimentology and microfaunal analysis followed by detailed geochemistry and sedimentology on key sites. The stratigraphy will be confirmed by radiocarbon analysis – subject to further proposals. Specific Objectives are:

(1) Determine the influence of climatic change on deep-water formation in Fram Strait during the late Quaternary (last 125ky), through detailed analysis of sediment cores. This will include sedimentological logging and photography, detailed particle-size analysis of the sortable silt (10-63 μm), smear-slide studies, x-radiography, magnetic susceptibility, oxygen isotopes, radiocarbon dating, geochemistry (stable isotopes and REE for current pathway tracers) and microfaunal analysis (foraminifera and dinoflagellates). Analyses of key cores are expected to provide important new information on the history of watermass fluctuations during glacial-interglacial cycles of the late Quaternary.

(2) Determine the gross palaeoceanographic history. Through seismic-stratigraphical analysis tied to reference boreholes and seismostratigraphical reflectors (ODP site 986, Solheim et al., 1998) an attempt will be made to determine the age and origin of the main depositional units, and establish a chronological framework of major Arctic palaeoceanographic events. More detailed study of variations in the nature and geometry of the major contourite drifts, the regional distribution, wavelength, orientation, and size of any sediment waves associated with drifts and features of erosion, will be used to gain specific information about the changes in the timing and intensity of watermass flow in Fram Strait throughout the Late Cenozoic (<40Ma).

(3) Decipher and map the regional extent of contourite drifts and associated deposits. This will utilise high-resolution sparker and boomer seismic profiles, plus sediment cores to delineate the various depositional processes and map their resultant depositional features (e.g. contour currents, debris flows submarine channels and fans, drift deposits etc), and thereby establish the various interacting sedimentation processes(e.g. downslope, parallel-to-slope, glaciomarine) that have recently affected Fram Strait.

These objectives will met by an initial phase of detailed acoustic mapping of seabed and subseabed features across the area. Following this, core analysis will begin with detailed logging, x-radiography and subsampling for particle size characterisation further to microfaunal work (Year 1, into Year 2). Once core material has been analysed and a gross lithostratigraphy for the region compiled, areas of specific key importance (e.g. Molloy Deep and the drifts of the western Svalbard Margin) will be targeted, and up to five piston cores targeted for the final, high-resolution work (sortable silt for palaeospeed estimates, oxygen isotopes, ^{14}C dating) leading to the palaeoceanographic study (Years 2 & 3).

Methodology

Initial data collection will be during the SAMS NSP Arctic cruise in August 2004. As a preliminary to this, the pre-existing multibeam bathymetry and Topas sub-bottom profiles, collected as part of the SAMS NSP Arctic RRS James Clark Ross cruise from July 2002 will be revisited and target localities selected. Specific core sites (up to 10) will be identified following the collection of the new high-resolution seismic data using the critieria of (i) Current-influenced sites; drifts and waves. (ii) Potential regions of high-resolution records e.g. thick hemipelagic sequences on the margin and (iii) regions where notable and extensive reflectors condense or appear at, or near seabed to tie together the regional lithostraigraphy. Using the British Geological Survey's deep-tow boomer high resolution seismic system run in tandem with the sparker single-channel seismic, data on the contouritic signature of the current-influenced margin will be collected and sites of drifts and waves targeted for coring. Onshore studies aim to compile the seismic data into a series of regional maps showing modern seabed processes and in the longer-term, Late Cenozoic drift morphology and development along the margin. The regional seismostratigraphy of the margin has been documented by Solheim et al., (1998) although this work concentrated on the deposits of the slope, related to Cenozoic ice-sheet dynamics.

A piston corer (UKORS) will be used to obtain up to ten, 10m long sediment records spanning at least the last glacial-interglacial cycle. The initial ten sampling stations will be selected from sites of current-influenced sedimentation on the Western Svalbard Margin and northward onto the Yermak Plateau and onto the eastern margins of Fram Strait. Target survey and coring sites will depend on sea ice conditions, however during the 2002 James Clark Ross cruise, ice-free waters extended north onto the northern Yermak Plateau. Site selection is based on both the pre-existing Topas sub-bottom surveys and short cores collected during the SAMS JR75 Cruise of the James Clark Ross (July 2002) (Figures 2a&b), and the new high resolution seismic collected during the cruise. Key areas of bottom-current influenced sedimentation have been identified; the drifts of the western and northwestern Svalbard Margin (including the Yermak Plateau), Fram Strait centred around the Molloy Deep, and the southern Svalbard margin. Utilising sediment texture, microfauna and geochemistry the timing and influence of deglaciation and its relationship to deep-water formation will be examined. Cores will be split, photographed, logged and passed through a Bartington MS2 magnetic susceptibility loop, at 2cm intervals onboard before being stored in a cool (4°C) room prior to removal to the SAMS sediment sample core store.

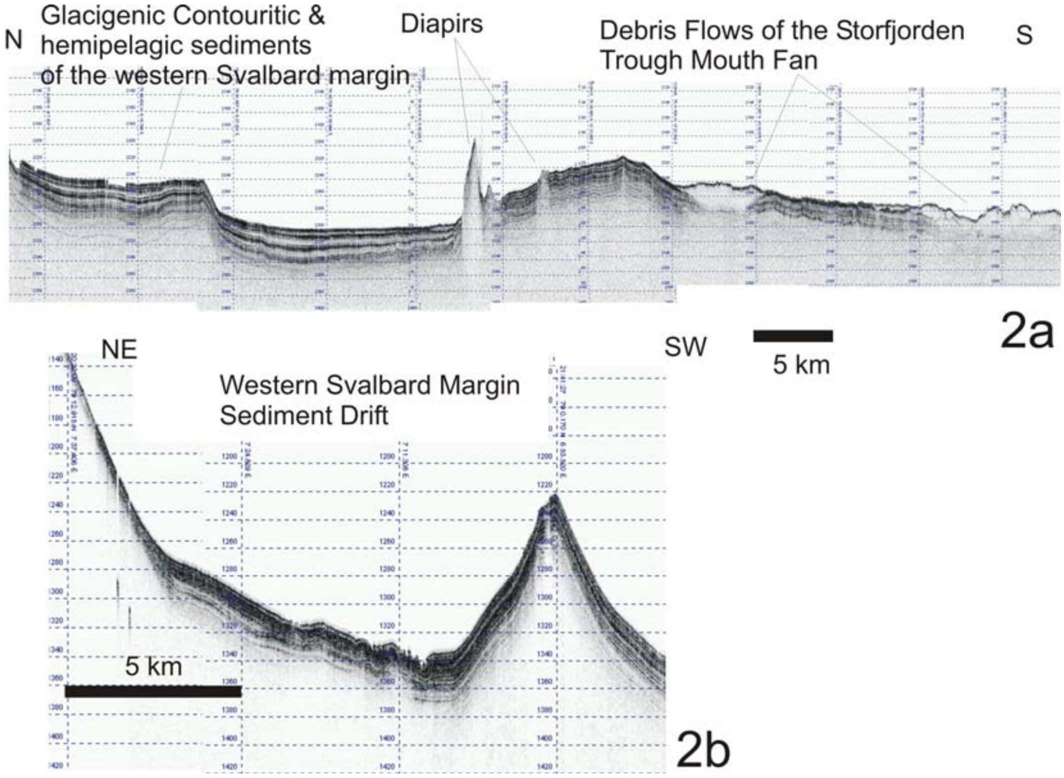


Figure 2a: Topas sub-bottom profile of the continental margin between the Storfjorden Trough Mouth Fan (TMF) (76˚N) and SW Svalbard margin, Spitsbergen (77˚N). To the south the predominant debris flows and downslope mass-movements of the TMF give way to diapiric structures and current-influenced deposition, as the margin narrows towards Fram Strait. 2b: Topas sub-bottom profile of a small (<10km) elongate contourite drift on the western Svalbard margin. The location of both profiles is shown in figure 1.

The onshore phase of the project begins with the construction of a seabed process map utilising the deep-tow boomer and sparker data collected during the SAMS NSP Cruise in 2004 but also drawing upon previous EM120 multibeam and Topas sub-bottom profile data collected along the western Svalbard margin during 2002. This phase will be conducted between SAMS and BGS (Howe and Stoker).

Detailed seismic analysis of drift build-up and morphology will be conducted between the British Geological Survey (BGS) and the University of Tromso (Stoker and Dahlgren) leading to the development of a model for Cenozoic for drift initiation. This approach will use standard seismostratigraphic techniques and utilises the BGS Landmark Unix-based computer system to view the seismic data.

Onshore laboratory work will focus on the final five cores selected from the initial ten that best sampled contouritic sediments and will concentrate on the technique of particle size analysis for sortable silt following the method of Haas (2002) to separate the sortable silt signal from ice rafted debris (IRD). The determination of palaeocurrent speeds from grain size distributions is based on the assumption of constant current speed, sediment source, and an environment free from external processes such as IRD, turbidity currents or gravitational mass-movements. Clearly Fram Strait is a region of extensive of IRD input – however the method of Haas uses a statistical regression to extract the silts sorted by bottom currents not input by ice. This method assumes that the input of sand into the sediment is via ice, thus the grade of resemblance between silt and sand can be used to calculate relative bottom current velocities. This simple statistical method has the potential to yield improved clarity in the sortable silt record. This method will be combined with radiocarbon dating of the cores to constrain the chronology of palaeocurrent events over the cored sequence (<125 ky). The detailed particle size work will take place at the new SAMS Dunstaffnage Marine Laboratory, Oban. Estimates of sea surface temperature (SST) will be made using the dinoflagellate fauna, following the method of de Vernal et al., (1994; 2001). Rex Harland of the University of Sheffield has already conducted a pilot study as part of the SAMS NSP and reported abundant cysts both at the core tops and with changes in downcore abundances and assemblages in response to climatic variability (Harland pers. comm.. 2003). Further to the onboard magnetic susceptibility measurements, more detailed measurements will be made at SAMS on the split core sections using a Bartington MS2 hand probe at 1cm resolution. Oxygen isotope analysis will be performed on picked *N. pachyderma* and *C. wullerstorfi*, with ^{18}O measurements made at the University of Edinburgh. The presence of meltwater pulses during deglaciation (Hald et al., 2001) leads to lower foraminiferal abundances, however the use of alternative proxies such as dinoflagellates will provide a workable biostratigraphy. Geochemical analysis specifically inorganic bulk and REE elements with ^{210}Pb and ^{137}Cs isotopes to define the modern sedimentation rates and will identify cores with high sedimentation rates which may lead to follow-on high-resolution palaeocurrent work. Radiocarbon dating will also be undertaken to establish the absolute chronology of the slides. Further ^{14}C dates to those requested are dependent on the submission of proposals to the radiocarbon steering committee, NERCRCL, East Kilbride (Moreton).

Programme of Research

Task/Month	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**	**30**	**32**	**34**	**36**
Cruise Prep.																		
Data collect.																		
Regional Seismics and Mapping																		
Core Log & Mag. Sus.																		
PSA																		
Geochemistry																		
Palynology																		
Sortable Silt																		
^{14}C and Oxygen																		

Justification of Resources

The bulk of the requested funds are needed to support the onboard survey work (£33000) using the BGS deep-tow boomer and sparker system. This has been proved to work efficiently at high latitude in a range of water depths and seafloor types. Both the seismic systems and corer have been deployed successfully from a number of vessels and have been proved to operate efficiently. Similar systems are available within the UK but lack the vertical (metre-scale) resolution necessary to tie in the seismic reflection profiles with the subsequent core lithologies. The project is piggy-backing on the SAMS NSP so funds are not requested for either ship time or use of the UKORS piston corer. Capital expenditure is for a Qados digital x-radiograph (£58750) a Bartington MS2 magnetic susceptibility probe and loop (£4711). These are facilities that are not available at DML. The magnetic susceptibility meter is used to determine the ratio of terrigenous to biogenic sediment volumes and is a useful tool in identifying possible sediment intervals in core section of glacial-deglacial fluctuation. The digital x-radiograph cabinet is essential to determine the internal structure, amounts of IRD and levels of bioturbation within the cores, which are destroyed by more invasive methods. Dinoflagellate analysis (£6500) will be performed on a single core at 10cm resolution to decipher the palaeoproductivity and SST. Twentyfive radiocarbon dates (£11250) are requested within this proposal to aid constraint of the oxygen isotopes (£8750) and palynology, further dating proposals are expected once a basic core stratigraphy has been established. The detailed particle size work (£15000) on the SAMS Coulter Counter is a vital component of the core analysis, this combined with the geochemistry on the SAMS ICP-MS (£21000) will provide the fundamental data to enable the palaeoflow records of THC to be revealed. To enable this detailed program of analytical work to proceed, staff time is requested for two technicians (£46200, 26 months total), this is essential for help in conducting sediment digestions, microfaunal preparation and core curation.

The T&S expenses (£7619) are requested to allow the PI and Co-PI to visit respective institutes and to visit the University of Tromso in the final year of the project to enable the record from the Norwegian Arctic seismic programme to be contrasted with any potential record of bottom-current signatures from the western Svalbard margin. Additional funds are requested to allow Prof. Dorrik Stow to visit SAMS to examine the core and seismic data. Funding to allow the presentation of results at the annual AGU conference in the final year of the project is also requested.

Management and Long-term Stewardship of Data

The project will be managed by the PI at SAMS, Oban. Cruise participation will be limited to the PI and Co-PI only as well as the relevant BGS technical staff. Once the project has been completed all data (core logs and seismic profiles) will be available to the wider community. The data specifically relating to any potential palaeospeed estimates of THC from this study will be compiled and made available to the RAPID community. A limited run of CD's will be made available containing the final report and all the seismic and core data pertaining to the surveyed area. These will be available from the Dunstaffnage Marine Laboratory upon request. An outline and some data will be placed on the SAMS website. All core and seismic data will be stored at SAMS. The final year of the project (2007) coincides with the fourth International Polar Year and clearly the widest dissemination of the results during a time when media and scientific focus is on high latitude environments would be very advantageous.

Appendix 3 Reconstructing Pleistocene ice limits in the Central North Sea: implications for climate change — new PhD project

The following proposal was accepted for UCAC funding in late 2002. A PhD student — Mr Alistair Graham — was accepted in the summer of 2003, and has just begun his studies. Most of his time will be spent at Imperial College, but he will visit BGS Edinburgh in January 2004 to develop his knowledge of the Quaternary stratigraphy of the North Sea region, under the supervision of M. Stoker. The following summary outlines the scope of the study.

UCAC — BGS–Imperial College University Collaboration

Reconstructing Pleistocene ice limits in the Central North Sea: implications for climate change

Supervisors: Lidia Lonergan (Imperial College) and Martyn Stoker (BGS) with Chris Elders (Royal Holloway University of London), and Jenny Collier (Imperial College)

Project start date: October 2003

Aim: To quantify the extent and characteristics of NW European Quaternary ice sheets in the central North Sea basin by combining existing commercial 3D seismic reflection datasets and BGS Quaternary borehole and shallow seismic databases, thereby providing a critical parameter for climate modelling.

<u>Motivation</u>

Achieving a better understanding of the Earth's climate system is currently a major focus of scientific research. One requirement is to obtain a more detailed and accurate quantification of the past climate, against which to test the emerging global climate models (e.g. McAvaney *et al.* 2001). The extent and thickness of the Quaternary high-latitude ice sheets (which directly affect sea level and palaeo-shorelines, and indirectly affect ocean circulation) is one of the parameters of the natural climate variation that needs to be determined with greater accuracy. Although the position of terrestrial ice-sheet limits are now reasonably well known on land, and particularly so for the Last Glacial Maximum (e.g. Clark & Mix 2002), the limits of the last ice in NW Europe over currently submerged regions remains ambiguous, and a topic of some controversy. One of the major barriers to accurate ice-sheet reconstruction has been the lack of definitive subglacial bedform indicators, such as glacial striae and moraines. On traditional, widely spaced, 2D high-resolution seismic profiles the recognition of these types of feature is problematic, and without the plan-view offered by 3D imagery will always remain highly subjective. In this study we will use a hitherto underutilized marine dataset—merged commercial 3D seismic reflection data volumes from the North Sea—to further constrain and quantify the extent and nature of the NW European Quaternary ice sheets.

<u>Background</u>

During the 1970s and 1980s the BGS conducted extensive studies of the Quaternary sediments in the North Sea. This involved the acquisition and interpretation of many thousand kilometers of 2D boomer and sparker seismic reflection profiles, numerous vibrocores and over 100 shallow boreholes. This research effort resulted in the first stratigraphic and sedimentological interpretation of the North Sea Quaternary in the UK sector, and the identification of 3 major incisional unconformities attributed to the 3 major expansive Quaternary glaciations recognized onshore; namely the Elsterian (Anglian), Saalian (Wolstonian) and Weichselian (Devensian) respectively (e.g. Stoker *et al*. 1985; Cameron *et al*. 1987; Long *et al*. 1988).

In the last 20 years a wealth of commercial 3D seismic reflection data has been collected by the hydrocarbon industry in the North Sea and now almost 'wall-to-wall' carpet coverage exists within the area 53°–63°N and 1°W–3°E. Although these data were acquired with the aim of imaging deeper geological targets, the quality of the data in the top 0.5 seconds TWT (two-way time) spanning the Quaternary record are remarkably good. The strength of these datasets lies in the fact that the 3D coverage allows very subtle glaciogenic features to be resolved in plan view; giving data similar to aerial imagery on land, but with the added advantage of being able to generate images back in time. Our preliminary studies of some of these 3D seismic-reflection datasets already available at Imperial College and Royal Holloway, document a number of glacial signatures in the proposed study area. These include 5km long sets of linear striae that, by analogy to modern-day ice sheet signatures (Anderson 1999), are interpreted as having formed in seabed sediments beneath a grounded ice sheet and document ice movement directions (Fig 1). Shorter curved-irregular lineations were most likely formed by ice bergs, and anastomosing networks of tunnel valleys are thought to form by meltwater drainage beneath grounded ice sheets during ice sheet retreat (Fig 2). An earlier study by Praeg (1996) in the southern North Sea, of a single 39km x22km 3D seismic dataset and a regional 2D seismic grid, also documented the detailed morphology of Elsterian-aged tunnel valleys, and highlighted the potential of the type of study we propose here.

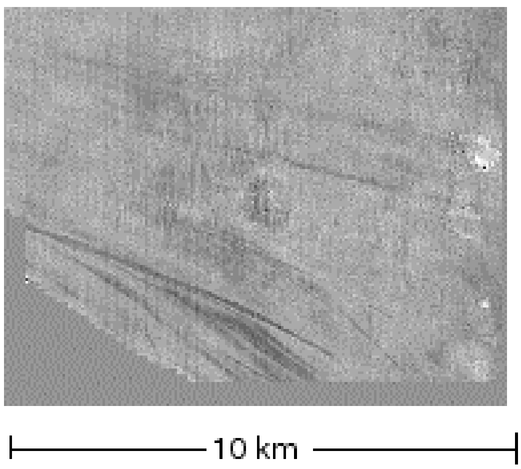


Fig 1. Timeslice through 3D seismic data volume which images glacial lineations in sediments within 45m of the sea bed in the Central North Sea.

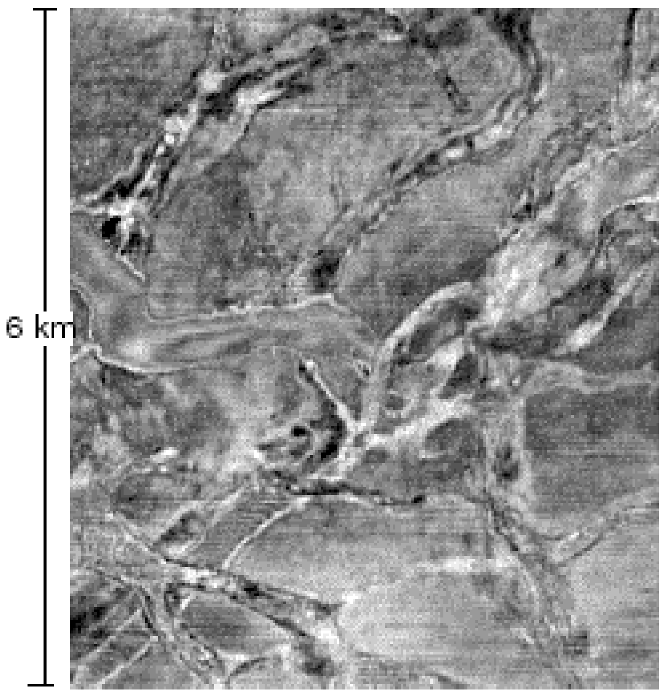


Fig 2. Cross-cutting Pleistocene glacial tunnel valleys in the Central Graben. Timeslice through 3D seismic data volume at ~150ms TWTt (or c.120m) beneath sea bed in the Central North Sea

Project outline

We propose conducting a systematic regional study of the merged commercial 3D seismic datasets in the north central North Sea (53°–63°N and 1°W–3°E). The seismic data will be calibrated by integrating with the existing BGS stratigraphic database. The study provides an opportunity to map with greater accuracy than previously possible the extent of the NW European ice sheets at different times in the last 0.5 Million Years and to investigate the dynamics of ice-sheet disintegration during the more extensive glacial episodes.

Datasets & facilities

Imperial College has a long history of working with the hydrocarbon industry on the interpretation of 3D datasets. It has a state of the art 3D seismic interpretation laboratory with all the necessary hardware, software and data storage facilities to handle a project of this size. Both BP and Shell, who between them have about 75% coverage of Central North Sea license blocks with 3D seismic data, have agreed to release the top 0.5 seconds of their 3D seismic datasets to Imperial (via the PGS Central North Sea megamerge project). Additionally Shell has agreed to allow access to high-resolution site survey seismic data and stratigraphic data in selected, key areas. The stratigraphic components of the project will require the student spending some periods of time based at the BGS offices in Edinburgh and will work there under the supervision of Martyn Stoker (and other relevant staff). The BGS group has extensive experience in the interpretation of high-resolution seismic data, as well as a published record in the development of Quaternary seismic-sequence stratigraphies around the entire UK continental margin. The student will have access to all relevant BGS seismic and geological data in the Central North Sea, which is accessible through an ArcView database. Computing facilities, including Landmark workstation, is available.

Work Plan:

(1) Set up stratigraphy for seismic study by correlating the BGS Quaternary borehole dataset and released commercial hydrocarbon boreholes with the 3D seismic datasets (3-6 months).

(2) Erect a seismic-stratigraphic framework for the Quaternary deposits above the Aberdeen Ground Formation (encompassing Elsterian–Holocene deposits) using the merged 3D datasets and some key regional 2D tie lines if necessary. Map the major depositional sequences identifying onlapping–offlapping packages and major erosional surfaces. Interpret these in terms of glacial, glacio-fluviatile or glacio-marine deposits (9-12 months).

(3) In selected areas of high data quality conduct a more detailed investigation of subglacial phenomena, including ice sheet striae, and tunnel valleys. For example the morphology of the channel systems will be studied by mapping the base of the channels and then visualizing them in 3 dimensions. From the maps of channel outlines measure a range of geomorphological parameters that will identify the channel forming processes (e.g. channel widths, depth of incision, sinuosity, aspect ratio, density of channels per area of ice sheet) (6 months).

(4) Data synthesis and project write-up (last year).

Milestones:

End Year 1- stratigraphic template defined and correlated with 3D seismic database; preliminary maps of major depositional sequences.

By 18 months- Imperial College M.Phil- PhD transfer report complete; completion of seismic mapping.

End Year 2: Completion of detailed mapping of subglacial features and collection of channel geometry database.

End Year 3: Thesis complete.

Deliverables:

1) Seismostratigraphic study of Elsterian and younger Quaternary deposits of the Central North Sea Basin; focusing on extent and distribution of ice-sheet related deposits.

2) Maps of sub- and pro-glacial geomorphic phenomena (including striae, channel systems etc.).

3) Database of tunnel valley and other channel type geomorphological characteristics.

4) Reconstruction of ice sheet advances/retreats for the major Quaternary glacial cycles present in the North Sea.

References:

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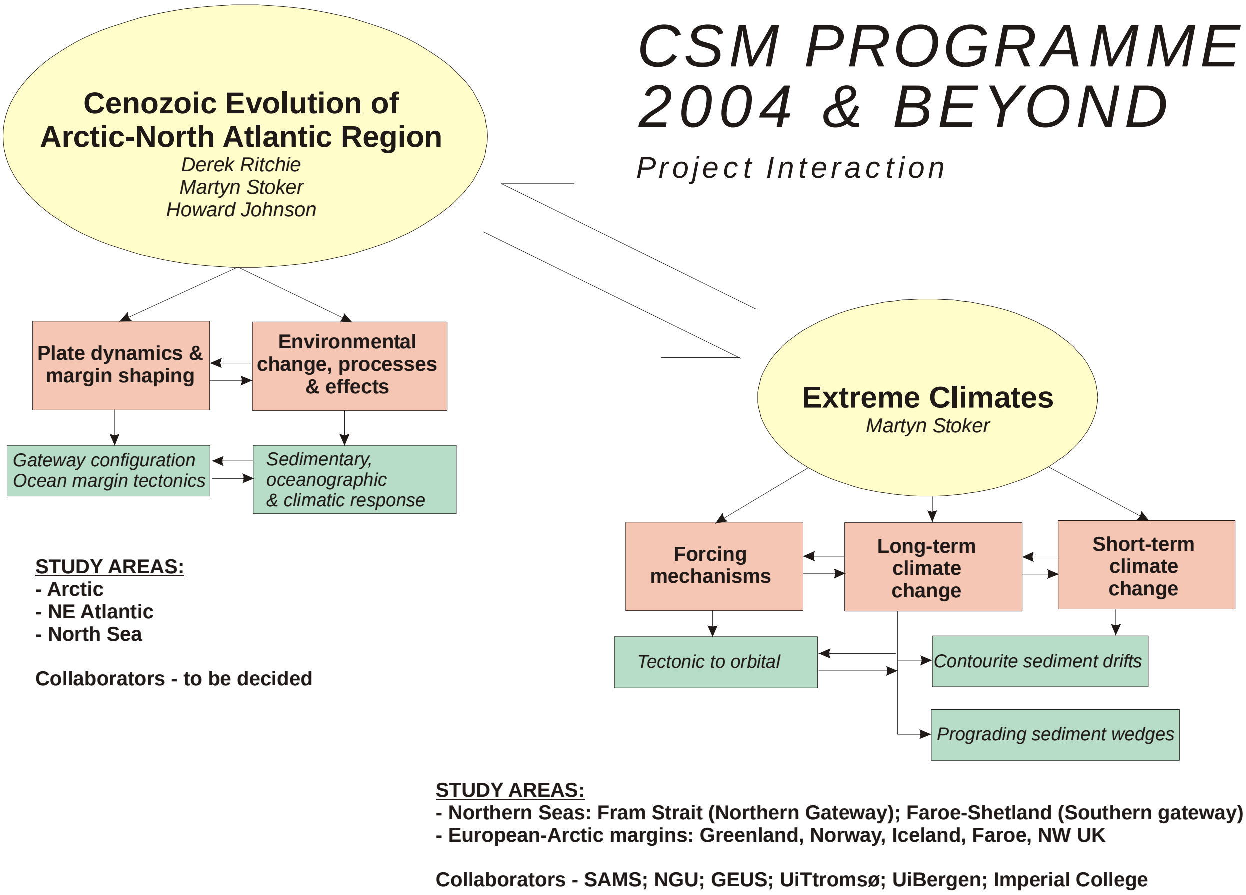
Budgets:

Joint funding of 3 year PhD studentship by Imperial College and BGS

Projected costs:

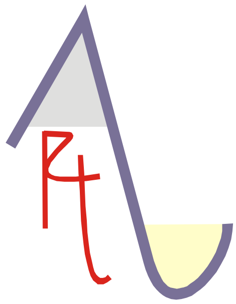
Year 1		BGS	IC	IC source
Fees	£ 2,900	£ 1,450	£ 1,450	Department
Student bursary	£ 10,000	£ 5,000	£ 5,000	Department
Travel costs (student visits bgs)	£ 1,000	£ 1,000	£ 0	
Seismic Lab operating costs	£ 3,500	£ 1,500	£ 2,000	LL other grants
Year 2				
Fees	£ 3,000	£ 1,500	£ 1,500	Department
Student bursary	£ 10,000	£ 5,000	£ 5,000	Department
Seismic Lab operating costs	£ 3,500	£ 1,500	£ 2,000	LL other grants
Year 3				
Fees	£ 3,000	£ 1,500	£ 1,500	Department
Student bursary	£ 10,000	£ 5,000	£ 5,000	Department
Travel costs for student to attend 1 international conference	£ 700	£ 500	£ 200	LL other grant
Totals	£ 47,600	£ 23,950	£ 23,650	
total per annum	£ 15,867	£ 7,983	£ 7,883	

Appendix 4 Internal CSM collaboration



The above diagram illustrates the possible relationship between the *Extreme Climates* initiative and another major project — *Cenozoic Evolution of Arctic–North Atlantic Region* — planned for 2004/05. The latter project would have greater focus on the plate tectonic evolution of the North Atlantic region, with a specific objective to determine the mechanisms controlling plate reconstructions. However, such mechanisms are all part of understanding the forcing mechanisms behind environmental change. As such, the potential projects very much complement each other. An IODP drilling proposal, regarded as part of the outcome of the Cenozoic Evolution project, would also benefit the Extreme Climate initiative. Both of these proposed studies represent truly generic research, not previously undertaken on this scale.

Appendix 5 'Peak to Trough (P2t)': a potential key BGS geoscience initiative



The following text (in red) is a summary of key points contained in an e-mail response by the author to the BGS Science Strategy team (SST) charged with establishing the foundations for the new programme from 2005 onwards. The e-mail was sent to Vicky Hards (on behalf of the SST), and copied to Martin Smith and Robert Gatliff. Additional explanatory notes are included as parentheses in grey font. The development work of the SST has prompted the P2t initiative.

1. To a large extent the (key generic) themes (sustainable land use; sustainable resources; safer environment; common geoscience issues; information infrastructure) appear to be very much the key areas that have been identified for some time, and have been communicated in previous documents. I support these themes as outcomes of our work. However, I do feel that a key generic issue that underpins all of these themes is the development of an understanding of how the UK landmass and its offshore area has been shaped, especially during the mid- to late Cenozoic interval. To understand aspects such as the exhumation history of the landmass, landform development, ocean-margin shaping etc. — all of which are pertinent to your defined themes — requires a basic understanding of the linkages between tectonics, oceanography and climate change. Plate forces and mantle convection have driven uplift and subsidence in and around the UK over the last 35 Ma, and have had a massive bearing on the development of the oceanographic circulation pattern off NW Britain, which in turn has played a major role in northern hemisphere climate change. Our recent history has, geologically, been very dynamic. One only has to imagine a kind of source-to-sink transect from upland Britain to the floor of the Rockall Trough to appreciate that the last 4 Ma has seen km-scale vertical movements, which has resulted in a remarkable history of denudation (including glaciation) and continental margin building. The key to better understanding this system is stratigraphy, without which we are unable to present a proper evaluation of their (tectonic movements, denudation, climate change) causal linkage. For example, glaciation has had a profound effect on the UK landscape as well as shaping the continental margin. How ironic then that despite +150 years of study, we still cannot determine the limits of the last ice sheet! Without such basic information, how can we model either short-term or long-term Earth system processes? We are constantly battered with the possible implications of climate change, yet the boundary conditions necessary for accurate modelling have not been accurately set. My basic plea here is to invest in essential generic research. I agree that your (SST) suggestion that we couple with other scientific disciplines is absolutely crucial.
2. This kind of strategy document is fine, BUT a general comment of my colleagues is that it is 'management speak'. As is common with such documents, it lacks real focus, and I would conclude that that is also one of the biggest problems with our (BGS) use of the science budget. On the back of this kind of general document is a need to be clear about where all the current (and future) projects fit into such a scheme. We need an organisational focus: perhaps this is an opportunity.

The Peak-to Trough (P2t) initiative — concept note

The key to really advancing our understanding of near-surface and surface Earth system processes, with particular respect to the late Cenozoic shaping of the UK landmass and continental margin, lies on a NW European plate scale, that is, to identify their spatial distribution within a high-resolution chronostratigraphic framework. There is thus a prime need for better resolution of the timing and magnitude of processes, and a requirement for better regional correlations and syntheses of these data in order to establish a UK model.

Such an effort demands the forging of closer links across disciplines, both internal and external to the BGS. For example, the sequence stratigraphers working on the offshore seismic record need greater awareness of the many contributions made by onshore geomorphologists and vice versa. Better resolution of climate variation through Cenozoic time is of paramount importance in constraining long- and short-term rates of erosion and sediment transport. In this way, depositional systems analysis offshore can be linked more effectively to surface uplift onshore, and lags between uplift and sediment flux from the uplifted regions can be identified.

This research problem is very demanding and multidisciplinary. The concept of a 'task team' focused towards a better process understanding is the obvious way forward to achieve an integrated model. The P2t initiative would be a potential way forward, providing the 'organisational focus' for such a wide-ranging geoscience theme. If the concept of the P2t initiative is accepted, a more detailed programme of research can be established.