BRITICE-CHRONO: TRACK RECORD OF CONSORTIUM TEAM

The British-Irish Ice Sheet (BIIS) has been the subject of investigation for over 100 years yielding a large volume (>2000) of papers, reports and Ph.D. theses. The nature of investigation, mostly by detailed fieldwork at local sites, resulted in an almost overwhelming volume of information spread over disparate published sources, which combined makes it difficult to reconstruct and assess ice sheet wide syntheses and address wider glaciological questions. We could reconstruct aspects of ice extent, timing and dynamics for some places, but the big picture remained elusive. For this reason a major initiative (called BRITICE) reviewed all sources of information, abstracting the key landform evidence and compiling it together for the first time as a published Glacial Map, GIS data files and as a bibliography. The project was funded jointly by the British Geological Survey (BGS) and the University of Sheffield, and led by our consortium PI (Clark) and including three of our Co-I's (Evans, Bradwell and Bateman). The outputs above were made available for free download from the now very well known and used (> 25,000 downloads) BRITICE web page; http://www.shef.ac.uk/geography/staff/clark_chris/britice. It is clear that this compilation (Clark et al. 2004; Evans et al. 2005) has stimulated new field investigations and increased mapping and large-scale reconstructions. However, the database only covered the land area of Britain and revealed many key gaps. The availability of high resolution digital elevation models and satellite images galvanised renewed mapping endeavours and, supervised by Clark, two Ph.D. students (Hughes and Greenwood) completed mapping the glacial landforms of Britain and Ireland. Together with the original compilation we now have a **near-complete record of landforms** recording ice sheet retreat over the terrestrial areas.

The next major advance came from utilisation of geophysical data recording the **seafloor geomorphology**, notably the unexpected discovery of an extraordinary series of moraines recording ice recession to the north and east of Scotland, led by Bradwell. This was important because it confirmed the much larger footprint of the ice sheet and that it had significant marine-influenced sectors. Further investigations by O'Cofaigh and Benetti reported similar finds to the west and north of Ireland, and Clark completed reconnaissance-level mapping around the entire continental shelf. Together, these data permitted a reconstruction of the overall retreat pattern of the ice sheet (Fig. 4 of CfS). So, over the last 10 years, led by consortium members, the ice sheet has experienced a step-change in knowledge about its pattern of retreat.

Information on timing of this retreat is the subject of our proposal, and in preparation we compiled a database of all known **geochronometric dates** (~800, nearly all terrestrial) relevant to the ice sheet (Hughes, Greenwood and Clark 2011), but thus far this database has not been subjected to careful quality analysis in the context of improved calibration and dating methodologies. These data originated in many different laboratories. Verifying the data and normalising it to currently accepted standards requires an intimate familiarity with calibration and normalisation methods. To conduct this vital task, which is estimated to drastically reduce the number of robust legacy dates, we have a consortium geochronology team (led by Fabel, and including Duller, Bateman, Moreton, and Freeman) with expertise across TCN, OSL, ^{14}C, and AMS methods, and their application to research questions relating to glacial and formerly glaciated contexts. They are well placed to do this because of many years respectively of running dating laboratories, including the most productive AMS Laboratory in Europe, which achieved NERC Recognised Facility status in 2008 to facilitate the broadest UK academic access, applying dating methodologies to samples, and analysing geochronometric datasets. The consortium geochronology team also has established working relationships with many of the laboratories that produced the legacy data, and will have access to the raw data through this network, and with many of the key workers generating the data (Ballantyne, McCarroll). Furthermore this same team will utilise its expertise in applying dating methodologies (from field sampling to publishing ages) to complete the dating programme and strict quality control protocols required to establish the BIIS as the best temporally constrained ice sheet in the world. Bayesian statistics are widely used to mathematically find the most plausible age probabilities from sets of possible ages and are routinely used for continuously accumulating sequences (e.g. lake sediments). Chiverrell is experienced in applying these methods to geomorphological sequences, where interpretative reasoning provides the reasoned order for the dated horizons (the prior model). Davies will bring her expertise in tephrachronology to help constrain the glacimarine drapes where ^{14}C will be used to home in on core intervals likely to contain key tephra horizons, that once found and characterised will provide strong chronological ties with the Greenland ice core record.

The third major strand of recent advances by our team was led by Scourse, who with colleagues (e.g. Pieńkowski), acquired, analysed and compiled a **synthesis of ice-rafted debris** from adjacent deep ocean cores, and from this it is possible to estimate timing of ice presence and activity on the shelf, providing the key dataset with which to link our reconstructed ice mass loss events.

For acquiring samples to date from the **marine record**, O'Cofaigh has considerable experience from participating and leading NERC cruises in Antarctic and Greenland waters and in situations with virtually no pre-existing knowledge of the seafloor geology and geomorphology. Such experience, combined with the high level of knowledge regarding our proposed targets in British and Irish waters reassures us of the likely success of the project. Benetti also has experience of leading cruises and has conducted the pilot survey to the west of Ireland (Fig. 4 in CfS) demonstrating successful acquisition of cores suitable for dating. Further experience of marine geology and geophysics is provided by Stoker, Van Landeghem, Scourse, Gafeira and Bradwell who have conducted widespread seafloor mapping of the Irish and Scottish sectors, yielding key insights into the activity of ice flow. Xavier Monteys from the Geological Survey of Ireland has geophysical, geomorphological and core logging experience covering project transects on the Malin Shelf, Galway Bay and Irish Sea (T7-T5-T3). As a GSI PP he will also provide expert guidance on the Irish marine datasets. Our colleagues in Bergen (Sejrup) have decades of experience of marine geological and geophysical investigations in the North Sea, including close co-operation with industry in providing key datasets, and this experience will be crucial in investigating interactions between the BIIS and Fennoscandian Ice Sheet.

Sampling from the **terrestrial record** will be led by Chiverrell who has experience of geomorphological and stratigraphical research around Britain and Ireland, and he has led mapping, borehole and geophysical field campaigns in contract research for Aggregate companies, English Heritage, the Welsh and Isle of Man Governments. He leads a team of investigators (O'Cofaigh, Clark, Evans, Bradwell, Ballantyne, Hambrey, Hughes, Livingstone, Roberts) expert in their respective locations. Terrestrial geophysical surveys will be conducted by the Geophysics Unit (Liverpool) with dedicated technical support (John Hakes) for the state-of-the-art Ground Penetrating Radar and Electrical Resistivity equipment. Borehole sampling will be undertaken by the experienced BGS drill crew. The significance of research by the terrestrial team is testified to by key papers on all sectors of the former BIIS (see references).

Ice sheet modelling is led by Hindmarsh who has a strong record in this field and who has specifically worked on the stability of marine ice sheets and ice sheet mechanics across the sheet to ice shelf transition. We will use his British Antarctic Survey ice sheet model (BASISM). He is widely connected in the modelling field, making him well placed to also lead our International Advisory Board of modellers, and has assembled an impressive team including Pollard (Penn State), Ritz (Grenoble), Milne, (Ottawa), Flowers, (Vancouver) and Rutt, Hubbard, and Vieli from the UK. Also contributing to the ice sheet modelling component, Rutt is chair of the international Glimmer-CISM steering committee, and has been a key developer of Glimmer-CISM since 2003. He was responsible for coupling Glimmer-CISM to FAMOUS for the Hadley Centre, as part of CPOM NERC Centre of Excellence. His modelling expertise has expanded into finite element and finite volume methods in collaboration with CSC, Finland (Zwinger), with whom he has been working on developing and evaluating calving criteria. The links between ice mass loss, calving rate and the appearance of IRD in ocean cores will be explored using established **iceberg trajectory modelling** (Bigg) and **palaeotidal model** simulations of tidal range change since the LGM (Scourse).

In summary, our consortium of researchers have already made significant advances to the understanding of the BIIS, have demonstrated an ability to take on and deliver demanding and ambitious research and have a proven track record of working at the whole ice sheet scale necessary for this project. In addition, our publication record demonstrates expertise across all of the elements necessary for the success of the project. We are confident that we have the appropriate team, and the high degree of co-publication indicates a productive record of existing collaboration.

Key papers demonstrating relevant track record (Investigators and project partners in **bold**)

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BRITICE-CHRONO: Constraining rates and style of marine-influenced ice sheet decay

Executive summary. *Given concern about retreat / stability of the marine-influenced West Antarctic and Greenland Ice Sheets, and consequent sea-level rise, it is imperative that we can predict the future rates of change of these large ice masses. The Intergovernmental Panel on Climate Change (IPCC), amongst others, have highlighted that our current ability to do so is limited and a major weakness in climate science. Numerical ice sheet models - capable of making predictions - exist and are being refined, but they have yet to be adequately tested against data on the pattern and timing of a shrinking ice sheet. Recent work has constrained the pattern of retreat of the marine-influenced ice sheet that once covered the British Isles but its timing is inadequately constrained.* ***We propose a systematic and directed campaign to collect and date material to constrain the timing and rates of change of the collapsing ice sheet.*** *This will be achieved by focussing on eight transects running from the continental shelf edge to a short distance (10s km) onshore and acquiring seafloor and terrestrial samples (marine fauna, sand and rock) for geochronometric dating by radiocarbon (^{14}C), Optically Stimulated Luminescence (OSL) and Terrestrial Cosmogenic Nuclide (TCN) methods; with sampling accomplished by two research cruises using a NERC vessel and eight fieldwork campaigns. Results will reveal the timing and rate of change of ice margin recession for each transect, and combined with existing landform and dating databases, will be used to build an ice sheet-wide empirical reconstruction of the shrinking ice sheet. Simulations using two numerical ice sheet models, fitted against the margin data, will yield insights regarding their predictive abilities, and the significance of controls on retreat rate such as from sea-level rise, bed topography and ice shelves. The retreat of the British - Irish Ice Sheet (BIIS) will become the best constrained anywhere and a benchmark against which predictive ice sheet models can be improved and tested, thus making significant contributions to glaciology, climate and Quaternary science and to reducing the uncertainty of sea-level predictions. Although parallel advances are being made constraining the style and timing of ice mass loss across the continental shelves around Antarctica and Greenland, investigation of a former marine-influenced ice sheet has the advantage of yielding information across the marine-terrestrial transition, and with much greater accessibility and thus reduced cost.*

1. RATIONALE Given the recent warming of climate (IPCC 2007) and of reductions in mass of the Antarctic and Greenland ice sheets, and consequent sea-level rise (Rignot et al. 2011), it is imperative that we can predict rates of change of these ice masses over timescales of decades to millennia. The IPCC, amongst others, have highlighted that our current ability to do so is limited and a major weakness in climate science. Using modelling, it is a relatively simple matter to predict the amount of ice melting arising from warmer temperatures, and fairly robust predictions of melt from ice sheets can be made. However, for most of Antarctica and for large parts of Greenland, mass is mostly lost by iceberg calving once it is delivered by ice flow to the marine-terminating fringes of the ice sheet. Herein lies a considerable complexity because the rate of delivery of ice to the margins (mainly by fast moving ice streams) is highly sensitive to controls at the marine margin (e.g. tides, relative sea-level changes, slope of the seabed, loss of buttressing ice shelves), leading to incompletely understood *ice-dynamical controls* on ice flux and retreat. The IPCC (2007) assessment of sea-level rise (180 to 590 mm) by 2100, has been considered very conservative (e.g. Hansen et al 2007) and superseded by an estimate that is double this range (Allison et al 2009), with an upper limit of about two metres, because of a better appreciation of such ice-dynamical effects via observations of ice thinning and flow acceleration and by numerical modelling. The latest observations of the mass balance of Antarctic and Greenland ice sheets (Rignot *et al* 2011) reveal that, combined, they are losing mass at 475 gigatons per year (~1.3 mm a^{-1} of sea-level rise) and, importantly, that this rate is accelerating and is predicted to make ice sheets the dominant contributor to sea-level rise this century. That the contemporary observational record frequently exceeds model predictions and surprises us clearly underlines the need to better understand and model ice-dynamical effects. Accordingly, the international glaciological community is further developing theory and numerical models (Figs 1 and 2) to reduce uncertainty. But there is a long way to go because some key physical processes and feedbacks have yet to be fully understood and incorporated into ice sheet models and tested against observational data. Until this is achieved the validity of model predictions of the fate of ice sheets and projected sea-level rise remain questionable.

Over the next century society will demand increasingly robust predictions of global sea-level rise with quantified uncertainties. Our proposal thus takes a medium term view, recognises the global significance of the problem and anticipates imminent resolution of the ice-dynamical problems of marine-terminating margins. We anticipate new model formulations will urgently require data on real ice sheet retreat rates either to test physically-based formulations or, if these fail, to derive empirical-stochastic approaches.

***Fig1**. Modelled extent and ice elevation (m) of a much reduced (ca. 13% of original mass) Greenland Ice Sheet when forced with a climatology with 4x the pre-industrial levels of CO_2, yielding a SL rise of 6.4 m.*

From Irvine et al 2009.

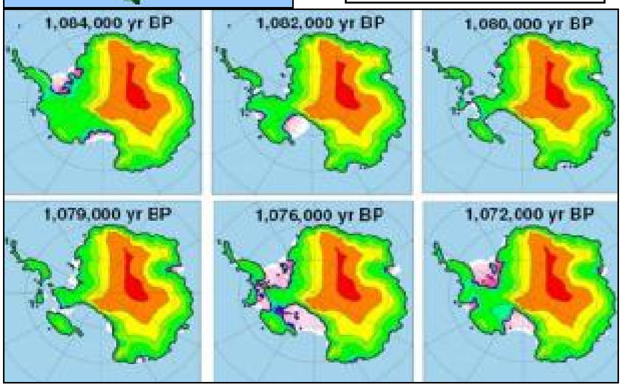

***Fig 2**. Combined ice sheet – ice shelf model simulation of retreat of the West Antarctic Ice Sheet during a warm (interglacial) phase one million years ago. Note dramatic ice volume losses (~ 5 m of SL) over a millennial timescale. Loss of the fringing ice shelves permitted flow acceleration and rapid grounding line retreat leading to collapse of the ice sheet. From Pollard and DeConto 2009.*

We would be unwise to base any major societal response on ice sheet models that cannot sensibly simulate (or predict) retreat rates through different water depths, in different tidal regimes, with and without fringing ice shelves, and to do so without considering topographic pinning points, continental-shelf slope angles and coastal geometries. Neither do we understand how an ice sheet responds to the loss of marine-terminating margins once it back-steps onto land. The retreat rate must change because calving is lost and only melting remains. Do the margins stabilize and require much more climate forcing for the next stage (stepped retreat), or maybe they are prone to readvances back into the ocean? How does this affect internal ice elevation thinning? Changes in retreat behaviour consequent upon the processes in operation (discharge into open ocean versus ice shelf or on land) provide demanding tests of ice sheet models. The Greenland Ice Sheet, for example, now has a mixed terrestrial and marine margin, and future retreat will change this balance and thus the retreat rate and behaviour.

In addition to these important ice-dynamical effects, ice sheets with large sectors grounded below sea level (so-called marine-based ice sheets) have long been argued as being susceptible to destabilisation leading to catastrophic retreat or collapse (Mercer 1978; Vaughan 2008; Fig 2). The IPCC cite a potential sea-level rise of 5 m arising from a collapse of WAIS (modified to 3.3 m by Bamber *et al*. 2009). This instability arises because a small sea-level rise (trigger) can ‘unpin’ (floating) ice-shelves leading to increased ice outflow to the margins, and because of the specific topography of the ice sheet bed. Where bed elevation declines towards the interior (adverse slopes), the ice retreats into progressively deeper water forcing rapid disintegration of part of the ice sheet. It is known that the WAIS underwent such collapses in the past (Scherer *et al.* 1998).

Our consortium of glaciologists and marine and terrestrial Quaternary scientists will provide the best reconstruction yet of the demise of an ice sheet as it underwent the transition from marine-terminating margins to being entirely land-based. Because the existing ice sheets have yet to deglaciate sufficiently, we will collect new data on the former British-Irish Ice Sheet (BIIS) (Fig. 3) to reconstruct the rate and style of retreat starting with its maximum extent, through loss of marine sectors until it back-stepped some distance onshore. Margin isochrones (Fig 3) will be produced for successive timeslices through ice sheet decay.

Fig 3. E*mpirical reconstruction of British-Irish Ice Sheet at 27,000 years ago. Clark et al. 2010.*

Once achieved the integrated data will permit an ice sheet-wide empirical reconstruction of a disintegrating ice sheet highlighting the circumstances controlling rapid versus slow margin retreat, and identifying any catastrophic or oscillatory behaviours such as marine-based collapse of sectors, ice purges, or readvances. Of course the BIIS existed on a bed that is not the same as those in Greenland or Antarctica, and with climate and sea-level boundary conditions that are not identical to contemporary and future scenarios. So whilst important general lessons about ice sheet retreat will be learnt from the BIIS they are unlikely to be *directly* transferable to present day ice sheets. However, the main contribution will be that our reconstruction will be available to test purportedly-leading ice sheet models, or to use them in a more experimental way in developing them, e.g. to assess which model implementations of iceberg-calving, grounding lines and ice stream are best suited for predicting retreat of existing ice sheets?

2. WHY THE BRITISH-IRISH ICE SHEET?

Though intensively investigated for over 100 years, there has been a step-change in our understanding of the ice sheet over the last 10 years from interpretations of a mostly terrestrially-constrained, small, ice sheet to a version twice as large (ca. 840,000km^2; Fig 3) covering the continental shelves to the shelf-break and most of the North Sea. That large parts of the ice sheet were marine-based and drained by ice streams, and that the bed has many adverse slopes and troughs, makes it a useful analogue for the WAIS but at an estimated one third of its volume. The fjord topography of Scotland, with extended outlet glacier / ice streams purging interior ice, provides a useful analogue for much of the Greenland Ice Sheet.

Most of the recent advances, led by members of our consortium, arise from new geophysical data revealing extensive moraine systems across the continental shelf (Bradwell et al 2008), new mapping of the entire terrestrial area from digital elevation models (Clark et al 2010), and an analysis of adjacent deep ocean records of ice-rafted debris (IRD) (Scourse et al 2009). Together they provide the most complete record of the *pattern of retreat* of a shrinking ice sheet (Fig 4), and via the IRD analysis, an indication of non-steady ice discharges suggesting a non-linear response to climate and sea-level forcing. A review of all available geochonometric dates with which to fix elements of the pattern in time, revealed >800 dates spread across Ireland and Britain (Hughes *et al.* 2011), but poorly distributed over space, and with a notable scarcity offshore and are unable to constrain the marine-terrestrial transition. This is not surprising since these data were mostly collected *ad hoc* over many decades.

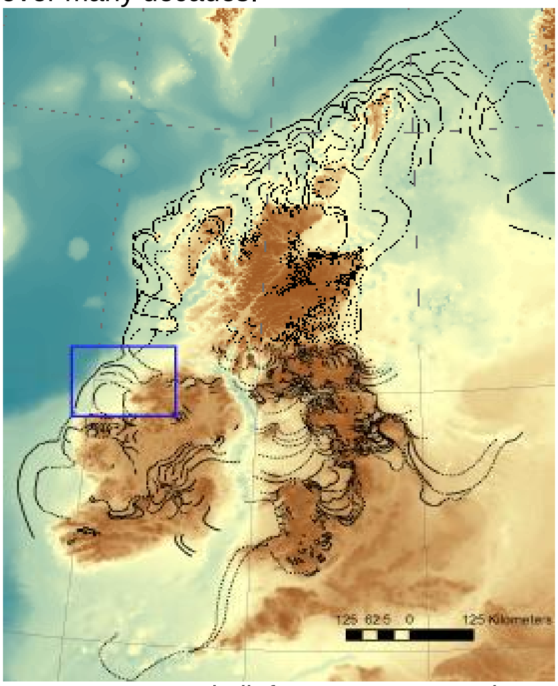

Fig 4. Retreat pattern built from 26,000 recently mapped landforms and information from the BRITICE database recording earlier work (Clark et al 2010).

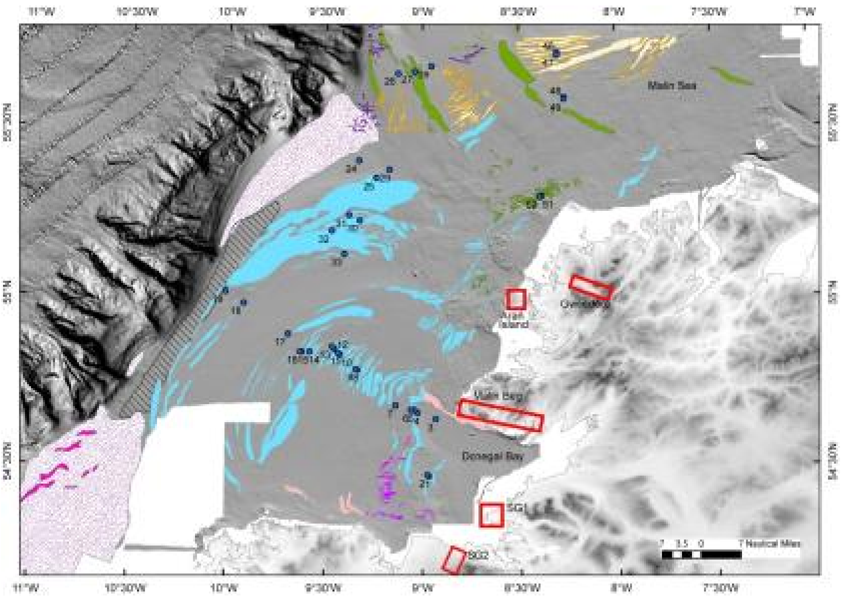

***Fig 5**. Detail of recent mapping offshore of NW Ireland (see box in Fig 4). Blue and green are moraines (O'Cofaigh et al in press), already collected cores are shown as are planned onshore fieldwork targets (red boxes).*

The pattern of retreat summarised in Fig 4 (some detail in Fig. 5) now provides an exceptional opportunity to date the retreat of the ice sheet because with strong geomorphic control, fewer dates are required to constrain it, as 'point-dates' can be extrapolated spatially; we therefore now have a landform structure within which to direct a systematic sampling campaign.

The small size of the BIIS is an advantage since a modest computational effort is required for any modelling experiments. It is challenging because its size yields rapid response to changes in boundary conditions (high dynamism) and it is positioned adjacent to the North Atlantic Current (NAC) component of the thermohaline circulation that has experienced large and rapid oscillations during the Quaternary, and it is known to have been drained by several vigorous ice streams. We should therefore expect it to be one of the world's most rapidly changing and dynamic of ice sheets and therefore to provide an exacting test of any ice sheet model.

3. SCIENTIFIC AIMS - *We propose a systematic and directed campaign to collect and date material to constrain the timing and rates of change of the marine-influenced sectors of the collapsing British-Irish Ice Sheet*. Once the data is compiled in an ice sheet-wide synthesis it will be used to address key uncertainties, organised into three main hypotheses:

Hypothesis 1: that the marine-influenced sectors collapsed rapidly (<1000 years) and that once onshore the ice sheet stabilised and retreated more slowly. This hypothesis is consistent with the consensus view on unstable marine-influenced ice sheets; we want to test if such behaviour actually occurred. The alternative view was favoured in a recent reconstruction (Clark et al 2010) where widespread purging of ice was invoked while marine-margins retreated slowly, thereby thinning interior (land-based) ice, and preconditioning the ice sheet to more rapid retreat once it was terrestrially-based. The existing chronologies of ice retreat cannot yet distinguish between the alternatives because of insufficient dating constraints in the marine sectors. This hypothesis is relevant to the Greenland Ice Sheet, because uncertainty exists as to the wider mass balance significance of 'dynamic-thinning', and how mass balance will be affected when marine-influenced sectors are lost.

Hypothesis 2: that the main ice catchments draining the BIIS retreated synchronously in response to external climatic and sea-level controls. This might be expected if external forcings outweigh the more local controls on ice retreat, for instance related to different water depths, adverse or normal bed slopes, differing tidal ranges and the presence or absence of buttressing ice shelves. However, we expect that such local factors should influence or modify retreat rates, and the extent to which this happens is vital for attaching significance, for example, to observed retreat rates in Pine Island Bay, Antarctica. How cautious should we be in regarding observed retreat rates at a specific place as being representative of the wider ice sheet system? Are ice streams merely slaves to mass balance, or do they profoundly alter the course of deglaciation?

Hypothesis 3: that the ice-rafted debris (IRD) fluxes derived from the BIIS on the adjacent continental margin is a function of changes in ice sheet mass balance. IRD analysis has become a powerful tool for reconstructing the timing and magnitude of ice sheet discharges into the ocean and has been used for major contemporary and palaeo ice sheets. Considerable divergence of interpretation occurs in how to relate IRD flux to ice sheet behaviour (Scourse et al 2009). Is the purging of ice a consequence of positive mass balance and margin advance (i.e. more ice to discharge) or of a negative mass balance (collapse of a marine-based sector)?

The project will provide the following tangible outcomes:

1. An empirically-based reconstruction of ice retreat that best satisfies existing and newly collected data. This will take the form of palaeo-glaciological maps at timeslices during deglaciation, and ice sheet modelling experiments fitted to these timeslices will yield ice sheet thickness from which volume estimates of mass loss can be computed and converted into sea-level equivalent contributions. Such optimised ice thickness data will also be critical for improved glacial isostatic adjustment (GIA) model simulations with implications for our understanding of the rheological properties of the lithosphere.

2. BRITICE-CHRONO data compilation. Following an earlier published inventory of glacial landforms as a map and Geographic Information System (GIS) data (BRITICE; www.shef.ac.uk/geography/staff/clark_chris/ britice), this will be updated and will include: all geo-chronometric data made available for future multidisciplinary research as a quality-controlled database (all existing and new dates,~1600) with metadata and GIS layers. Reconstructed ice margins from 1) will be made freely available specifically to encourage future ice sheet modelling. On the advice of our modellers data will be released in formats and geographic projections of most use and with appropriate levels of metadata.

3. Engagement of the modelling and evidence-based communities. Through our involvement with leading ice sheet modellers on our Advisory Panel, and their participation in some of the annual meetings and integration of our data in model simulations we anticipate a much stronger engagement between the modelling and palaeodata communities. It is strongly argued that such increased engagement is vital for model developments and for reducing uncertainty in model predictions of future sea-level rise.

4. WHY A CONSORTIUM APPROACH?

Because individual outlets and ice streams are merely part of a wider regulatory system within ice sheets, it is necessary to cover the whole ice sheet i.e. there is likely no ‘typical’ margin or outlet to investigate. Although ice drainage basins exist within ice sheets, intervening ice divides are not fixed and adjust their position according to varying fluxes between adjacent basins. It is thus vital to treat ice sheets as an integrated system and caution should be exercised in presuming that specific margin behaviour is representative of the ice sheet as a whole. Because of this a consortium approach is essential and because at the whole ice sheet scale the geochronological constraints need to be compatible with the scale of the modelling. Furthermore, the coordinated and systematic effort with expertise drawn from terrestrial and marine geology and geophysics, geochronology, glaciology and modelling requires a consortium approach. The scope is beyond the capability of a few small teams and the task too important to be allowed to continue to progress incrementally over many decades. The urgency to provide better ice sheet modelling to assist in making robust sea-level predictions is of paramount global societal significance.

5. SAMPLING STRATEGY. The recently developed retreat pattern (black in Fig 4 and 6) forms the basis for a systematic sampling scheme and, when viewed along with the locations of existing dates (~800) from our recent review (Hughes et al 2011), we have identified the main uncertainties and the positions where the smallest number of dates would maximize the information on retreat. Given that our focus is on retreat rates from marine-calving to terrestrial-melting margins (hypothesis 1), our sampling is organised via a series of transects from the continental shelf edge to a short distance (~30 km) onshore (Fig 6) with each transect leader responsible for both aspects.

Eight transects are required in order to test our second hypothesis in relation to the synchrony, or otherwise, of the various sectors. A large volume of possibly unstable ice existed over the North Sea. Its deglaciation is virtually unknown and so with a parallel research proposal by Norwegian colleagues (see letter of support from Sejrup; NORDICE-CHRONO) we have designed transects to investigate the North Sea with a focus on the northern and southern margins. Note that for

Transect 1 (East Shetland) we plan to co-operate closely in order to cover this key location in detail should both projects be funded; as a contingency in case only one is funded it is retained in both proposals.

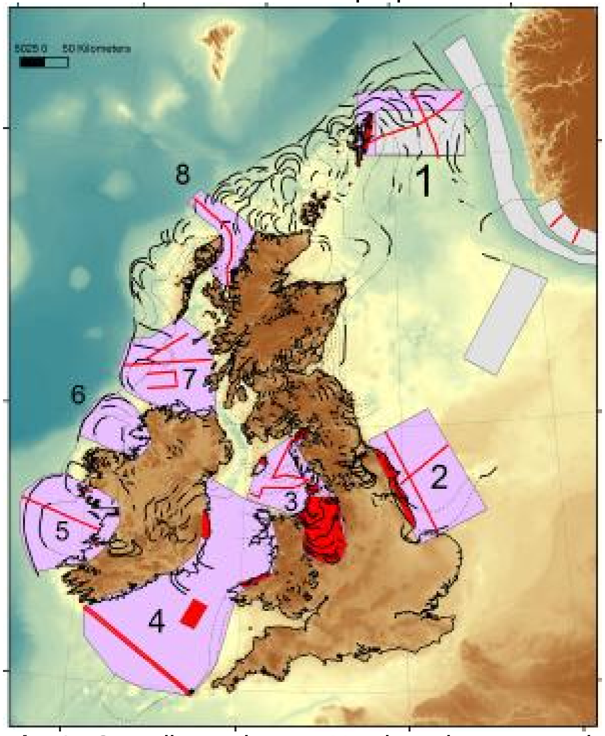

Fig 6. *Sampling scheme. Numbered transects in violet and which all stretch onshore for tens of kilometres (red). In red also are the proposed ship cruise tracks for acquiring geophysical data and sediment cores. Black shows the known retreat pattern. Transects proposed by our sister project, NORDICE-CHRONO, are shown in grey. Note that no shiptime is required for T6 because cores have already been acquired by INFOMAR, ~Fig 5.*

	Cores	**^{14}C**	**OSL**	**TCN**
T1 East Shetland	18	72	10	22
T2 Southern North Sea	10	60	35	0
T3 Irish Sea-east	10	85	25	15
T4 Irish Sea-west	20	70	20	15
T5 Galway Bay	20	78	25	25
T6 Donegal Bay	0	82	0	25
T7 Malin Sea	13	80	0	20
T8 The Minch.	15	60	25	36
	102	**587**	**140**	**158**

Table 1. *Each transect leader made a written case for the number of cores and marine and terrestrial dates and their type required to meet the objectives. Rather than specifically allocate these resources to each transect, they are treated as indicative targets, and once good samples have been obtained and a case made, resources will be distributed competitively and within constraint of the overall budget. This ensures good management of, and best value from, the budget, and reflects the uncertainties in the recovery of samples.*

The next criterion is that chosen transects would cover normal and adverse bed slopes, a variety of water depths and tidal ranges, trough-outlets of varying widths, possible pinning points and exposure of the ice margin to different sea surface temperatures and topographic contexts conducive to ice shelf formation. From a wider initial selection of transects those in figure 6 were chosen on a competitive basis with regard to how well they matched our criteria, as above.

Example Transects: Two-page cases-for-support exist for all transects and were used by the Steering Group to ascertain which should gain support and to facilitate overall planning and logistics. We summarise two examples. Transect 1, is designed to capture a major and possibly catastrophic element in marine-based deglaciation. We will constrain timing and rates of change of the 'unzipping' of the British and Scandinavian ice sheets (Fig 7). Once separate, these lobes permitted ingress of water to an enlarged ice sheet perimeter, likely increasing the potential for rapid mass loss through calving. We hypothesise that separation along the suture (red) was a tipping point in deglaciation leading to destabilisation of ice cover over the North Sea and considerable reorganisation of flowpaths and ice configuration of over Scotland.

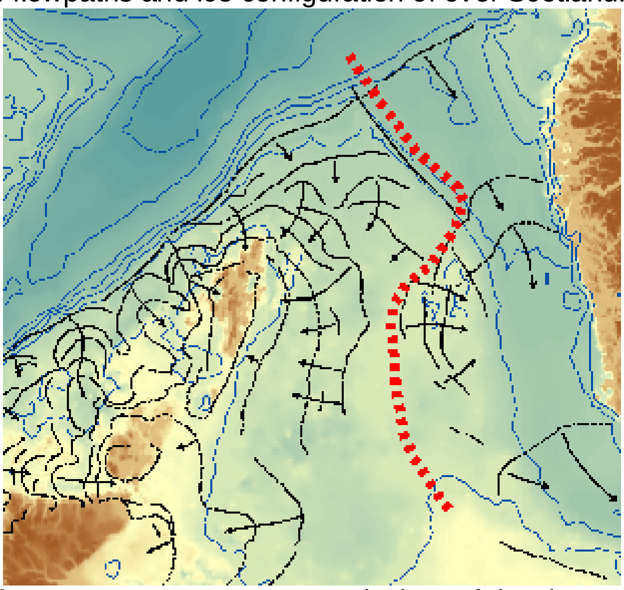

Fig 7*. Retreat pattern & 'unzipping' of ice between Scotland and Norway as revealed by moraines.*

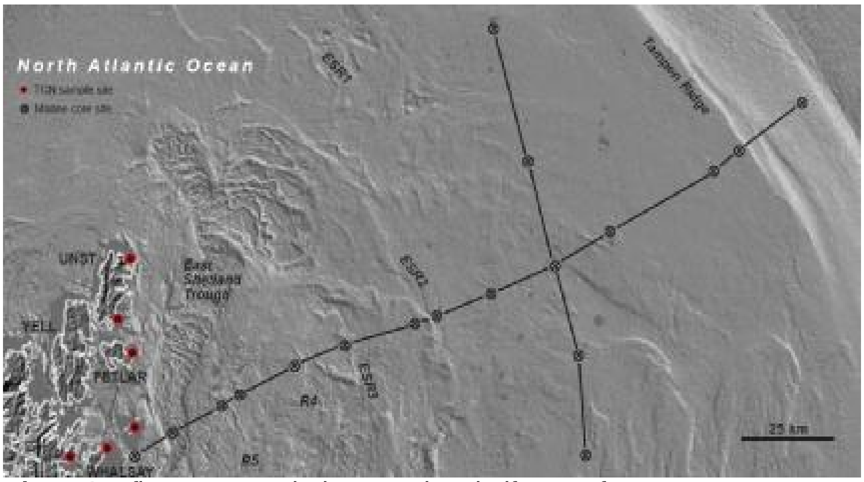

***Fig 8**. Seafloor geomorphology on the shelf east of Shetland and our ship tracks and sampling locations. Large arcuate moraines and lobate till aprons mark the limit of a retreating ice sheet margins, annotated ESR1-3 and R4-5 and numerous intermediate stillstands between these. All limits are currently undated. Potential sampling sites for TCN (onshore) and marine cores are indicated.*

Our targets for sampling are indicated in Fig 8, a combination of AMS ^{14}C dating of marine fauna found in 18 seabed cores (~4 dates per core) and terrestrial cosmogenic nuclide (TCN) dating on the periphery of East Shetland so that the marine-terrestrial transition can be assessed. The eastern headlands of Unst, Fetlar, Whalsay and Out Skerries have been identified as appropriate sites for TCN sampling.

For Transect 6 detailed moraine positions have been mapped and cores have already been collected using a vibrocorer, but have yet to be dated. In Fig 5 the core locations and planned terrestrial fieldwork sites are indicated. Most of the cores have been split and described and show a succession of glacial diamicton overlain by fining-upwards gravel with abundant shells and shell fragments into Holocene sands. This pilot investigation indicates that sampling by vibrocorer will yield useful materials and that the stratigraphical context of glacial deposits with overlying dateable material is common.

6. Specific objectives

The known pattern of retreat along prioritised transects will be used to collect samples (rock, sand, organics) that will be subjected to geochronometric dating analyses to yield time constraints on the retreating ice sheet. Specific objectives are listed below.

1. Optimise target locations for sampling, based on archived or recently available marine geophysical data. BGS has a large 'legacy archive' of seismic lines and our existing and developing links (see letters of support) with industry (e.g. Centrica have acquired detailed data in the Irish Sea in pursuit of potential windfarms) mean that seismic and high resolution bathymetric data can be used to locate optimum sites for coring so increasing the probability of retrieving good samples. Onshore we have detailed knowledge of existing sites, mostly quarries, and coastal sections.

2. Conduct two cruises to collect marine geophysical data (swath bathymetry and sub-bottom profiling) to further refine targets and to extract cores and retrieve samples for dating.

3. Conduct equivalent onshore campaigns, to sample from known sites and use terrestrial geophysics and mobile drilling rigs to acquire samples from new sites.

4. Synthesise new with existing data and make science cases for submitting samples for dating. The project steering group and geochronology team will assess the viability of proposed samples.

5. Use selected samples to yield age estimates using ^{14}C, OSL and TCN, with full quality control and reporting of errors.

6. Make a critical quality assessment of all known geochronometric assessments related to retreat of the ice sheet. An extensive literature and database search has compiled all known dates (^{14}C, OSL, TL and TCN) related to the ice sheet. Many of these dates will need 'retiring' because they are unreliable because of outdated technology or lack of reliability, and many will need recalibrating. The geochronology team will assess each date and conduct a strict quality assessment and also informed by Bayesian analysis (see below).

7. Where opportunities arise, reconstruct sea surface temperatures (SST) relevant to the retreat history of ice margins, via micropalaeontological analysis of marine core samples. This will help inform controls on retreat rates. The BIIS was adjacent to large shifts in the position of the Polar Front resulting in marked SST variability strongly registered in foram assemblages (Scourse et al 2009).

8. Compile outputs of existing palaeotidal modelling for the region (Uehara et al 2006) to assess degree of influence tidal range has on retreat rates (under objective 9).

9. Reconstruct retreat history for each transect. Each transect leader will compile the full retreat history for their transect from the shelf edge until onshore. Inferences on the control on retreat rates will be sought from the transect-specific characteristics, e.g. for retreat in the Irish Sea, did the margin pause at topographic narrowings or overdeepings? As a means of better utilising point-data (with uncertainties) on timing to constrain a spatial pattern of recession, and possible readvances, we will conduct Bayesian analysis of the chronological data to reconstruct retreat rates.

10. Submit all new geomorphological, geological and geochronological data centrally for recording in GIS and database form. This will be used to inform empirical reconstruction of whole ice sheet retreat and as constraint data for ice sheet modelling.

11. Conduct an empirical ice sheet–wide reconstruction that best fits new and existing evidence base. Produce timeslice maps of margin retreat**.**

12. Conduct ice sheet modelling experiments to fit to reconstructed timeslice maps. This will highlight what is easily accommodated by existing model formulations against what cannot be sensibly simulated and is therefore lacking. For example we may learn that it is impossible to explain aspects of the retreat rate change across different water depths because the calving rules are inadequate, or that the only way of simulating retreat in a specific place is by invoking an ice shelf. The secondary objective here is to estimate ice thickness and volumes at each timeslice.

13. Assess the nature and degree of correlation between ice volume losses at specific times and sectors against the (published) abundance of ice-rafted debris recorded in adjacent cores. The aim here is to assess the glaciological explanation of changes in IRD flux - positive versus negative mass balance, build up vs. collapse. To better link ice losses to specific core locations we will use an established and tested iceberg trajectory model that plots the course and melting of icebergs as they move in accordance with ocean and wind fields.

8. METHODOLOGY

Most of the methods to be employed are tried and tested and investigators have wide experience in executing them (see publication lists). We briefly report these, but provide more detail on a specific novel element (Bayesian analysis of ice sheet retreat from chronological data). The initial task is to acquire materials (sediment, organics, rocks of appropriate mineralogy) in appropriate stratigraphic contexts to constrain the timing of ice sheet retreat, and submitting these for dating analysis.

8.1 Targeting of specific materials for sampling.

8.1.1 Marine targeting. The acquisition of marine geophysical and geological data will fully exploit existing records and core materials (notably British Geology Survey, BGS, Geological Survey of Ireland, GSI, and industry data). Our cruise activity is along transects only where existing coverage is absent or sparse, or in localities where existing data indicates that fresh seismic survey or coring will address key geochronological issues (see earlier). For instance, the existing OLEX geophysical data east of Shetland has identified clear recessional moraine sequences from which core sites have been planned (Fig 8); similarly sub-bottom profiling west of Ireland (T5) has identified morainal bank complexes from the shelf edge to the present coast which we will constrain by coring glacimarine drapes associated with each bank complex. Regions for which there are sparse existing data will be subject to geophysical survey (e.g. Scilly-Fastnet, T4), from which decisions will be made regarding core sites onboard. The consortium includes BGS staff and investigators familiar with BGS seismic and core materials and Geological Survey of Ireland (GSI) staff as Project Partners; this expert familiarity with the existing datasets will ensure that the resource will be fully exploited and prevent any unnecessary duplication.

Geophysical data collection: We will use the hull-mounted Kongsberg Simrad, EM120, 12kHz multibeam echo sounder (RRV *James Clark Ross*, JCR) to obtain high-resolution images of the morphology of the sea floor on the offshore portions of each transect. This will allow the mapping of large-scale features (10^2 km) such as cross-shelf bathymetric troughs and the identification and mapping of smaller-scale features (10^{-1}-10^2 m) such as streamlined subglacial bedforms and moraines diagnostic of former ice-sheet retreat across the shelf. Processing of the swath bathymetric data will utilise Kongsberg-Simrad post-processing bathymetric software. The TOPAS sub-bottom profiler on JCR will be used simultaneously with the EM120 to obtain information on shallow acoustic stratigraphy. The TOPAS system has a secondary frequency of 0.5-5 kHz and can penetrate through up to about 50 m of sediment with a resolution better than 1 m. Depth of penetration depends on the sediment characteristics. TOPAS data will indicate the nature of the sediments beneath the sea floor and allow patterns in sediment thickness to be determined. The stratigraphic context and thickness from the TOPAS data will be used to select suitable sites for coring.

8.1.2 Terrestrial targeting. The last decade has seen an unprecedented focus on mapping and recording the glacial geomorphology of Britain and Ireland aided by the availability of high quality remotely sensed data e.g. the NEXTMAP GB and Ireland Digital Terrain Models. There is therefore no requirement for new mapping; the collection of new geomorphological or stratigraphical data will be limited to characterising depositional contexts at known key dating sites. Each transect leader has compiled a two-page case reporting known sites, existing quarries or sections for sampling and the specific targets for dating. An extract from the onshore part of the Irish Sea-East transect report (T3) illustrates this:

The pattern of ice withdrawal from the Cheshire-Shropshire basin is well known from landform data and the relative timing can be split into 5 zones (Fig. 9) from which we will specifically target:

Zone 1: the maximum position will be dated by excavation at the Four Ashes site (^{14}C) and OSL dating of distal sandur deposits in south Shropshire (Barnsley Lane Pit and 2x drill sites).

Zone 2: in the Shrewsbury retreat positions we will target sandur (i.e. sands) deposits at Condover and aggregate quarries in the north and south of the zone for OSL dating.

Zone 3: Whitchurch moraine belt: OSL dating at Wood Lane Pit, basal lake deposits (Ellesmere), and sample from Chelford sand extraction sites.

Zone 4: Wrexham moraine belt: OSL dating sandur deposits at Borras Quarry and other sandur sites.

Zone 5: Manchester embayment: gravel pits around Delamere – OSL dating of sandur deposits

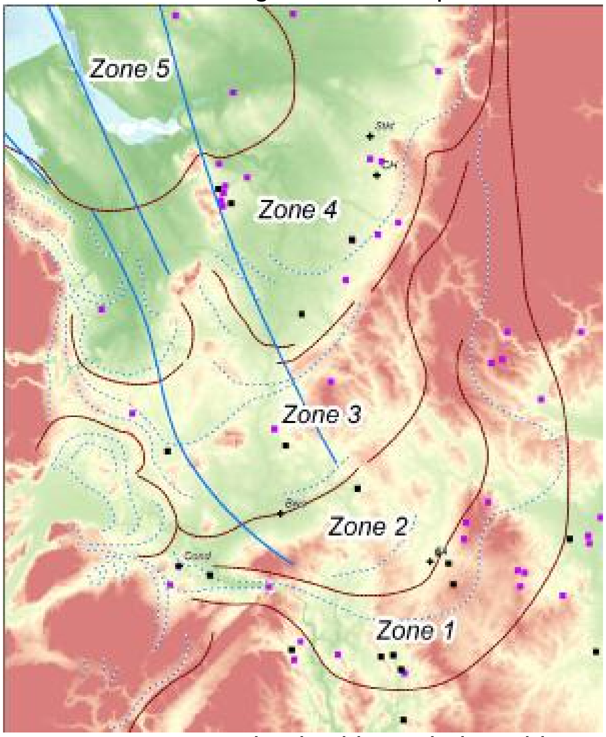

Fig 9 *Ice retreat pattern in Cheshire and Shropshire, split into 5 zones.+ existing dates, ■ quarries / pits currently active and therefore with new faces for sampling; ■ inactive pits.*

Geophysical data collection. Where sediment exposures are lacking, geophysical techniques will be used to assess the sub-surface structure and stratigraphy to guide the location of boreholes and will be used more extensively on transects lacking sediment exposure. Ground penetrating radar (GPR) and electrical tomography (ET) surveys across target core locations informed by the geomorphology (e.g. BRITICE 2) and existing borehole data (BGS), will utilise a high resolution GPR surveying system, GSSI Sir-3000 and a PulseEKKO 100 GPR, with 50, 100, 200 MHz antenna with data interrogation using GPR-SLICE ground penetrating radar imaging software. GPR data will be supported with parallel electrical resistivity (ER) survey by Tigre or Campus electrical tomography systems. The geophysical survey forms a discrete and focused (45 days) component towards the end of the terrestrial campaign and is a precursor to borehole sampling. The importance here is to collect samples from where they are required to constrain retreat and readvances rather than where just happens to be convenient with regard to existing exposures.

8.2 Extracting samples.

8.2.1 Marine cores. The primary objective in collecting marine cores is to provide geochronological data on ice sheet recession from key localities targeted by prior geophysical data. This demands 1. that the depositional context of facies are identified and 2. that the cores contain dateable material from critical depositional contexts. The cores will therefore be investigated using non-invasive logging onboard and in the laboratory, and by subsampling for a variety of techniques in order to elucidate depositional environments and sediment genesis as well as to obtain suitable material for AMS ^{14}C dating. Onboard techniques will include: logging of sedimentary structures from visual description, physical properties from multi-sensor core logging (e.g. Geotek Multi-Sensor Core Logger) including magnetic susceptibility, P-wave velocity and bulk density. X-radiography will help further refine lithofacies interpretations from examination of sedimentary structures. Laboratory techniques will include grain size analysis, measurement of Total Organic Carbon (TOC) content, micropalaeontological analysis of benthic and planktonic foraminifera. These techniques will define depositional contexts and highlight materials contained in cores suitable for dating. AMS ^{14}C dating of calcareous microfossils and bivalves from the sediment cores will be used to establish the onset of deglaciation and allow calculation of retreat rates across the shelf and will identify temporal changes in water mass properties on the shelf which may have acted as a driver of ice sheet retreat.

Sediment cores will be collected guided by the TOPAS geophysical data. We will mostly utilise a 6 m BGS vibrocorer (see attached quote from BGS, who will supply equipment and manpower) which can operate in water depths down to 2500 m and has been used successfully to recover subglacial and deglacial sediments on high-latitude continental shelves (e.g. Greenland, JCR cruise 175 led by Ó Cofaigh). Vibrocoring will therefore be used to obtain samples from sediments which record the most recent glacial retreat cycle on the shelf. The longer piston corer (from the National Marine Equipment Pool, NMEP) will be used to recover thicker sequences of soft glacimarine muds.

The manual extraction, counting and geochemical or micropalaeontological fingerprinting of individual IRD grains from continental slope sediment cores is a time-consuming, laborious, destructive and expensive process. We propose a new approach for the rapid and non-destructive fingerprinting of IRD to parent ice streams; ITRAX non-destructive XRF logging will be applied to marine shelf and terrestrial cores to characterise the geochemical composition via multiple elemental ratios of sediment sequences deposited by discrete ice streams. These data will be analysed by multi-variate statistical techniques (e.g. MDS) to fingerprint the distinct geochemical assemblages characteristic of each source ice stream catchment. The “downstream” continental slope cores have already been analysed by ITRAX; these data will be analysed statistically to compare the assemblages with the end-member source ice stream cores that we will collect. This comparison will underpin the geochronological data relating ice stream collapse to IRD flux by confirming the attribution of IRD to specific ice stream sources or ice sheet sectors. Additionally we will extend the iceberg trajectory modelling of Bigg et al. (2010), using estimated ice fluxes from the ice sheet model to seed icebergs into the ocean, modelling their track until melting and delivery of sediment load. This will assist in matching specific ice outlets to the IRD record.

8.2.2. Terrestrial sampling. The terrestrial campaign will be run as a series of land-based campaigns, led and co-ordinated centrally (by Chiverrell and PDRA) and conducted so that resources and manpower are optimised across all of the onshore parts of the transects. For example, all of the Irish sites will be conducted in a single phase. Site descriptions, sediment logging and analyses will be conducted for exposed sections, and with the field assistance from the geochonometric team, appropriate samples extracted for ^{14}C, OSL and TCN dating. Field gamma spectrometry will be undertaken to calculate environmental dose rates for OSL dating. JCB (digger) hire will enable excavation of specific sites; excavations will be limited in nature and conducted in liaison with landowners and conservation bodies e.g. Natural England, Scottish Natural Heritage and Countryside Council for Wales (see letters of support).

Subsequent to the first field campaign the 35 day borehole campaign will secure materials for dating (OSL or AMS ^{14}C) for sectors and locations lacking natural or quarry exposure. The field campaign and geophysical surveys will identify a list of borehole targets. Drilling will be accomplished using a Dando Terrier Rig operating in both percussive and rotary drill modes. A two-man drill crew to operate the rig and they will work alongside the PDRA and transect team members in the collection of borehole samples. The Dando operates with casing to prevent backfill and collapse of the sides of boreholes. Samples are collected in 1 m length PVC liners, with opaque liners available for the dark sampling required for OSL dating. The system has the capability to drill through loose and compacted sand and gravels, and to sample both loose and cohesive materials. The drilling can proceed at approximately 15 m per day, with the majority of target locations envisaged to be <6m in total depth.

Materials suitable for measurement by AMS ^{14}C from terrestrial sections and cores will consist of pre- and post-glacial organic sediments/peats (e.g. kettle hole infills), providing older-than and younger-than contexts, but sites yielding both are not likely to be common. In settings where glacigenic sediments contain reworked shell fragments multiple determinations will be undertaken on such material from individual localities to identify the age range of the population; the age of the youngest material (corrected for the marine reservoir effect assuming the shells are marine in origin) will have a context constraining the age of the subsequent glacial advance (cf. O'Cofaigh & Evans, 2007).

Optically stimulated luminescence (OSL) ages will provide a range of older-than, younger-than and coeval contexts constraining glacigenic units. An ideal situation is a glacigenic unit (i.e. till) overlying sands and gravels and which terminates downstream at a moraine with a distal sandur plain. OSL dates on the sands can be used to constrain the ice advance and maximum limit. Further OSL or ^{14}C samples from above the glacigenic unit constrain the retreat.

For TCN dating we will use both ^{10}Be and ^{36}Cl depending on the lithologies encountered, with ^{10}Be in quartz being the preferred TCN due to less complicated production rate systematics and sample preparation. TCN concentrations are very sensitive to the factors affecting cosmic-ray flux (such as changing sample geometry as a result of post depositional movement) and TCN removal at the sample surface by erosion. Minimising the risk of poor sample selection requires sound geomorphology and a good understanding of TCN systematics. Consistency in sampling will be achieved through the participation of Fabel and/or Glasgow PDRA in all TCN sampling campaigns.

8.3 Geochonometric assessment. Absolute ages will be derived using ^{14}C, OSL, TCN on our collected samples, and tephrachronology for further age constraints.

8.3.1 Quality Assurance and filtering of existing dates. We will review all the existing dates in the BRITICE database (Hughes et al. 2011) for quality and any suspect dates will be filtered out. Criteria for exclusion will likely include measurement using outdated technology or lack of reliability in relation to the weight of other data (i.e. clear outliers). We will recalibrate all ^{14}C dates using the latest protocols (CALIB 6.0, OxCal).

8.3.2 Radiocarbon and tephra. *In situ* calcareous forams and bivalve molluscs will be used to constrain the marine cores using AMS ^{14}C. Glacimarine drapes genetically associated with morainal bank complexes and/or immediately overlying glacigenic sequences will indicate the presence of dateable materials and enable the interpretation of depositional context critical for ensuring that the geochronological data can be clearly related to ice limits and/or deglaciation. Dating from marine cores will be dominated by early younger-than contexts given restrictions on coring penetration and likely insufficient reworked material (e.g. shell) within recovered till units. Where glacimarine drapes can be unequivocally associated with individual morainal banks it will be possible to use AMS ^{14}C to provide dates that constrain the timing of the ice limit constituting the morainal bank. Where possible, bivalves will be used in preference to forams as the dated material. Whilst only one or two bivalves often yield sufficient carbon for dating, up to 1000 individual forams are often necessary for a single determination. Not only is picking >1000 forams a time-consuming task, but paired dates have indicated that forams are frequently older than shells by several hundreds to even thousands of years (Heier-Nielsen et al. 1995). This is usually attributed to the integration of a significant component of reworked specimens within the samples since forams are more readily eroded and transported than bivalves. ΔR corrections will be based on the Marine 07 database (Reimer et al. 2009).

Temporal and spatial variability in ΔR nevertheless remains a problem that compromises the accuracy of age models for the marine cores based on AMS ^{14}C alone. Based on ^{14}C rangefinder age models we will target specific core sections for known tephra layers that can be correlated to the Greenland ice core records to provide isochronous horizons that will yield superior age constraints (Davies et al. *in press*). This will, in addition, provide assessment of temporal variation in ΔR in addition to the Marine 07 database that can be used to correct AMS ^{14}C determinations for the marine reservoir effect.

All radiocarbon sample preparation and measurement will be performed by the NERC Radiocarbon Facility (NRCF). Moreton (Co-I), as the NRCF-based collaborator, will oversee the sample preparation, QC at all stages up to AMS analysis, and will have a strong link with the Glasgow PDRA in synthesizing the new and legacy geochronological data. We are budgeting for 587 ^{14}C analyses of which 59 (10%) are budgeted as small samples (0.1-0.5mg C) incurring twice the sub-FEC science price for NERC.

8.3.3 Optical stimulated luminescence. The use of the optically stimulated luminescence (OSL) signal from quartz for dating Quaternary sediments within the last 100 ka is now well established. The method calculates the last exposure of quartz grains within the sediment to daylight, and thus provides an absolute age for deposition. Although originally developed for dating aeolian sediments where exposure to daylight during transport and deposition could be assumed, the last decade has seen the development and application of techniques to allow accurate OSL ages to be obtained from glacio-fluvial sediments. A key development has been to undertake replicate measurements on different sub-samples, or aliquots, of a sample. By reducing the size of these aliquots, ultimately down to individual sand sized grains, it is possible to differentiate between grains which were exposed to sufficient daylight at deposition to give a reliable age and those which were not (Duller 2008). Statistical analysis of the resulting distribution of equivalent dose values permits accurate ages to be produced, as demonstrated by recent comparisons with TCN ages (Duller 2006) and by widespread adoption of the technique throughout northern Eurasia and Canada. Samples collected in this project will be prepared and analysed in the Aberystwyth and Sheffield luminescence laboratories by dedicated PDRA's. The Co-Is will ensure that appropriate protocols for measurement and analysis are followed. The single aliquot regenerative (SAR) dose protocol will be applied to the quartz OSL signal using either small aliquots or single grains as required. Single grain measurements will be used where possible, but experience suggests that for some samples such procedures are not appropriate because the OSL signal is so weak. In such situations the most accurate ages are obtained using small aliquots consisting of between 30 and 100 grains. Where overdispersion beyond that expected from sediments is seen, statistical analysis of the dose distributions will be undertaken using the minimum age model (MAM) or finite mixture model (FMM) (Roberts and Galbraith in press). Radionuclide dose rates will be determined by geochemical analysis of samples. Analytical protocols will be agreed between the two laboratories and a laboratory intercomparison will be undertaken early in the project to ensure the comparability of results.

8.3.4. Surface exposure dating. Surface exposure dating using in-situ produced TCN is an established technique for determining glacial chronologies and has been successfully applied in the UK (for a review see Ballantyne 2010). We will use the terrestrial cosmogenic radionuclides ^{10}Be and ^{36}Cl, which are produced at known rates in minerals exposed to secondary cosmic radiation at the Earth's surface. In essence, the concentration of TCN in an erratic boulder, or a boulder exposed on a glacial moraine, should reflect the depositional/ stabilisation age of the boulder/ moraine, and hence the last time the ice stood near the boulder (simple exposure). Similarly, glacially eroded bedrock should yield a TCN concentration commensurate with the time the ice retreated from the bedrock (deglaciation) and exposed it to cosmic radiation. The assumption in both cases is that there were no TCNs in the sampled surface prior to the ice retreating from the sites. In order for this assumption to be valid, (1) covering ice had to be thick enough (>50m) to block secondary cosmic rays, (2) moraine material had to be subglacially derived, or (3) if the sampled surface has been exposed previously, more than 2 m of rock had to be removed (glacially eroded) from the sampled surface during the last ice overriding to remove any previously accumulated TCN concentration, effectively resetting the TCN clock.

Because of the problem of incomplete removal by glacial erosion of TCNs in bedrock from earlier exposure phases (Fabel et al. 2002; Lilly et al. 2010) we will target erratic boulders and moraines rather than bedrock.

Currently analytical precision of surface exposure dating is on the order of 2-4%, but global reference production rates are only known to 9% (Balco et al, 2008), which makes it impossible to statistically differentiate between an age of 16.0±1.4 ka and 14.0±1.3 ka. There are two ways of addressing this problem: (1) collect multiple samples from a single moraine and determine the weighted mean age, and (2) determine a local production rate. We address the first point by collecting at least 3 samples from each chosen locality. The second point has been recently determined by Fabel and will be published prior to commencement of the project. This new production rate has an uncertainty of <5%, allowing differentiation between 16.0±0.8 ka and 14.0±0.7 ka. Combined with multiple samples, this will provide sufficient resolution to differentiate between millennial scale glacial retreat positions, and will allow direct comparison of TCN with other geochronological techniques.

To expedite sample processing and measurement, TCN analysis will be split between University of Glasgow-SUERC (GU-SUERC) cosmogenic isotope laboratory (managed by Fabel and Miguens-Rodriguez) and the NERC-Cosmogenic Isotope Analysis Facility (NERC-CIAF). GU-SUERC and CIAF have taken part in inter-laboratory comparisons and are confident that samples are directly comparable.

8.4 Data synthesis. The original BRITICE compilation of glacial landforms will be updated to include our own discoveries and those recently reported in the literature. A new BRITICE-CHRONO inventory comprising our newly-acquired dates and filtering of existing dates will be constructed as GIS layers and an interactive database comprising metadata (e.g. location, context, uncalibrated and calibrated ages). These inventories will be published and made freely available via the BRITICE website.

For the first time in the context of reconstructing ice sheet dynamics, we will adopt a Bayesian modelling approach to existing filtered and newly-generated geochronological data. It provides a basis for identifying data that may be suspect and offers a methodology for integrating different forms of dating control (Rhodes et al., 2003) to refine probability distributions when presented as a relative order of events. It has been routinely applied to sets of closely spaced, stratigraphically related samples (e.g. ^{14}C ages for lake sediment cores), and the relationships identified used to restrict the overlapping uncertainty distribution implicit in age estimates (Bronk Ramsey 2009). This *prior* information can be used to modify the independent probability distribution of each dating sample in a series to restrict the uncertainty ranges for individual ages when several overlapping distributions occur. The extensive database of age control for the advance and retreat stages of the BIIS is complex since it will be based on different dating techniques at multiple locations. Individual ice streams are, however, responsible for observed stratigraphy and geomorphology, so it is possible to construct one or more hypothetical 'relative order' models (*sensu* Chiverrell, et al., 2009) of the expected chronological order of the dating control. The models comprise younging sequences with events arranged into a pseudo-stratigraphical order reasoned from landform-sediment relationships independently from the dating control. Any lack of conformity determined in the relative order models either reveals problems with individual age determinations or indicates that the relative order interpretation may be flawed. These discrepancies need explaining. As a pilot study we have tested Bayesian approaches implemented using OxCal (Bronk Ramsey 2009) to identify the relative order models for the advance and retreat phases of the Irish Sea Ice Stream (ISIS; T4) using existing geochronological data (Chiverrell et al., in prep.) We use ISIS as an example since it is at present the best-dated sector of the BIIS.

AMS ^{14}C, TCN and OSL dating techniques have all been applied to glacially scoured bedrock surfaces, boulders and glacigenic sedimentary sequences to constrain the timing of marginal positions associated with the former ISIS. These data have been critically analysed stratigraphically prior to analysis to identify their age contexts. The Bayesian statistical integration (Bronk Ramsey, 2009; Chiverrell et al., 2009) of all the dating control for the ISIS shows a conformable agreement between the chronological measurements and the proposed relative order of events (Overall = 131.1%: Acceptance level > 60%). This analysis indicates that the ISIS expanded from source areas in the period 30-24.6 ka BP culminating in the rapid advance of the ice front some 200 km from the south coast of Ireland 27-23.4 ka BP reaching a maximum position impinging on the Isles of Scilly at 24.1-22.8 ka BP (Fig 10). These timings are close to the timing of pulses of ISIS-sourced IRD (Scourse et al., 2009; Haapaniemi et al., 2010) delivered to the adjacent continental slope. The correspondence between the Bayesian model timing for the maximum advance to the Scillies and peak ISIS IRD flux – dated by tuning the slope records to the Greenland ice core (GISP2) isotopic record - is a strong independently-dated test of the available chronological control for the ISIS, demonstrating the feasibility of the Bayesian approach.

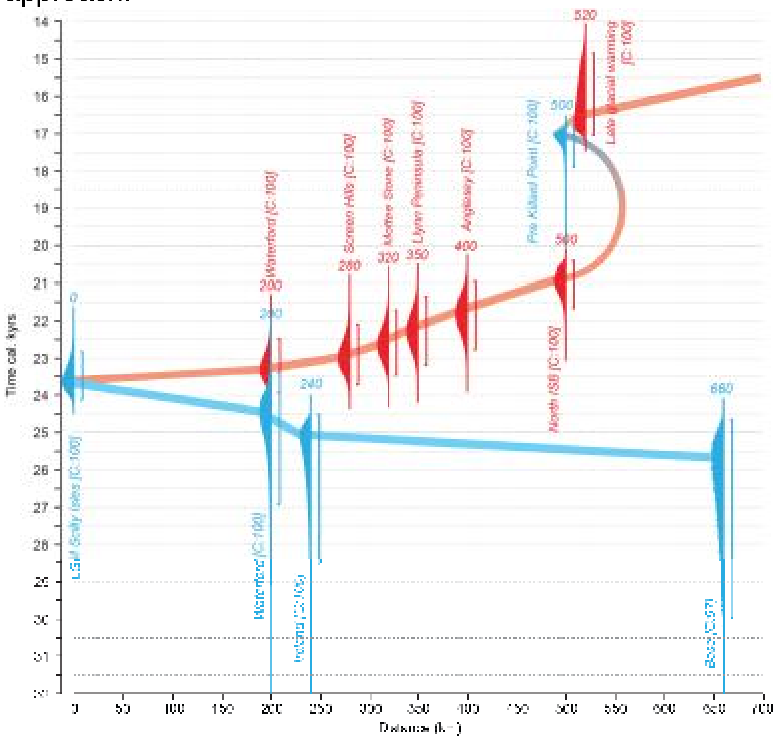

Fig 10. *Time-distance probability plot of advance (blue) and retreat (orange) of the Irish Sea Ice Stream (transect T4) demonstrating the Bayesian approach for reconstructing ice retreat. North to the right.*

We will seek to improve the geochronological database for the ISIS and to generate data of similar resolution for the other sectors of the ice sheet. Bayesian analysis within each sector, constrained sequentially by the observed geomorphology and stratigraphy, will provide empirical reconstructions of retreat. Comparison of these empirical reconstructions between sectors will then enable the primary aims to be addressed and provide the observational basis for ice sheet modelling.

8.5 Empirical reconstruction of retreat and assessment on controls. Based on the *pattern* evidence contained in BRITICE (landforms) and *timing* in our BRITICE-CHRONO database and from the Bayesian analysis above, reconstructions of ice margin retreat will be explored within the GIS to yield an optimised synthesis of ice sheet recession, both per transect and for the whole ice sheet. Maps of ice sheet margins for key timeslices (e.g. 27, 25, 23, 21, 19, 17, 15 ka BP) will be produced and rates of margin retreat calculated and compared to the varying topographic, sea level, and SST controls. These will form the basis for assessing the degree to which these controls (objectives 7,8, & 9) have on the rate of margin retreat.

8.6 Ice sheet modelling. Our approach is to model the ice-sheet-ice-shelf system at discrete time-slices forced to fit the margins derived above and using loading/isostasy and palaeo-elevation constraints to constrain the thickness. For our aims this is better than attempting to match a fully time-dependent model to the data, since with the time-slice approach we can achieve an exact match to the important margin data. We lose some definition of the transient state but this loss may be to a certain extent illusory, since it is not clear how well rates of change can be defined in the first place. Also, we can be more flexible in our approach to understanding, for example, the role of possible ice shelves and their forcing.

We will use two models (i) the British Antarctic Survey Ice Sheet Model (BASISM) simulator (Hindmarsh, 2009), which is a vertically integrated 3d ice-sheet model including horizontal stress gradients. Its vertically integrated scheme gives high performance, enabling multiple parameter sweeps; (ii) Glimmer-CISM, the community ice-sheet model (Rutt et al., 2009 and subsequent developments), which has a more sophisticated mechanical model. Using two models allows us to investigate the sensitivity of simulations to the ice-sheet model used.

As input palaeo-topographies, we will use data generated by PP Milne and co-workers. These palaeo-topographies are associated with loading histories that have been constrained by relative sea level records using a geodynamical model of earth response (Shennan et al, 2006; Bradley at al., in press). The ice-loadings will form a target for matching the ice-sheet model thickness in combination with the palaeo-elevation and palaeo-flow data. A large range of poorly-constrained possible parameters exist to tune the model palaeo-thicknesses constrained by margin isochrones and the palaeo-thickness and paleao-flow direction data. Principal among these are the surface accumulation and ablation rates, surface temperature and basal friction in ice-streams.

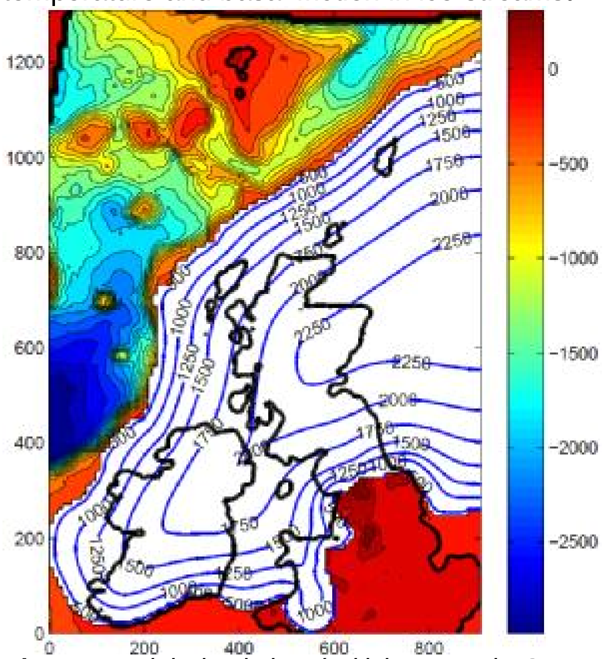

***Fig 11**. Model simulation (British Antarctic Survey Ice Sheet Model; BASISM) matched to margin positions for the reconstructed ice sheet near its maximum at 27 ka BP. Note that the SW to NE disposition of the main ice divide matches well with the empirical reconstruction (Fig 3) from landform data.. Ice thicknesses, especially over the North Sea may be unrealistic because of our treatment of the interaction with the Scandinavian ice.*

Because of our time-slice approach, we will be able to perform a large number of parameter sweeps to investigate the ranges of these parameters consistent with the data. The models will also compute the consistent flux and stress conditions at the grounding line. These provide the information to constrain ice-shelf models. We will run shelf models to equilibrium, using the input ice fluxes, to identify which parameter ranges of calving and melting result in shelves consistent with the data and the ice-sheet model outputs. For example, if the shelf grounds in its approach to equilibrium, it is inconsistent with the data.

We believe that for initial studies with complex data-sets, the time-slice approach wins over the approaches where the dynamical evolution of the ice-sheet is computed, as the computational cost is reduced by one to two orders of magnitudes, and we will have exact matching of margin position. We recognise that there are issues with in particular thermal lags, but are confident that we can develop approaches that mitigate these problems.

9. FUNDING SOUGHT FROM NERC. To support our activities we request **£3,424,545.33** from NERC, as detailed in the JeS proforma. Additionally, to fund use of the NERC vessel for the cruises, the onboard geophysical equipment and piston corer (from the National Marine Equipment Pool) we require **£233,185.88** as quoted by NERCs Ship and Marine Equipment (SME) application, attached. Total budget requested from NERC is therefore **£3,657,731.21**

10. ASSOCIATED COLLABORATIONS AND CO-FUNDING. Given the marine geological emphasis in UK and Irish waters we are pleased to have strong support from the British Geological Survey (BGS) and the Geological Survey of Ireland (GSI). BGS are integral to the project; a co-I will lead two of the transects and another will assist, and the BGS has agreed (letter of support) to match the funds charged to NERC for their investigator time (**value of £36k**) to ensure they can fully contribute to the science objectives. BGS will also contribute (letter of support) 50% of the costs associated with use of their vibrocorer, which will be installed on the NERC vessel for the two cruises, **value of £160k.** The GSI will contribute by making Xavier Monteys of the survey's INFOMAR program (www.infomar.ie) available to attend meetings, assist with core-targeting and providing access to legacy marine datasets (letter of support). This represents an 'in kind' contribution in excess of **£300 k**. For transects 6 & 7 (shelf west of Ireland see Fig 5) over 30 cores and much geophysical data have already been acquired by the INFOMAR programme and the University of Ulster (UCC). These are perfectly suited to our objectives and all that is required is to sample from the cores for dating. They have agreed to allow us access to these cores yielding a saving to the project of ~ **£350k**. Through our planning with regard to 'Impact' we have built up strong collaborations with industry especially with regard to those seeking infrastructure investments offshore (cables and windfarms). In addition to our impact plans on assisting their work, great benefit comes to the project via use of their extensive and high resolution marine surveys. We gain additional information on seabed geomorphology to enhance our reconstruction of the pattern of retreat, can use the high resolution data to accurately target key moraines for coring and use their existing archive of cores for dating. We have committed collaboration with Centrica energy (offshore windfarms; letter of support) for a large area in the eastern Irish Sea (Transect 3) and with SP Transmission who are working with Scottish Power and National Grid in developing the high voltage direct current link (i.e. seafloor cable). They will grant us access to their geophysical data and 245 vibrocorer samples from the proposed route which is relevant for transects 3,4 and 7. Such data likely exceeds **£1 million in value.** Once it became known that a similar proposal (now called NORDICE-CHRONO) was being prepared by our Norwegian colleagues (Sejrup of Bergen) for the eastern North Sea, we made sure to plan our transects in harmony. The PIs of both projects will act as steering group members (letter of support) for the sister project, ensuring cooperation throughout. Their proposal is costed at 23.1 million NOK (~**£2.5 million**) and is a further enhancement to the overall scientific endeavour. Committed direct funding to the project amounts to **£196k** and with an estimated **£1.45 million** of in-kind contributions, and the anticipation of significantly more via industry as the project progresses.

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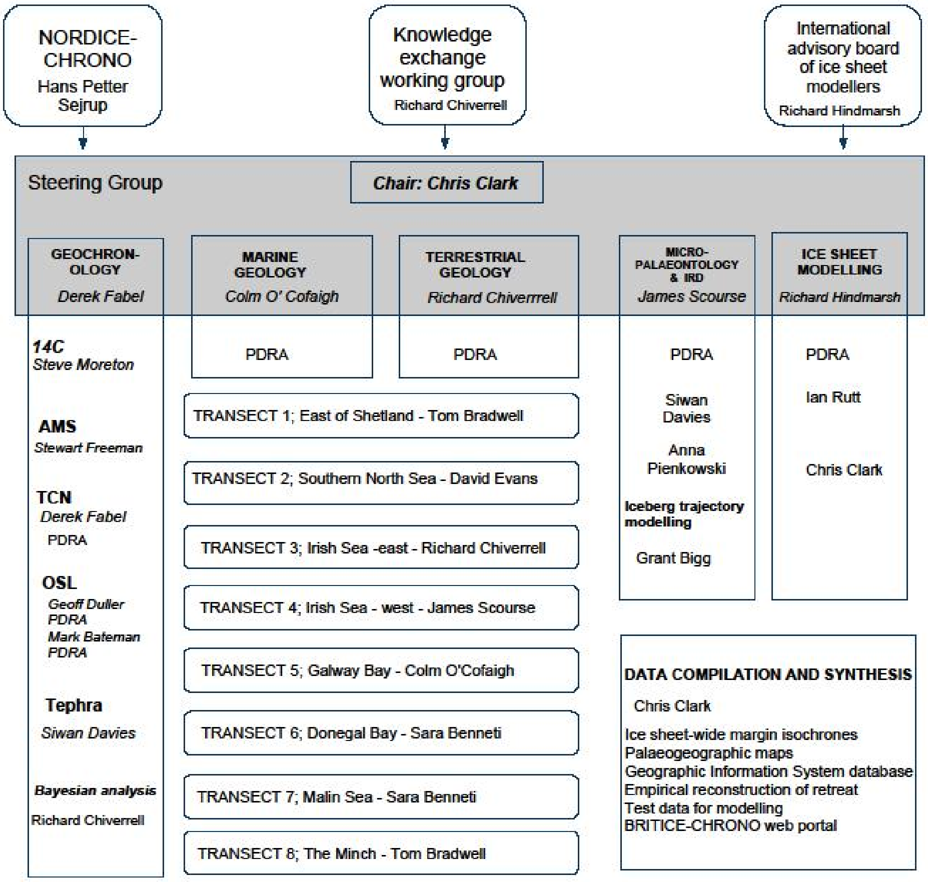
BRITICE-CHRONO: PROJECT MANAGEMENT is specifically designed to ensure effective delivery across the programme. We deliberately avoided the tempting route of each transect representing a separate entity and management/cost structure (i.e. each transect as an autonomous 'standard grant'). Whilst initially appearing as the most convenient structure, this would result in considerable duplication of effort, redundancy of expertise and would not permit funds going to the most promising aspects once samples and their stratigraphic contexts are better known subsequent to the field programme. Given our emphasis on dating and the NERC policy of sample and science cases being vetted prior to resources being committed for analyses (e.g. via the NERC Radiocarbon Facility Steering Committee), we have designed a management structure that retains this control and makes best use of resources.



Roles and responsibilities (see chart). The programme *Steering Group* (SG) has overall responsibility for the delivery of the programme to schedule and budget, led by the Chair. A part-time (50%) administrator will be employed to assist. The Steering Group will convene formally twice a year and *ad hoc* as necessary, to assess scientific progress, monitor the budget and timeline, and for forward planning. Each Steering Group member also provides leadership for a major theme of activity and it will be their responsibility to ensure smooth running and progress. Each theme-leader will submit a written report detailing progress, scientific achievements and budget to the Steering Group prior to each meeting. These tabled documents will permit oversight and integration across the programme of work. To maintain coherence over this large consortium of researches we will have an annual scientific conference reporting internal activities and scientific achievements.

In addition to managing the project, the SG will interact with our three external bodies: the sister project, NORDICE-CHRONO, the Knowledge Exchange Working Group and the International Advisory Board of Ice Sheet Modellers. To ensure close cooperation with NORDICE-CHRONO, it's PI (Sejrup) will attend our steering group meetings and Clark will attend their meetings. To facilitate *impact activities* we will invite members of the Knowledge Exchange Working Group (see letters of support) to our annual project conference, with a dedicated extra half-day at the end to specifically encourage exchanges in both directions. The *International Advisory Board of Ice Sheet Modellers*, led by Hindmarsh, will meet with the entire team early in the project lifetime to provide steers with regard to future data requirements for modelling. Near the end of the project a further meeting will be used to provide detailed exposure to our preliminary results and to decide on the best means of data delivery to the community.

At the core of the project are the individual transects each with a named *transect leader* responsible for overseeing both the marine and terrestrial aspects, drawing expertise and resources from elsewhere in the programme, making the science case for dating resources, and synthesising and writing up the science outputs per transect. To avoid duplication of effort and to maintain a systematic and directed approach aimed at delivering our science objectives, *Marine Geology (O'Cofaigh)* and *Terrestrial Geology (Chiverrell)* will be planned and executed centrally (and their investigator and PDRA time spread over all transects) and these investigators hold the funding and responsibility for these aspects. Likewise, ***Geochronology (Fabel)*** sits as a separate entity and will receive and vet cases for dating support from the transect leaders. Further along the project timeline, the ***Micropaleontology and IRD (Scourse)*** theme will provide support to each transect team with regard to SST reconstructions and they will lead the work matching ice purges from specific sectors/outlets to the offshore IRD record. ***Data compilation and synthesis (Clark)*** will bring all the results together and which will be made freely available across the project and beyond. Once sufficient data on timing has been achieved Hindmarsh will lead the ***Ice Sheet Modelling*** simulations assisted by Rutt and Clark.

	2012		2013				2014				2015				2016				2017	
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
PDRA STAFFING																				
Marine geology (Durham)			■	■	■	■	■	■	■	■	■	■	■	■						
Marine geology (Bangor)			■	■	■	■	■	■	■	■										
Terrestrial geology (Liverpool)	■	■	■	■	■	■	■	■												
OSL dating (Aberystwyth)					■	■	■	■	■	■	■	■								
OSL dating (Sheffield)					■	■	■	■	■	■	■	■								
TCN dating (Glasgow)	■	■	■	■	■	■	■	■	■	■	■	■								
Data synthesis/GIS/Ice sheet modelling (Sheffield)									■	■	■	■	■	■	■	■	■	■	■	■
MARINE TASKS																				
Optimise target locations from archived geophysical data	■	■	■			■	■													
CRUISE 1: transects 3 - 7				■																
CRUISE 2: transects 1,2 and 8								■												
Core analysis and sample delivery to labs					■	■			■	■										
Micropalaeontlogical analysis							■				■									
TERRESTRIAL TASKS																				
Planning, logistics and site permissions 1.	■																			
Fieldwork- T3 (Irish Sea-east)	■																			
Fieldwork- T4 (Irish Sea-west)		■																		
Data compilation, archiving, sample delivery to labs		■																		
geophysical data processing			■																	
Planning, logistics and site permissions 2.																				
Fieldwork- T2 (east coast England)				■																
Fieldwork-T1 (Shetland)				■																
Fieldwork- T8 (Hebrides)				■																
Data compilation, archiving, sample delivery to labs					■															
Planning, logistics and site permissions 3.				■																
Fieldwork- T4 (SE Ireland)					■															
Fieldwork- T5 (Galway)					■															
Fieldwork- T6 (Donegal)					■															
Fieldwork- T7 (N. Ireland)					■															
Fieldwork -T7 (SW Scotland)						■														
geophysical data processing						■														
Data compilation, archiving, sample delivery to labs							■													
Borehole programme							■													
Data compilation, archiving, sample delivery to labs								■												
All transect data summary and delivery to central database								■												
GEOCHRONOLOGY TASKS																				
Quality analysis & recalibration of existing dating databse	■	■																		
OSL dating - lab analysis and quality control			■	■	■	■	■	■	■	■										
TCN dating- lab analysus and quality control			■	■	■	■	■	■	■	■	■	■								
C14 dating- lab analysis and quality control			■	■	■	■	■	■	■	■	■	■								
Quality analysis and calibration of final dating databes											■	■								
DATA SYNTHESIS / GIS / MODELLING																				
Meetings of ice sheet modelling advisory board		■													■					
Update BRITICE glacial landform GIS									■	■										
Compile BRITICE-CHRONO GIS and database													■	■						
Empirical ice sheet reconstruction															■	■	■			
Ice sheet modelling experiments											■	■	■	■	■	■	■	■	■	
iceberg trajectory modelling and IRD matching																	■	■	■	■

Data management, archiving and availability The project is committed to making vital data available for the wider scientific good, especially to provide data on ice sheet retreat to all modellers internationally. All relevant data will be released in digital form via the BRITICE-CHRONO web portal and widely advertised via conferences and learned society newsletters (we have included funding for this). For the first time in the UK a full quality-assessed database of dates constraining the ice sheet (likely approaching 1600 in number) will be released via publication and the web portal. After analysis, all cores will be transferred to BOSCORF for archiving, and funds for van hire and T&S have been costed for this activity. All geophysical data will be archived in NERCs National Geoscience Data Centre (NGDC) held and managed by the BGS.