Contents

We gratefully acknowledge the support of the sponsors for making this meeting possible.

Oral Presentation Programme

Thursday 2 June 2016	
08.15	**Registration & Tea, Coffee & refreshments (Main Foyer and Lower Library)**
08.45	**Welcome**
	Glaciated Margins: Plenary session
09.00	**Peter Talling (University of Southampton)** What is the relationship between glacial cycles and large (>500 km3) submarine landslides and associated tsunami?
09.15	**Ebbe Hartz (Det Norske Oljeselskap)** Tilts and vertical motion related to ice-loading and glacial erosion: The science and its application
09.30	**Tom Rydningen (The Arctic University of Norway)** On the evolution of glaciated continental margins
09.45	**Sandra Passchier (Montclair State University)** An Antarctic stratigraphic record of step-wise ice growth through the Eocene-Oligocene greenhouse-icehouse transition
10.00	**Questions for speakers**
10.15	**Break: tea, coffee, refreshments and posters (Lower Library and Arthur Holmes room)**
	The Deep Time Archive
10.45	**Marie Busfield (Aberystwyth University)** Sedimentology of the Sturtian icehouse: characteristic glaciomarine environments
11.00	**Max Lechte (University of Melbourne)** A sub-ice setting for Neoproterozoic iron formations within the Sturtian glacial sequence? Insights from Australia and Namibia
11.15	**Ian Fairchild (Birmingham University)** Neoproterozoic glaciations in Svalbard: a Snowball and an enigma
11.30	**Jean-François Ghienne (Université de Strasbourg)** Incisions in the Late Ordovician glaciated margin of Morocco: tunnel valleys or submarine canyons?
11.45	**Andrew Rees (Saudi Aramco)** Depositional Evolution and Internal Architecture of Late Ordovician Pro-glacial Outwash Fans in the Subsurface of Northwest Saudi Arabia
12.00	**Saeed Al Tofaif (Royal Holloway University of London)** Sedimentological and Stratigraphic Architecture of an Hirnantian Palaeovalley, NW Saudi Arabia
12.15	**Questions for speakers**
12.30	**Lunch and Posters (Lower Library and Arthur Holmes room)**

	The Antarctic and the Southern Hemisphere I (Margin architecture/long-term records)
13.15	**Keynote: Professor Carlota Escutia (Universidad de Granada)** Sedimentary records of past warmth at the Wilkes Land margin: Results from IODP Expedition 318
13.45	**Robert Larter (British Antarctic Survey)** Geometry and seismic characteristics of Antarctic glacial margin sequences: implications for depositional processes and continental margin development
14.00	**Karsten Gohl (Alfred Wegener Institute)** Documenting past retreats of the West Antarctic Ice Sheet – Drilling targets in the Amundsen Sea Embayment
14.15	**Jennifer Horrocks (Durham University)** First high-resolution record of Late Quaternary environmental changes in the Amundsen Sea, West Antarctica, revealed by multi-proxy analysis of drift sediments
14.30	**John Smeilie** Glaciated margins – what the glaciovolcanic record can teach us
14.45	**Questions for speakers**
15.00	**Break: tea, coffee, refreshments and posters (Lower Library and Arthur Holmes room)**
	Resource Potential: Case studies and Dilemmas I
15.30	**Keynote: Professor Jonathan Craig (Eni S.p.A. Upstream & Technical Services, Milan)** Glacially-influenced Hydrocarbon Systems - Ancient and Modern
16.00	**Phil Hirst (Royal Holloway University of London)** Depositional Model for the Ordovician Glaciated Margin of Jordan
	The Antarctic and the Southern Hemisphere II (Grounding-line processes/products)
16.15	**John Anderson (Rice University)** Variable styles and rates of grounding line retreat revealed by high-resolution multibeam data from Ross Sea, Antarctica
16.30	**Lauren Simkins (Rice University)** Signatures of meltwater influence on ice-sheet retreat from Antarctic continental shelves
16.45	**Lindsay Prothro (Rice University)** Contribution of localized processes to large-scale ice-margin instability
17.00	**Questions for speakers**
17.15	**The William Smith Lecture** **Keynote: Professor Julian Dowdeswell (University of Cambridge)** The marine-geophysical signature of past ice sheets
18.15 - 20.00	**Wine reception (sponsored by MSG)** **Hot fork buffet dinner & posters (Lower Library and Arthur Holmes room)**

Friday 3 June 2016	
08.15	**Registration & Tea, Coffee & refreshments (Main Foyer and Lower Library)**
08.45	**Welcome**
	Arctic and the Northern Hemisphere I (The BIIS & glaciation of the North Sea)
09.00	**Keynote: Professor Chris Clark (University of Sheffield)** Constraining the timing of retreat of the last British-Irish Ice Sheet with a focus on the marine-to-terrestrial transition
09.30	**Louise Callard (Durham University)** Offshore extent and timing of ice sheet retreat in the Malin Sea sector of the last British-Irish Ice Sheet
09.45	**Phil Rose (Apache North Sea Ltd)** Abundant evidence for Early to Mid Pleistocene regional grounded ice sheets in the middle of the UK central North Sea.
10.00	**Rachel Harding (University of Manchester)** All change at the base Quaternary: Reconstructing the geomorphology of Marine Isotope Stages 103-92 from basin-wide 3D seismic data in the southern North Sea
10.15	**Emrys Phillips (British Geological Survey)** Large-scale glacitectonism as a result of active retreat of the Fennoscandian Ice Sheet across Dogger Bank during the Last Glacial Maximum
10.30	**Questions for speakers**
10.45	**Break: tea, coffee, refreshments and posters (Lower Library and Arthur Holmes room)**
	Arctic and the Northern Hemisphere II (Glaciated margin architecture & processes)
11.15	**Matthew Owen (University College London)** Sediment failures within the Peach Slide (Barra Fan, NE Atlantic Ocean) and relation to the British-Irish Ice Sheet
11.30	**Dayton Dove (British Geological Survey)** Unravelling the North Sea Lobe; Extensive bathymetry and marine seismic data offer new perspectives
11.45	**Serena Tarlati (University of Ulster)** British-Irish Ice Sheet dynamics during the last glaciation and deglaciation and its influence on sedimentary processes in deep-water along the North Atlantic Passive Margin, North-West Ireland.
12.00	**Rachel Lamb (University of Manchester)** Grounded glaciation in the central North Sea during the Calabrian (1.78 to 0.78 Ma)
12.15	**Lara Peréz (Geological Survey of Denmark and Greenland)** Large-scale evolution of the central-east Greenland glaciated margin from late Miocene to Present
12.30	**Questions for speakers**
12.45	**Lunch and Posters (Lower Library and Arthur Holmes room)**

	Resource Potential: Case studies and Dilemmas II
13.45	**Emmanuelle Arnaud (University of Guelph)** Subsurface heterogeneity in ice marginal deposits and its hydrogeological implications
14.00	**Monica Winsborrow (The Arctic University of Norway)** Subglacial gas hydrate regulation of ice stream flow
14.15	**Karin Andreasson (The Arctic University of Norway)** Interactions between grounded ice sheets, deeper hydrocarbon reservoirs and methane emissions
14.15	**Graham Goffey (Soliton Petroleum Consulting)** Lille John oil field, Denmark: a glacially-driven trap and charge model
15.00	**Alan Heward** Oil in Permo-Carboniferous ice-marginal deposits in Oman: why oil accumulations occur and what makes them challenging.
15.15	**Rebecca Smith (Badley Ashton and Associates Limited)** New insights into the Al Khlata to Lower Gharif succession of North Oman
15.30	**Questions for speakers**
15.45	**Break: tea, coffee, refreshments and posters (Lower Library and Arthur Holmes room)**
	Arctic and the Northern Hemisphere III (Ice dynamics and retreat signatures)
16.00	**Patrick Lajeunesse (Université Laval, Québec)** Late-Wisconsinan grounding zone wedge systems off the Québec North-Shore (eastern Canada)
16.15	**Sarah Greenwood (Stockholm University)** Dynamics of and controls on post-Younger Dryas retreat of a Bothnian Sea ice stream
16.30	**Heather Stewart (British Geological Survey)** Ice sheet dynamics of the western North Sea Basin: Shallow seafloor glacial landforms preserved offshore eastern Scotland and north-eastern England.
16.45	**Katharina Streuff (Durham University)** The Holocene geomorphological and sedimentary record of Jakobshavn Isbræ, West Greenland
17.00	**Katrien Van Landeghem (Bangor University)** Evolution in palaeo-ice stream behaviour during rapid retreat
17.15	**Questions for Speakers**
17.30	**Concluding remarks and close of conference**

Posters

The Deep Time Archive

Dilshad Ali (Royal Holloway University of London)
The Port Askaig Formation of the Garvellachs islands, Scotland: a Neoproterozoic glacial succession with many diamictites and complex geometries
(Lower Library)

P. Dietrich (Université de Strasbourg)
Deglacial sequences and glacio-isostatic rebounds: Quaternary vs. Ordovician glaciations
(Arthur Holmes Room)

Edward Fleming (CASP, Cambridge)
Comparison of the glacigenic strata of northeastern Svalbard and Northeast Greenland and implications for dynamic glaciation in the Cryogenian Period
(Arthur Holmes Room)

Dan Le Heron (Royal Holloway University of London)
The Kingston Peak Formation, California: A 720 Ma rifted glaciated margin and the challenge of distinguishing glacial from non-glacial deposits.
(Arthur Holmes Room)

Steven Robinson (UCL)
Did 'Snowball Earth' experience tropical levels of chemical weathering?
(Arthur Holmes Room)

P. Stone (British Geological Survey, Edinburgh)
An Early Permian sedimentary record of deglaciation from the Falkland Islands
(Arthur Holmes Room)

Antarctica and the Southern Hemisphere

Chris Brown (Keele University)
The significance of glacial plough marks in the North Falkland Basin
(Lower Library)

Claus-Dieter Hillenbrand (British Antarctic Survey)
Subglacial and glacimarine bedforms on the continental shelf of the SE Weddell Sea, Antarctica: New findings from hydroacoustic data acquired during RV "Polarstern" expedition PS96 (2015/2016)
(Arthur Holmes Room)

Javier Hernández -Molina (Royal Holloway University of London)
Sedimentary stacking pattern and evolution of the Antarctic Peninsula, Pacific Margin offshore of Adelaide Island
(Lower Library)

Dominic Hodgson (British Antarctic Survey)
Grounding zone wedges, reverse bed slopes and the stability of the Coats Land ice margin
(Arthur Holmes Room)

Kelly Hogan (British Antarctic Survey)
Meltwater features on the western Antarctic continental margin: observations and modelling
(Arthur Holmes Room)

Benedict Reinardy (University of Bergen)
Repeated advance and retreat of the East Antarctic Ice Sheet on the continental shelf during the early Pliocene warm period
(Arthur Holmes Room)

Zoe Roseby (University of Southampton)
Deglacial history of the Anvers Palaeo-Ice Stream Trough, western Antarctic Peninsula
(Lower Library)

Heather Stewart (British Geological Survey)
Continental slope records indicate a grounded ice sheet margin during past glacials, South Shetland Trench, Antarctica.
(Lower Library)

Resource Potential: Case Studies and Dilemmas

Diana Sahy (Brtiish Geological Survey)
Timing of methane release on the Norwegian margin after the Last Glacial Maximum
(Arthur Holmes Room)

Heather Stewart (British Geological Survey)
Understanding Late Cenozoic glaciation and basin processes: implications for offshore CO2 storage (North Sea). International Ocean Discovery Program (IODP) proposal #852-CPP.
(Lower Library)

Arctic and the Northern Hemisphere

Joshua Allin (School of Ocean Sciences, University of Southampton)
Were the Trænadjupet and Nyk Slides multi-staged?
(Lower Library)

Christine Batchelor (**Scott Polar Research Institute, University of Cambridge)**
Lateral shear-moraines and marginal-moraines at the margins of palaeo-ice streams
(Arthur Holmes Room)

Mark Bateman (University of Sheffield)
What controls the eastern sector of the British and Irish Icesheet?
(Arthur Holmes Room)

Antonio Benvenuti (University of Geneva, Switzerland)
Provenance investigations on the pre-glacial and the Elsterian tunnel valley deposits from the Dutch North Sea – new evidences on the glaciogenic origin of the TV infill
(Arthur Holmes Room)

Stephen Davison (CGG Services (Robertson) Ltd)
The retreat pattern of the Late Devensian ice sheet on the UK continental margin west of Shetland.
(Arthur Holmes Room)

Laura Eddey (University of Sheffield)
Late Glacial lake levels in the Vale of Pickering, Yorkshire UK – implications for the dynamics of the Last British-Irish Sheet in eastern England.
(Arthur Holmes Room)

Elena Grimoldi (Durham University)
Seismic stratigraphy and sedimentary signature of Pleistocene glaciations in the western North Sea
(Arthur Holmes Room)

Lorna Linch (University of Brighton)
The style and intensity of deformation by the ploughing/scouring action of iceberg keels in diamicton offshore of East Greenland
(Lower Library)

Sasha Montelli (Scott Polar Research Institute, University of Cambridge)
Palaeo-glaciology of the mid-Norwegian continental shelf through the Quaternary from 3D seismic data
(Arthur Holmes Room)

Alessandro Mozzato (National Oceanography Centre, Southampton)
Modelling the effect of large submarine landslides on the ocean circulation
(Arthur Holmes Room)

Andrew Newton (University of Manchester)
A Plio-Pleistocene record of glaciation offshore mid-Norway
(Lower Library)

Catriona Purcell (School of Ocean Sciences, Bangor University)
Establishing the indicative meaning of ice-rafted detritus: ice sheet advance, collapse, or both?
(Arthur Holmes Room)

Benedict Reinardy (University of Bergen)
Late Pliocene-Pleistocene development of the central northern North Sea
(Arthur Holmes Room)

Sam Roberson (British Geological Survey)
A Late-Glacial sedimentary sequence between Derryoge and Kilkeel, Co. Down, Northern Ireland: origins and wider significance
(Lower Library)

Kevin Schiele (Ulster University)
Onshore-offshore correlations on the western margin of the last British-Irish Ice Sheet
(Arthur Holmes Room)

Bartek Stępień (University of Lodz, Poland)
Glaciotectonic deformations of Quaternary sediments in the margin zone of Lodz moraine upland
(Arthur Holmes Room)

Bartek Stępień (University of Lodz, Poland)
Glaciotectonic deformations of the Late Saalian ice sheet foreland in the North of Łódź (central Poland)
(Arthur Holmes Room)

David Vaughan-Hirsch and Emrys Phillips (Fugro Survey Limited)
Mid-Pleistocene thin-skinned glaciotectonic thrusting of the Aberdeen Ground Formation, Central Graben region, central North Sea
(Lower Library)

Kasper Weilbach
Late Quaternary retreat of the British-Irish Ice Sheet on the continental shelf offshore of NW Ireland.
(Arthur Holmes Room)

Oral Presentation Abstracts

What is the relationship between glacial cycles and large (>500 km^3) submarine landslides and associated tsunami?

Peter J. Talling[1], Camilla Watts[1], Alessandro Mozzato[1], Joshua Allin[1], Ed Pope[1], James Hunt[1], David Tappin[2], Matthieu J.B. Cartigny[1], Julian A. Dowdeswell[3], Haflidi Haflidason[4,5], David Long[2], and Jennifer Stanford[6].

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[4]Universitetet i Bergen, 5020 Bergen, Norway.
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Submarine landslides on glaciated margins can be far larger than terrestrial landslides and may produce very damaging tsunami. For example, the Storegga Slide that occurred 8,150 years ago remobilised over 3,000 km^3 of material from the Norwegian Margin, generating a major tsunami that locally ran-up to heights of 20 m above sea level. It is thus important to understand the frequency of submarine landslides, especially large volume events that are more tsunamigenic. Previous work on the Storegga Slide concluded that another ice-stream advance to the shelf edge is needed to deposit sediment rapidly and cause another large landslide. Their recurrence interval was therefore thought to be > 100ka. This is a primary reason why such landslide-tsunamis do not currently feature on the UK National Risk Register. Here we show that multiple large (400 to > 3,000 km^3) volume landslides can occur from the same source area without another glacial cycle or ice-steam advance, although it appears that not all of these large-volume submarine landslides produced major tsunamis. We first show that an even larger submarine landslide occurred at 55-60 ka B.P. from the same source area as the Storegga Slide. These two very large events thus occurred during the same longer-term (110 ka) glacial cycle. We then study the Trænadjupet (~4.5 ka B.P.) and Nyk (19-21 ka B.P.) Slides located further along the Norwegian margin. We show that much of the Trænadjupet deposit is actually part of the underlying Nyk Slide, meaning that both had very large volumes (400-720 km^3), and implying that multiple large volume events can occur within < ~15ka. However, coastal lakes along the adjacent Norwegian coast provide no evidence of a major tsunami associated with the Trænadjupet Slide, even though they do contain a well-developed Storegga tsunami deposit. It appears that the Trænadjupet Slide was slow moving or multi-stage, disintegrated to a much lesser extent, and did not generate a widespread tsunami. While multiple large volume slides can occur from a single source area without another ice-stream advance, these landslides may not always produce a major tsunami.

NOTES

Tilts and vertical motion related to ice-loading and glacial erosion: The science and its application.

Ebbe H. Hartz [1,2]; Sergei Medvedev[2]; Jon Erik Skeie[1]; Daniel W. Schmid[3] and Karthik Iyer[3]

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3. GeoModelling Solutions GmbH, Hardturmstrasse 120, 8005 Zurich, Switzerland

During the Quaternary, the northern hemisphere was intensely sculptured by thick icecaps, and ice-streams. In some areas, like central East Greenland, or NE Canada, huge fjords and inlets are carved more than 3 km below the summit surface. This erosion cause major unloading, and thus uplift which we model by numerically placing back eroded material, and calculating the flexural isostatic response (vertical motion) repeatedly backwards in time until eroded features are filled to the summit surface.

The exercise is carried out with a Northern perspective of the Earth with coverage reaching as far south as Southern Norway (ca. 60^{o}N). We ensure that only eroded depressions are re-filled excluding oceanic crust (except Iceland and the Faroe Islands), and continental deep water basins that are clearly tectonic in nature such as the outer Northeast Greenland shelf, the outer Norwegian Sea and Baffin Bay. Prior to the modelled isostatic response, major icecaps are numerically removed and their load is compensated.

Model results show that Late Cenozoic (mostly glacial) erosion has caused dramatic vertical motions and tilts. Regions such as greater Ellesmere-NW Greenland and central East Greenland have experienced regional erosional uplift in excess of 1 km, which is of the scale of the vertical displacement (down) induced by the load of the Greenland icecap. Interestingly, this erosional uplift solves long-standing enigmas of the occurrence of marine sediments above 1 km altitude in tectonically quiet areas like East Greenland, and add systematics between regional AFT ages and elevation. In some areas, like Svalbard and Iceland, modelled erosional uplift and associated down flexing are highly influenced by the assumed effective elastic thickness, and the results thus give direct input to our understanding of the Earth's interior. Central Siberia and Alaska return even more extreme flexural isostatic response when cavities are filled, but the glacial influence in these regions are more ambiguous.

In addition to the scientific interest, erosional unloading in combination with Late Cenozoic sedimentary loading has direct implications for hydrocarbon exploration. A prominent effect is the sub-ice compaction evident in e.g., the Barents Sea and North Sea. Furthermore, we can show that tilts associated with Quaternary glaciations dramatically influenced the migration routes, filling and spilling and of major oilfields. For example the tilt models may explain the paleo-oil columns of the giant Sverdrup and Troll fields (North Sea) and Snøhvit –Goliat petroleumsystem in the Hammerfest basin (SW Barents Sea).

NOTES

On the evolution of glaciated continental margins

TOM ARNE RYDNINGEN[1], JAN SVERRE LABERG[1],MATTHIAS FORWICK[1], POLINA A. SAFRONOVA[2]

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Glaciated continental margins at both northern and southern high-latitudes have evolved through repeated glaciations where shelf-wide and grounded ice sheets have provided the main sediment input. The evolutions of such margins are, therefore, different from their low-latitude counterparts, where eustatic sea-level variations possess a fundamental control and where fluvial systems provide the main sediment input.

One of the best studied glaciated margins, the Norwegian – Barents Sea margin, show great morphological variations including sectors of small and higher gradient fan-shaped protrusions and submarine canyons located between sectors of wider and lower-gradient prograding wedges and trough mouth fans. We will elaborate on the following factors and their roles in continental-margin evolution: 1) Pre-glacial continental margin morphology controlling accommodation space and influencing sediment routing on long timescales; 2) Ice sheet glaciology including the location of fast-flowing ice streams where source-area morphology exerts a fundamental control; 3) Composition of the glacigenic sediments where the clay content in previous studies have been found to be important, and 4) Sea-level controlled both by eustacy and isostacy.

From three case studies (western Barents Sea, north and mid-Norwegian margin) the influence of these factors on the resulting large-scale morphology, sedimentary processes (continental slope to basin floor) and continental margin architecture will be discussed.

NOTES

An Antarctic stratigraphic record of step-wise ice growth through the Eocene-Oligocene greenhouse-icehouse transition

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Earth's current icehouse phase began ~34 million years ago with the onset of major Antarctic glaciation at the Eocene-Oligocene Transition (EOT). Deep-sea drilling and modeling provide evidence of step-wise cooling and ice growth at southern high latitudes. Near-field records of continental temperatures and ice-sheet advance onto the Antarctic margin, however, have been poorly studied in detail, because of a paucity of reliable recorders of past temperature changes and ice-sheet extent. The detrital sediment record extracted from three Ocean Drilling Project drill holes from Prydz Bay on the East Antarctic continental margin is presented within a new depositional and chronological framework spanning ~36-33 Ma and integrated with the existing geophysical interpretations of the continental margin. New core descriptions within a consistent classification scheme and particle size distributions highlight the onset of diamict deposition prior to the main isotope shift that marks the onset of global cooling. The chemical index of alteration (CIA) and the S-index, calculated from the major element geochemistry of bulk samples, yield estimates of chemical weathering intensities and mean annual temperature (MAT) on the East Antarctic continent. We document late Eocene warm events (35.8-34.8 Ma) that affected ephemeral ice sheets. An appropriate modern analogue for the late Eocene pre-EOT depositional system in Prydz Bay could be Malaspina glacier in Alaska, a temperate piedmont glacier that extends from a nearby mountain range into the partially vegetated coastal plain. The chaotic internal and upper reflections within the seismic unit are consistent with deposition as a prograding subaerial ice marginal complex. The glacial landforms for this type of glacier include glaciotectonized ice-marginal complexes, with stratified facies, including rhythmites, from seasonal meltwater discharge. From 34.4 Ma ice sheets advanced into Prydz Bay, coincident with a decline in chemical weathering and temperature. The decline is accompanied by the onset of deposition of sandy diamictite on the outer shelf of Prydz Bay and marks a shift in seismic stratigraphic signature from aggrading to steeply prograding clinoforms. Stratigraphic units represent glaciomarine sedimentation and ice-influenced mass-gravity flows associated with the arrival of an ice sheet grounding line within the Lambert Graben. We conclude that Antarctic continental ice growth commenced with the EOT-1 "precursor" glaciation and preceded Subantarctic surface ocean cooling. These results call for dynamic high-latitude feedbacks that are currently poorly represented in Earth system models.

NOTES

Sedimentology of the Sturtian icehouse: characteristic glaciomarine environments

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The sedimentary record of the Cryogenian icehouse is dominated by thick, heterogeneous glaciomarine sequences. These successions share many key facies characteristics across globally distributed Cryogenian glaciated margins, but also with the sedimentary record of younger Phanerozoic glaciations. Detailed examination of the Sturtian (older Cryogenian, *c.* 720 Ma) glaciomarine record in Namibia, Australia and the western US reveals a diverse suite of ice-contact to ice-distal deposits, with evidence of both primary and secondary glacial influence, and dominated by both mass flow processes and a strong meltwater influence throughout. In all of these disparate sedimentary basins there is substantial evidence for numerous cycles of ice advance and recession, leading to deposition of strongly progradational or retrogradational sequences, respectively. In places, ice advance results in warm-based deformation of the underlying sediment pile, suggestive of polythermal to temperate glacier thermal regimes. The extent of ice advance can also vary within individual sedimentary basins, raising the question as to whether underlying topographic constraints play a role in forcing a more pronounced advance compared to the unconstrained shelf. Cumulatively, these characteristics support the presence of dynamic, grounded marine-terminating ice masses which exhibit significant periods of ice meltback, and thus militate against the classic 'hard' snowball Earth hypothesis. It remains to be explored whether these dynamic ice masses could be defined as topographically constrained ice caps, or larger ice sheets feeding topographically constrained outlet glaciers.

NOTES

A sub-ice setting for Neoproterozoic iron formations within the Sturtian glacial sequence? Insights from Australia and Namibia

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The Sturtian glaciation (~717 - 660 Ma) is considered to be among the most severe glaciations in Earth history, potentially encompassing the entire planet and lasting for over 50 million years. Glacial deposits from the Sturtian can be found globally, and are often associated with iron formations: enigmatic chemical precipitates of predominantly iron minerals and silica, a geological phenomenon for which there is no clear modern analogue.

The Chuos Formation records sedimentation during the 'Snowball Earth'-type Sturtian glaciation in Namibia and contains iron formation horizons. The Holowilena Ironstone is a Neoproterozoic iron formation in South Australia that is also associated with Sturtian glacial deposits, and as such is considered to be broadly correlative with the Chuos Formation of Namibia. Similar deposits are found globally in Sturtian glacial sequences as the first occurrence of iron formation following a one billion year absence, and after this time iron formation essentially ceases deposition altogether. The influence of glaciation on the genesis of these Neoproterozoic iron formations remains contentious.

There are a number of key similarities between the Australian and Namibian Neoproterozoic iron formations in terms of the lithofacies present and geochemistry. The ferruginous horizons are characterised by iron-rich sediments (up to 55% total Fe) as diamictites, siltstones and bedded chert, primarily containing iron oxides and silica with minor clastic detritus. The geochemistry indicates deposition from anoxic seawater. These facies are laterally discontinuous and appear to be occupying palaeotopographic lows due to subglacial incision. The diamictites are characterised by a strong glacial influence with evidence of glaciotectonism. By contrast, despite repeated intercalation with glacial deposits the laminated ferruginous facies have a distinct lack of dropstones and other glacial indicators. The apparent palaeoenvironmental dichotomy of an intimate and conformable association of dropstone-free, laminated sediments with massive subglacial diamictites could potentially be explained by deposition under a thick ice sheet.

By comparing the Sturtian glacial deposits on two continents, a model for Neoproterozoic iron formations is proposed, in which iron minerals are precipitated due to the mixing of oxygenated brines and glacial meltwater with ferruginous seawater under ice cover. Periodic glaciotectonism and mass flow resedimentation intercalates massive diamictites with debris-poor laminated ferruginous muds. Dense oxic brines expelled during sea ice formation pool in depressions, providing a stable environment for preservation of iron minerals. This combination of glacial palaeoenvironment and ocean chemistry may help to explain the return of iron formations in the Neoproterozoic.

NOTES

Neoproterozoic glaciations in Svalbard: a Snowball and an enigma

Ian J. Fairchild[1], Huiming Bao[2], Doug Benn[3], Edward J. Fleming[4], Michael J. Hambrey[5], Carl T.E. Stevenson[1] and Peter M Wynn[6]

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Two episodes of panglaciation, the Sturtian (717-659 Ma) and Marinoan (650/645-635 Ma), are recognized in the Cryogenian Period (720 to 635 Ma) of the Neoproterozoic. Marinoan units tend to be thin and to be dominated by continental facies including aeolianites, fluvial and lacustrine deposits. Sturtian sedimentary units often reflect rift-related settings and display marine-dominated successions recording distinct glacial advances and retreats and evidence for open water. The distinctive cap carbonates for each unit likewise reflect contrasting base levels. Another interesting distinction is that non-mass-dependent ^{17}O depletion in carbonate-associated sulphate (CAS) or barite, consistent with high atmospheric CO_2 as predicted by Snowball theory, has been identified from Marinoan caps in several locations, but not in Sturtian caps.

In the classic sections of NE Spitsbergen (Svalbard), two distinct glacigenic units are assigned to Sturtian and Marinoan glaciations based on $\delta^{13}C$ of cap carbonate sequences, Sr isotopes, and allocyclic sedimentary rhythms in strata between the glaciations. Deposition of the Marinoan Wilsonbreen Formation (ca 160 m thick) during a Snowball Earth event has been confidently interpreted on the basis of a) a distinct basal periglaciated hiatus, b) extreme negative ^{17}O-depletions in fluvial and lacustrine limestones and c) a record of glacial advances and retreats associated with high PCO_2 consistent with Earth system models of a late-stage Snowball Earth subject to precessional forcing (Benn et al., *Nature Geoscience,* 2015). The facies assemblage displays a range of phenomena comparable with the modern Antarctic McMurdo Dry Valleys, critically including evidence for widespread bare ground and hyperaridity alternating with deposition of ice-rafted and subglacial sediment, along with evidence for glaciotectonism (Fairchild et al. and Fleming et al., *Sedimentology,* 2016).

The sedimentary record of Sturtian glaciation in NE Spitsbergen is thin (15-20 m, member E2 of the Elbobreen Formation) probably reflecting a rift-shoulder position. Deposits are predominantly subaqueous and marine: dolomitic diamictites, rhythmites, and redeposited matrix-rich conglomerates. A distinct carbonate cap with Sturtian characteristics is present, and is interlaminated with ice-rafted sediment at the base, which globally is highly unusual. Concretionary dolomite is common below and within the glacial member, the latter displaying high $\delta^{18}O$ values (typically 0 to +5 ‰ $_{VPDB}$) linked to low temperatures of formation. In one section, a distinctive breccia occurs near the base associated with evidence of evaporation (silicified anhydrite nodules) and dolomite with $\delta^{18}O$ up to +10 $‰_{VPDB}$; ^{17}O work is ongoing. Could this be a Snowball-type hiatus, or does it simply reflect the tectonic setting and glacioeustatic sea level fall?

NOTES

Incisions in the Late Ordovician glaciated margin of Morocco: tunnel valleys or submarine canyons?

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The Upper Ordovician (458-443 Ma) shelf stratigraphy in the Moroccan eastern Anti-Atlas is far more complex than the layer-cake sequence as classically proposed, with four phases of deep incision into an ice-marginal platform. Incision widths and depths range from 0.5 to 20 km, and from > 50 to 500 m, respectively; infill thicknesses are of same order. The incisions widen and deepen downslope. Megaconglomerates, with a sandy matrix dominated by intraclasts, are very common in almost all thalwegs.

The two older generations of incision (cut during the late Sandbian/early Katian to middle Katian) are characterised by modest incision depths (50-150 m). The infill consists of thin-bedded turbiditic deposits grading upward into bioturbated sandstones. The third and fourth generations are penecontemporaneous with the end-Ordovician glaciation (latest Katian to Hirnantian) and have the largest amplitudes, and an example of a subvertical walled incision. The deposits include glaciomarine plume deposits with striated dropstones, high-density turbidite sands, channel conglomerates and subglacial soft-sediment shear zones. Downslope, in the deeper parts of the incision, km-scale lateral facies changes are identified from thick, massive megaconglomerates up to thin-bedded, bioturbated turbiditic sands. Deltaic sequences or tide-influenced sandwaves paradoxically prevail in their more proximal reaches. Interestingly, the initial infill does not reveal any glacial influence, and is instead characterised by depositional facies similar to those of the first two generations of incision. The infill of the fourth generation comprises early Silurian graptolitic shales and sandstones representing a 5-7 Myr time span. Last but not least, the younger incision(s) commonly cut into the infill of the older one(s).

Hirnantian incisions may be misinterpreted as tunnel valleys because they include glaciogenics. Accounting for scale and geometry, their stratigraphic superimpositions and sedimentary infill suggest that Upper Ordovician incisions correspond to shelf canyons and associated upstream networks of shelf rivers. They were cut during the glacioeustatic sea-level falls that recurrently characterize the Late Ordovician. Only during the end-Ordovician, when ice-sheet fronts approached (but did not reach?) the shelf edge, inherited and underfilled canyons operated as accumulation zones for glaciogenic deposits. Canyons are therefore the missing link between the inner glaciated platform (Algeria, southern Morocco) and distal, thick (>400 m), turbiditic depocenters of northern Morocco. However, it currently remains uncertain whether processes of canyon downcutting or rather changes in sediment supply along the ice margin (e.g. the location of point sources) were responsible for the sandiest and highest-energy turbidites in the proglacial turbidite depocentres.

NOTES

Depositional Evolution and Internal Architecture of Late Ordovician Pro-glacial Outwash Fans in the Subsurface of Northwest Saudi Arabia

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The complexity of Hirnantian-age, glacial systems and the reservoirs subsequently developed, have received considerable attention in recent years, particularly the large petroliferous provinces in southeast Algeria and southwest Libya. Coeval, Late Ordovician, syn-glacial deposits of the Sarah Formation in northwest Saudi Arabia, also yield extensive hydrocarbon accumulations. The Sarah Formation is characterized by intense heterogeneity, rapid facies variations and complex erosional events. The location of the maximum grounding line provides a first-order control on the style of erosion and sedimentation, with areas inboard of this line prone to development of palaeovalleys, scoured by pressurized subglacial meltwater. There is no evidence that significant palaeovalleys occur outboard of the maximum grounding line, instead these locations are characterized by unconfined, glaciomarine fans and elongate ribbon channels, sourced by the erosion of tunnel valleys in ice proximal areas. The mapped basinal extent of palaeovalleys also coincides with a change in deformation style from sheared sub-glacial tectonite (locally referred to as the Zarqa Megafacies) to pro-glacial, gravity-driven slumps and dewatering structures. An important chronostratigraphic conclusion from dense palynological sampling of the proximal palaeovalley fill sediments, and the more basinal, outwash-fan deposits, is that the latter, pro-glacial system is older; suggesting glacial maximum sedimentation beyond the grounding line (as a clastic apron), was followed by later, transgressive-fill of tunnel valleys during glacial retreat.

This contribution establishes a preliminary framework, for the interpretation and reservoir characterization of pro-glacial outwash fans in the subsurface, based on an extensive dataset of conventional cores, image logs, sidewall cores and wireline logs from approximately 150 wells, which is augmented by 3D seismic amplitude time-slice maps, chemostratigraphy and palynology. High-resolution reservoir layering highlights a complex depositional system, characterized by an initial phase of deeply-entrenched, pro-glacial turbidite ribbon channels, and younger sheet-like depositional lobes. Cores and image logs from both elements of the outwash fan system, record extensive climbing dune cross-bedding; an unusual sedimentary structure described from many Upper Ordovician glacial successions in North Africa, and considered indicative of quasi-steady, sediment-charged flows, initiated by glacial outburst floods. Palaeoflow patterns determined from oriented image logs indicate that these climbing dunes prograded orthogonal to the long axis of stable, non-migratory ribbon channels. Eddy-related sidebars in Libyan outcrop examples may provide similar analogues. Detailed interpretation within these channels, using high-resolution, 3D seismic data, enables the identification of sidebar growth areas, and the prediction of porosity sweetspots, based on the location of coarser-grained thalweg facies. These lithotypes acted as permeability pathways for early fluid flow, resulting in deposition of clay pellicles (these contributed to a reduction in silica binding sites on the grain) and calcite cement (often dissolved during latter diagenetic phases, creating high, secondary porosity). The finer-grained, sidebar facies did not benefit from these early diagenetic phases, and subsequent quartz cementation resulted in complete reservoir destruction.

NOTES

Sedimentological and Stratigraphic Architecture of an Hirnantian Palaeovalley, NW Saudi Arabia

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Late Ordovician (Hirnantian) glacial deposits are of great importance in North Africa and the Middle East owing to their significance as reservoirs for hydrocarbons and groundwater. In NW Saudi Arabia, the sedimentary record of this glaciation (the Sarah Formation) is generally preserved in meridionally-oriented palaeovalleys that were cut beneath northward flowing ice sheets. In the Tabuk area, NW Saudi Arabia, an apparently intersecting complex of E-W and N-S oriented palaeovalleys occurs at Al Wizam area. Field relationships demonstrate two generations of palaeovalley incision, suggesting that the N-S oriented palaeovalley was cut subglacially, filled, subsequently deformed, and crosscut by the E-W palaeovalley. Abundant facetted and striated quartzite clasts occur at the base of each palaeovalley which testify to a subglacial origin. Detailed examination of the N-S oriented paleovalley shows it to be well-defined with symmetrical sides. Its fill is composed of 14 lithofacies grouped into 7 facies associations. Of this, some 70% of the fill comprises three sandstone facies which are: (i) thinly bedded well-sorted sandstone, (ii) moderate- to poorly-sorted sandstone with unique sedimentary structure resembling overlapping tongue-like projections, and (iii) massive to deformed sandstone. Throughout the stratigraphy, cm-scale extensional faults that developed in soft sediment are commonly found, along with some sheath folds and a glacially striated surface found mid-way through the succession. In summary, these features provides evidence for direct ice-contact, syn-glacial fill, and consequent reworking, cannibalization, and deformation by the fluctuating glacial (re)advances.

NOTES

Sedimentary records of past warmth at the Wilkes Land margin: Results from IODP Expedition 318

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Integrated Ocean Drilling Program (IODP) Expedition 318 recovered sedimentary archives from seven sites along a continental shelf-to-rise transect aiming to obtain the Cenozoic record of ice sheet history and related paleoclimate, paleoceanographic, and sea level changes. Nearly 2000 m of sediment was recovered expaning from the early Eocene to the Holocene. Here we present work conducted to date, mainly focused on understanding environmental conditions and ice dynamics during past warm intervals with CO_2 concentrations in the atmosphere within the range of those forecasted by the IPCC 2013 report. The sedimentary records provide valuable insights into changing environmental conditions in this sector of the East Antarctic margin such as: 1) early Eocene subtropical environments; 2) cooling during the middle Eocene; 3) the isostatic and sea level effects of the growth of a continental size ice sheet and the establishment of sea ice–dominated ecosystems in the early Oligocene; 4) a dynamic East Antarctic Ice Sheet and prolonged warm periods with open water conditions during the Oligocene; 5) the cooling leading to the Mi-1 event; and 6) ice retreat into the Wilkes Basin during the warm Pliocene. When compared with data from other Antarctic margins, such as Prydz Bay (ODP Leg 188) and the Ross Sea (ANDRILL, CRP), variations between different ice sheet margin sectors can be assessed. In addition, integration of records obtained from the Wilkes Land with continental and global records provide a better understanding of East Antarctica's role in the past, present, and future global system.

NOTES

Geometry and seismic characteristics of Antarctic glacial margin sequences: implications for depositional processes and continental margin development

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Most seismic reflection profiles across Antarctic continental margins show a similar progression in the geometry of late Cenozoic outer shelf and slope sequences. A transition is observed from older sequences with gently curved palaeo-shelf edges and mostly aggrading stacking patterns to prograding sequences with sharp palaeo-shelf breaks and oblique foreset reflections that are truncated beneath extensive planar unconformities. We refer to sequences with the latter characteristics as “Antarctic glacial margin sequences” and to the transition as the “base of glacial margin sequences” (BGMS). The BGMS has been interpreted widely as representing a significant change in the palaeoenvironmental regime prevailing during glacial maxima, although the exact nature of the change is still debated. Results from sites drilled on the Antarctic Peninsula shelf during Ocean Drilling Program Leg 178 constrain the time of the transition there to be younger than 8 Ma during the late Miocene. Although core recovery from the Leg 178 shelf sites was poor, the results indicate that the earlier late Miocene sequences were also deposited in a glacially-influenced environment. Furthermore, the recovered cores do not reveal a major lithological change across the BGMS. By long-distance seismic correlation, the age of the BGMS on the Amundsen and Bellingshausen Sea margins has been interpreted to be similar to that on the Antarctic Peninsula, although as yet there are no drill sites in those areas to confirm this interpretation. Whereas details of the range of palaeoenvironments that occurred and processes that operated during deposition of the earlier sequences remain uncertain, a detailed conceptual process model has been developed for the glacial margin sequences. We describe this process model and consider its implications for continental margin development and slope stability. We also review evidence from around Antarctica for the nature of the transition represented by the BGMS.

NOTES

Documenting past retreats of the West Antarctic Ice Sheet – Drilling targets in the Amundsen Sea Embayment

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The West Antarctic Ice-Sheet (WAIS) is likely to have been subject to very dynamic changes during its history as most of its base is grounded below modern sea-level, making it particularly sensitive to climate changes. Its collapse would result in global sea-level rise of 3-5 m. The reconstruction and quantification of possible partial or full collapses of the WAIS in the past can provide important constraints for ice-sheet models, used for projecting its future behaviour and resulting sea-level rise. Large uncertainties exist regarding the chronology, extent, rates as well as spatial and temporal variability of past advances and retreats of the WAIS across the continental shelves. By using the seafloor drilling device MeBo during an RV Polarstern cruise scheduled for early 2017, a series of sediment cores will be drilled on the Amundsen Sea Embayment (ASE) shelf, where seismic data show glacially-derived sequences covered by only a thin veneer of postglacial deposits in some areas. From analyses of seismic data, we infer that interglacial sediments can be sampled which may have been deposited under seasonally open water conditions and thus contain datable microfossil-bearing material. A shallow basin near the Pine Island Glacier front will be one of the prime targets for the drilling. The near-horizontal seismic reflection horizons may represent a sequence of continuously deposited, mainly terrigenous material, including ice-rafted debris, meltwater deposits and hemipelagic sediments deposited rapidly during the last deglaciation and Holocene or a series of unconformities caused by erosion resulting from grounding line oscillations through numerous glacial cycles. Subglacial bedforms imaged in multibeam bathymetric data indicate fast glacial flow over some shelf areas of the ASE, where seismic profiles show acoustic basement near the seafloor. It is unknown, whether fast ice-flow in these areas was facilitated by water-lubricated sliding over bedrock or presence of a thin layer of deformable till (perhaps less than a metre in thickness). The nature of this layer holds important clues for understanding the processes that operated beneath the margin of the ice-sheet, beneath ice-flows and on ridges between ice-streams during the Last Glacial Maximum. Grounding zone wedges (GZWs) are widely thought to be important in stabilising grounding line positions during ice-sheet retreat, but hypotheses about the processes and duration of their formation and their composition, are mainly based on conceptual models. Drill sites on and near GZWs are aimed to establish the nature of their sediments, their formation processes, their rates of growth and the palaeo-environmental conditions in their surroundings.

NOTES

First high-resolution record of Late Quaternary environmental changes in the Amundsen Sea, West Antarctica, revealed by multi-proxy analysis of drift sediments

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The Amundsen Sea sector of the West Antarctic Ice Sheet (WAIS) is experiencing rapid mass loss, and there is a pressing need to place the contemporary ice-sheet changes into a longer term context. The continental rise in this region is characterised by large sediment mounds that are shaped by westward flowing bottom currents and that resemble contouritic drifts existing offshore from the Antarctic Peninsula. Similar to the Antarctic Peninsula drifts, marine sediment cores from the poorly studied sediment mounds in the Amundsen Sea have the potential to provide reliable records of dynamical ice-sheet behaviour in West Antarctica and palaeoceanographic changes in the Southern Ocean during the Late Quaternary that can be reconstructed from their terrestrial, biogenic and authigenic components.

Here we use multi-proxy data from three sediment cores (PC494, PS58/253-1, PS58/255-2) recovered from two of the Amundsen Sea mounds to present the first high-resolution study of environmental changes on this part of the West Antarctic continental margin over the glacial-interglacial cycles of the Late Quaternary. Age constraints for the records are derived from biostratigraphy, AMS 14C dates and lithostratigraphy. We focus on the investigation of processes for drift formation, thereby using grain size and sortable silt data to reconstruct changes in bottom current speed and to identify episodes of current winnowing.

Data on geochemical and mineralogical sediment composition and physical properties are used to infer both changes in terrigenous sediment supply in response to the advance and retreat of the WAIS across the Amundsen Sea shelf and changes in biological productivity that are mainly controlled by the duration of annual sea-ice coverage.

We report sedimentary records extending from Marine Isotope Stage (MIS) 1 to MIS 10. All cores exhibit significant glacial-interglacial variations in clay mineral composition, with a typical doubling of smectite percentages and halving of kaolinite percentages during interglacials when compared to glacial periods. The detailed grain-size records of the cores suggest that condensed sedimentation caused by increased bottom current speed occurred during interglacial periods below ≤3720 m water depth on both drifts studied.

NOTES

Glaciated margins – what the *glaciovolcanic* record can teach us

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Glaciated margins are traditionally regarded as regions of landscape degradation. That view ignores margins where volcanoes have erupted coeval with glacierization, resulting in overall landscape construction in tandem with glacial modification. The volcanoes provide an opportunity to study glacial evolution over time in an unprecedented way. Since each effusive eruption replates the surface of the volcano, they provide fresh surfaces for the coeval ice to reform on and interact with. If each eruption can be dated, it raises the possibility of tracking the temporal evolution of terrestrial ice in far greater detail than was hitherto possible.

In Antarctica, numerous large long-lived polygenetic volcanoes were erupted along 800 km of the western Ross Sea margin between c. 20 Ma and present. The record is punctuated, i.e. it contains many gaps, because of the low frequency of volcanic eruptions generally. But it also contains more information on critical parameters of the palaeo-East Antarctic Ice Sheet than can be derived by any other means, including: establishing whether ice was present; the age of that ice; ice thickness; surface elevation; and basal thermal regime. Some of these properties are uniquely obtained from glaciovolcanic sequences and, of key importance, most are quantitative. Because thermal regime is a simple approximation for ice stability, its determination is particularly significant. With each eruption, the physical state of any ice present is preserved 'instantaneously', resulting in a series of remarkably accurate temporal snapshots of the conditions present at the time. Moreover, with the precise estimates for ice thickness thus obtained, glaciovolcanic studies should potentially enable much more realistic calculations of past ice volumes which previously could only be guessed by modelling.

However, there is an Achilles heel: the results are still bedevilled by imprecisions in isotopic dating, with errors on $^{40}Ar/^{39}Ar$ ages currently ± 40-60 ky (2-sigma). Advances in dating methodology and instrumentation are reducing errors to < 10 ky for suitable rocks of Neogene age, and greater precision has been demonstrated for potassic Quaternary rocks (± 1-2 ky). When such precisions become routine, they will enable ice sheet parameterization from glaciovolcanic studies to be placed within individual glacial cycles for the first time. Despite these limitations, glaciovolcanic studies have successfully deduced the characteristics of several parts of the Antarctic ice sheet, including a promising resolution to a long-standing controversy over the timing and nature of the transition from a dynamic to a stable East Antarctic Ice Sheet.

NOTES

Glacially-influenced Hydrocarbon Systems – Ancient and Modern

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The growing number of hydrocarbon discoveries made in ancient glaciogenic reservoirs in North Africa, the Middle East, South America and Australia in recent years has fuelled an increasing interest in the role that glaciation plays in the generation, expulsion, migration, trapping and ultimate destruction of hydrocarbons at both a play and prospect level. Many of these hydrocarbon discoveries have been in glacigenic reservoirs deposited during the major Palaeozoic glaciations (Ordovician and Permo-Carboniferous), but discoveries have also been made in 'glacially-influenced hydrocarbon systems' ranging from Precambrian (Neoproterozoic) to Pleistocene in age (Figure 1).

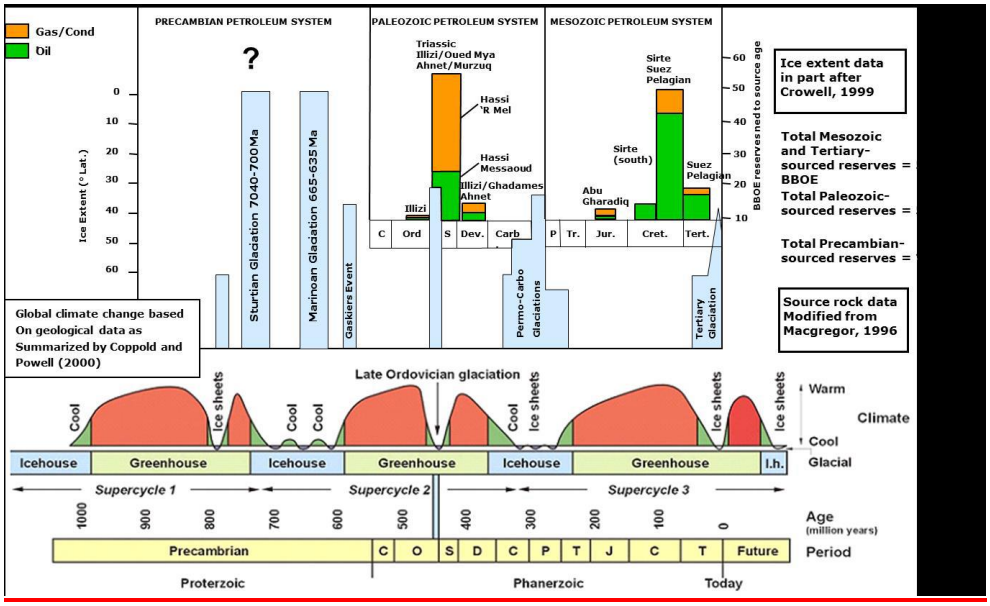

Figure 1. Global Climate, Glaciations and Source Rocks in North Africa

The term 'glacially-influenced hydrocarbon systems' can be applied to any hydrocarbon system where at least one element of the hydrocarbon system is linked to, or modified by, glaciation. Under this definition, we recognize glaciogenic reservoirs, deglacial source rocks, glaciogenic seals and glaciogenic deformation – the latter including both contemporaneous or near-contemporaneous glaciotectonics and the effects of, potentially much younger, glacial loading/unloading cycles on pre-existing hydrocarbon accumulations.

A common glaciogenic hydrocarbon play, developed during a single glacial/deglacial cycle, consists of glacial advance (lowstand) followed by the deposition of a thick clastic reservoir systems during the subsequent glacial retreat. Often, the porosity and permeability characteristics of these reservoirs are enhanced by reworking during the subsequent transgressive phase, before they are sealed by mudrock deposition during the later stages of the deglaciation and during the subsequent marine high stand (Figure 2). Where conditions

are favourable for both the deposition and preservation of organic matter, these mudrocks can be excellent hydrocarbon source rocks. Where the deposits of more than

one glacial cycle are preserved, glaciogenic reservoirs, seals and source rocks are sometimes vertically interbedded, but the rapid spatial
variation in depositional environments characteristic of most glacigenic systems can also lead to rapid lateral variations and complex spatial relationships between reservoir, source and seal with individual glacial cycles.

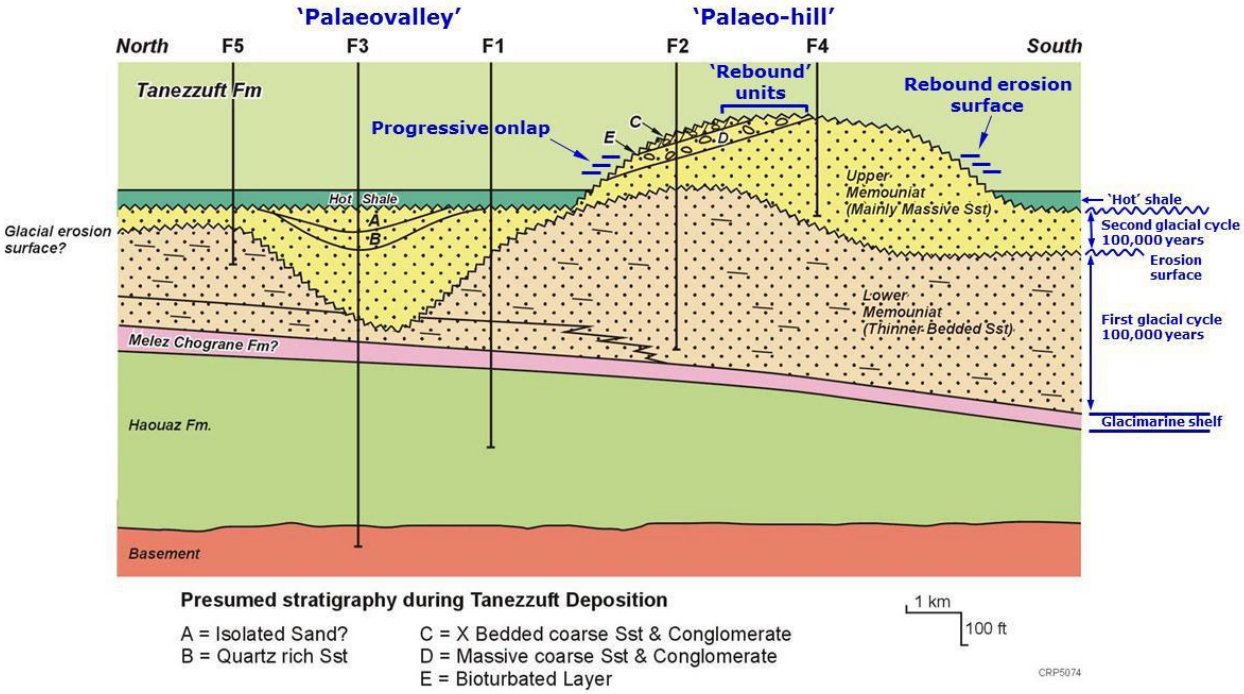

Figure 2. The classic 'glacially-influenced hydrocarbon system' – the late Ordovician glacigenic reservoir and early Silurian source/seal system in the El Feel Field, Murzuq Basin, Libya.

The Late Cenozoic glaciogenic deposits that occur widely across the formerly glaciated lowlands and shelf areas of northern Europe, Greenland, Russia and North America form excellent analogues for most ancient glaciogenic systems. Although there are a few small shallow gas fields in Pleistocene glacial deposits in the North Sea and Canada, most potentially gas-charged Late Cenozoic glaciogenic deposits represent significant shallow hazards that must be avoided during exploration for, and exploitation of, underlying hydrocarbon accumulations because of the risk they pose to safe drilling operations.
Late Cenozoic glaciogenic deposits do, however, provide critical insights into the likely distribution and characteristics of the key source, reservoir, seal and trapping elements in ancient glacially-influenced hydrocarbon systems. Perhaps more importantly, they provide information about the extent and duration of cycles of glaciation /deglaciation that affected the onshore and the shallow water continental margins in northern and southern polar latitudes during the Pleistocene, including major petroleum provinces in the Barents Sea, the Russian Arctic, the northern North Sea, the northern North Atlantic, Alaska and the Canadian margins. Changes in pressure, volume and temperature caused by repeated loading/

unloading by continental ice sheets and by subsequent post-glacial uplift can have a significant impact on deeper hydrocarbon systems, including hydrocarbon phase in the reservoir, top seal integrity, regional tilting, reorganization of hydrocarbon migration pathways and associated redistribution of hydrocarbons at both regional and local scales.

NOTES

Depositional Model for the Ordovician Glaciated Margin of Jordan

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Latest Ordovician glacial sediments crop out in southern Jordan and adjacent areas of Saudi Arabia where they comprise mainly coarse clastics; these sediments were deposited within steep-sided tunnel valleys with palaeo-transport approximately from south to north. In northern Jordan, the distal equivalents of some of these valley confined clastics are encountered in the subsurface where they form the reservoir units within the Risha gas field. Here the succession comprises stacked sandstone units ranging from a few metres to >20m thick which alternate with thinner mudstone events. Some of the sandstone intervals exhibit coarsening-upward profiles and they can be correlated over 10's kilometers between the wells. Their lateral extents are much greater than the tunnel valleys and they are interpreted as stacked proglacial outwash sheets which were deposited subaqueously to the north of the ice sheet.

NOTES

Variable styles and rates of grounding line retreat revealed by high-resolution multibeam data from Ross Sea, Antarctica

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During the Last Glacial Maximum, an expanded marine ice sheet covered most of the Ross Sea continental shelf. Our LGM paleodrainage reconstruction reveals that ice flowing from both East Antarctica (EAIS) and West Antarctica (WAIS) nourished the expanded ice sheet more or less equally, with the WAIS occupying the eastern Ross Sea and the EAIS the western Ross Sea. In eastern Ross Sea, large-scale grounding zone wedges (GZWs) back-step across the shelf and are separated by pristine mega-scale glacial lineations (MSGLs). These geomorphic features record episodes of ice sheet decoupling and retreat that were interrupted by episodes of grounding line stability. The history of the EAIS has remained more allusive.

A 2015 cruise on the Nathanial B. Palmer focused on the western Ross Sea and was aimed at studying the retreat history of the EAIS using an upgraded (Kongsberg EM122) high-resolution multibeam system. These new data reveal that the western Ross Sea is dominated by intermediate- and small-scale retreat features that were below the resolution of prior generation multibeam systems. An initial phase of grounding line retreat followed ice-shelf collapse on the outer shelf that resulted in fields of deep (-560 m), linear iceberg furrows on the seafloor. Alternating GZWs and closely spaced moraines record subsequent retreat when the grounding line remained in contact with the bed for approximately 200 kilometers. Variations in the size and sinuosity of these grounding line features reflect differences in grounding line stability. Meltwater channels incise GZW's, indicating that subglacial hydrology played a role in grounding line stability.

During the late stages of retreat, the ice sheet migrated up the flanks of banks, which supported individual ice rises, and toward the west and north, recording complex paleodrainage controlled by ice emanating from the Transantarctic Mountains. Widespread ice shelf breakup occurred during the final phase of deglaciation in the late Holocene. Ongoing work focuses on detailed sediment facies analysis and on establishing the timing of grounding line retreat.

NOTES

Signatures of meltwater influence on ice-sheet retreat from Antarctic continental shelves

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Basal meltwater has a significant influence on ice-flow dynamics. An improved understanding of subglacial meltwater is needed to assess the role of meltwater on ice-sheet instability. Formerly glaciated continental shelves around Antarctica contain a geologic record of the presence and influence of meltwater below the Antarctic Ice Sheet. Here we investigate circum-Antarctic geomorphic and sedimentologic evidence of meltwater and its influence on ice dynamics. Extensive subglacial meltwater channel complexes and storage basins incised into crystalline bedrock are known to occur on the inner continental shelf in Pine Island Bay and Marguerite Bay. These drainage systems likely result from erosion over multiple glacial cycles, indicating the pervasive presence of basal meltwater; however, the timing of meltwater occupation remains uncertain.

Resulting from a recent cruise in the austral summer of 2014-2015, we present high-resolution multibeam swath bathymetric images of subglacial meltwater channels incised into the post-LGM seascape of the Ross Sea continental shelf. These channels formed contemporaneously with recessional moraines and grounding zone wedges, indicating that they were active during late- stage deglaciation. There is also clear evidence that meltwater flowing within these channels contributed to localized erosion of back-stepping grounding lines. Sorted fine silts within Pine Island Bay and Ross Sea are interpreted as meltwater deposits produced by meltwater outbursts at the grounding line and span the LGM to present. Both geomorphic and sedimentologic signatures of meltwater indicate long-lived basal meltwater drainage under the Antarctic Ice Sheet, and, in Ross Sea, the association of meltwater outbursts with rapid grounding-line retreat.

NOTES

Contribution of localized processes to large-scale ice-margin instability

Prothro, L. O., Demet, B. P., Simkins, L. M., Halberstadt, A. R., Anderson, J. B., Majewski, W., Greenwood, S. L.

Ice-sheet stability is thought to largely be controlled by processes acting at the grounding line. Modern grounding lines are not easily accessible and, in the Ross Sea, the grounding line is located beneath the thick and expansive Ross Ice Shelf. Consequently, grounding-line processes that contribute to ice instabilities are poorly understood. Because multiple ice streams sourced from the East Antarctic and West Antarctic ice sheets formerly flowed over variable geology to converge in the Ross Sea, the continental shelf is an ideal setting to examine a variety of grounding-line processes.

Using high-resolution multibeam and Chirp sub-bottom profiler data acquired aboard the *RVIB Nathaniel B. Palmer* during the 2015 austral summer, a suite of sediment cores were targeted at the topsets, foresets, and toes of grounding zone wedges (GZWs) for the purpose of investigating processes that were active at the grounding line. Facies analysis based on sedimentological properties (e.g., grain size) and microfossil assemblages reveals evidence for till deformation, sediment gravity flows, and subglacially-derived meltwater deposits.

Ice-proximal facies reflect a spectrum of conditions, with two endmembers—passive basal melt-out and meltwater-intensive. The basal melt endmember is dominated by grain size distributions similar to subglacial till, often with concentrated soft sediment clasts. The meltwater endmember is dominated by a relatively well-sorted ~10 micron size mode, and is typically observed in the vicinity of subglacial meltwater channels or GZWs modified by meltwater processes. Intermediate conditions reflect a mixture of sediment gravity flows with the aforementioned processes. Additionally, in the southern portion of the western Ross Sea, where multibeam bathymetry reveals a series of volcanic seamounts and dikes, the prevalence of ash deposits coinciding with meltwater silts and open marine facies indicates grounding-line instability associated with volcanic activity. The abundance of closely-spaced recessional features in the western Ross Sea indicates the ice sheet was continually in contact with the bed during retreat, but the eastern Ross Sea is characterized by few, widely-spaced features, indicating a lift-off style of retreat. Sediment facies analysis of associated cores supports this geographic divide in retreat behavior. These combined results indicate that localized processes are quite influential on grounding-line stability.

NOTES

The William Smith Lecture:

The marine-geophysical signature of past ice sheets

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The deglaciation of high-latitude continental shelves since the Last Glacial Maximum has revealed suites of subglacial and ice-contact landforms that have remained well-preserved beneath tens to hundreds of metres of water. Once ice has retreated, sedimentation is generally low on polar shelves during interglacials and the submarine landforms have not, therefore, been buried by subsequent sedimentation. By contrast, the beds of modern ice sheets are hidden by several thousand metres of ice, which is much more difficult than water to penetrate using geophysical methods. These submarine glacial landforms provide insights into past ice-sheet form and flow, and about the processes that have taken place beneath former ice sheets. Examples will be given of streamlined subglacial landforms that indicate the distribution and dimensions of former ice streams on high-latitde continental margins. Distinctive landform assemblages characterise ice stream and inter-ice stream areas. Landforms, including subglacially formed channel systems in inner- and mid-shelf areas, and the lack of them on sedimentary outer shelves, allow inferences to be made about subglacial hydrology. The distribution of grounding-zone wedges and other transverse moraine ridges also provides evidence on the nature of ice-sheet retreat – whether by rapid collapse, episodic retreat or by the slow retreat of grounded ice. Such information can be used to test the predictive capability of ice-sheet numerical models. These marine geophysical and geological observations of submarine glacial landforms enhance our understanding of the form and flow of past ice masses at scales ranging from ice sheets (1000s of km in flow-line and margin length), through ice streams (100s of km long), to surge-type glaciers (10s of km long).

NOTES

Constraining the timing of retreat of the last British-Irish Ice Sheet with a focus on the marine-to-terrestrial transition.

Clark, Chris D.*, Chiverrell, R., Hindmarsh, R.C.A., Fabel, D., O'Cofaigh, C., Scourse, J., Bradwell, T., Evans, D.J.A., Benneti, S., Freeman, S., Moreton, S. and Ballantyne, C., Bateman, M.D., Bigg, G.R., Burke, M., Callard, L., Davies, S., Dove, D., Duller, G., Ely, J., Gafeira, J., Gales, J., Glasser, N., Greenwood, S., Gregoire, L., Hambrey, M., Hjelstuen, B., Hughes, A., Jamieson, S. Livingstone, S., Morgan, S., Medialdea, A., McCarroll, D., McCarron, S., Monteys, X., Pienkowski, A., Praeg, D., Purcell, C., Roberts, D., Rutt, I., Saher, M., Sejrup, H.P., Small, D., Smedley,R., van Landeghem, K.

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We have known for a long time that a kilometres-thick ice sheet largely covered Britain and Ireland during the last glacial, peaking at around 27,000 years ago. Most evidence for the geometry of this ice sheet arises from tens of thousands of geological and geomorphological observations, but almost wholly restricted to land. The earliest researchers (e.g. Geike 1867) were happy to use simple glaciological logic (presumed ice sheet symmetry) to reconstruct ice margins that reached far offshore and to the continental shelf edge. Such views were rejected by more conservative and evidence-based approaches that followed, leading to reconstructions of a mostly terrestrially-restricted ice sheet. Numerical ice sheet models of the time did what they were told regarding ice limits. Over the last decade the focus of investigation has moved offshore, enabled by new high resolution bathymetric and shallow seismic data, and leading to a 'gold-rush' of scientific discoveries that have transformed our understanding of the ice sheet. The continental shelf is found to contain abundant evidence of grounded ice cover, some of which has been dated to the last glacial.

Satellite measurements of Antarctic and Greenland ice sheets highlight that reductions in mass are occurring contributing to sea level rise. Glaciologists attempting to predict this ongoing deglaciation are hampered by deficiencies in process-knowledge and mathematical formulations in their numerical ice sheet models. Alarm is raised by some theory and evidence that tell us that rather than just steady and predictable retreat, that occasionally, marine-based ice sheets may undergo dynamical collapse of large sectors; is this likely to happen in Antarctica?

Combining the need of glaciologists to have a better understanding of the mechanisms of ice sheet retreat with the improved availability of offshore geophysical data, the BRITICE-CHRONO consortium of researchers is part-way through a five year project to constrain the timing of retreat of the British-Irish Ice Sheet by a systematic dating programme. The focus is on the marine-to-terrestrial transition covering the Irish and British continental shelves including the North Sea. From two research cruises some 18,000 km of geophysical data and 377 vibro- and piston cores are currently being investigated. The aims and objectives of the project and progress thus far will be reported along with some highlights from the various transects under investigation.

NOTES

Offshore extent and timing of ice sheet retreat in the Malin Sea sector of the last British-Irish Ice Sheet

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During the last glacial period ice streams drained much of western Scotland and northwest Ireland onto the continental shelf of the Malin Sea. This hypothesis is mainly based on terrestrial evidence and the presence of the Donegal-Barra fan on the continental margin, the largest glaciomarine sedimentary depocentre fed by the British-Irish Ice Sheet. The seafloor geomorphology of Irish waters is now well known due to extensive multibeam mapping as part of the Irish National Seabed Survey programme. The multibeam data reveal a number of glacial landforms on the shelf including terminal and recessional moraines. In UK waters analysis of BGS geophysical data has allowed production of a detailed seismo-stratigraphy and associated glacial history of the Inner and Outer Hebrides and Malin Sea area. However, there has been limited geophysical or sedimentological data on the offshore record of ice extent. Furthermore chronological control constraining the timing of ice advance and the pattern and timing of retreat in this region of the shelf is sparse.

This contribution presents new marine seismic, sedimentological and chronological data collected as part of the BRITICE-CHRONO project. A series of sediment cores up to 6 m in length were collected on cruise JC106 of the RRS James Cook in 2014 in the Malin Sea. Core analysis included lithofacies description, shear strength, magnetic susceptibility, bulk density and p-wave velocity. 39 AMS radiocarbon dates from both shell fragments and foraminifera assemblages provide a robust chronology. Subglacial tills in cores from the shelf and glacigenic debris flows in cores from the adjoining slope indicate that ice extended to the shelf edge. The radiocarbon chronology shows that retreat from the shelf edge was underway by 24.4 ka cal BP, and that the pace of retreat was rapid, with the majority of the continental shelf ice free by 22.6 ka cal BP. Cosmogenic nuclide dates, collected as part of the onshore component of the BRITICE-CHRONO project, from sites in the Inner Hebrides, Barra and northern Ireland indicate that sites along the coast were deglaciated as early as 21.5-20.8 ka cal BP. These onshore dates are supported by a deglacial date of 20.1 ka cal BP from a marine sediment core in the Sea of The Hebrides. Collectively these results indicate that the majority of the Malin Sea shelf was clear of grounded ice by ~21.5-20 ka cal BP. These are the first ages that constrain the retreat of the BIIS in this marine sector.

NOTES

Abundant evidence for Early to Mid Pleistocene regional grounded ice sheets in the middle of the UK central North Sea.

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The integration of regional seismic mapping with well log data, including three wells on UK Block 22/7 with a unique early Pleistocene core dataset, has allowed the collation of convincing evidence for regional grounded ice sheets in the middle of UK central North Sea during the Early to Mid Pleistocene. The events discussed in this presentation are the Early Pleistocene Crenulate Marker ice advance, located stratigraphically at the base of the Early Pleistocene, Central Basin Unit (as defined by Ottesen et al., 2014), and a younger Mid Pleistocene ice advance which is thought to have resulted in regional sediment deformation immediately above the Central Basin Unit.

The evidence for the Crenulate Marker ice advance was provided by well core and log data collected during the exploration and appraisal of the Aviat Field, an early Pleistocene gas accumulation, located in UK Block 22/7. The Aviat reservoir sits directly on top of the Crenulate Marker. The Crenulate Marker, a regional acoustically hard seismic event, and from core evidence is interpreted as an over-compacted glacial deformation till. Seismic mapping demonstrates that this is associated with SSW-NNE oriented mega scale glacial lineations (MSGL) that can be traced from the UK Block 21/24 area through Aviat to the UK / Norwegian border. These features occupy a NE-SW oriented trough in the Crenulate Marker horizon. The Crenulate deformation till can be mapped on the NW flank and in the bottom of the Crenulate Marker trough but it is absent on the SE flank of the trough.
Regional seismic mapping of the younger Pleistocene horizons has identified a spectacular set of MSGL that can be traced for over 60 km from UK Block 22/2 in the north to UK Block 22/13 in the south. This zone sits just above the Central Basin Unit. The deformation which characterises these lineations can be recognised within a package of sediment some 100 ms thick; the eastern margin of the package is associated with a mounded seismic feature which may represent a lateral shear margin moraine.

The units described in this presentation are all located within the Aberdeen Ground Formation of Stoker et al (2011), a package that has traditionally been thought not to have been directly affected by glaciation.

OTTENSEN, D, DOWDSWELL J., A., BUGGE, T., 2014 Morphology, sedimentary infill and depositional environments of the Early Quaternary North Sea Basin (56 - 62 N) Marine and Petroleum Geology **56**, 123-146

STOKER, M. S., BALSON, P.S., LONG, D., and TAPPIN, D.R. 2011, An overview of the lithostratigraphical framework for the Quaternary deposition the United Kingdom continental shelf. British Geological Survey Research Report, RR/11/03. 48pp.

NOTES

All change at the base Quaternary: Reconstructing the geomorphology of Marine Isotope Stages 103-92 from basin-wide 3D seismic data in the southern North Sea

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Continuous 3D PGS MegaSurvey seismic data and borehole data spanning the southern North Sea covers an expanded sedimentary record for the Late Pliocene and earliest Pleistocene, a period of intense climate change and eustatic sea level change. A high resolution chronostratigraphic framework on a glacial-interglacial cycle resolution (41 ky) coupled with high sedimentation rates has allowed a detailed understanding of the sediment infill of the basin during this period.

The stratigraphy is dominated by a prograding shelf prism fed by river systems draining northern Europe and Fennoscandia. In seismic data, this is imaged as low angle clinoforms (1-2°), 100-400 m in height. Using seismic geomorphology techniques and stratal slicing, the positions of the shelf edge and coastline through time have been mapped. Key seismic features such as terrestrial channels, slope channels, basin floor fans, iceberg scours and current scours correlated with palynological, geochemical and lithological data have been used to reconstruct the depositional environments of the Late Pliocene- earliest Pleistocene. The stratigraphy records clear changes in the geomorphology of the coastline and associated continental shelf with an order of magnitude increase of sedimentation rates in the first 70,000 years of the Quaternary. The shelf edge progrades up to 75 km into the basin during the first major glacial-interglacial cycle of the Quaternary. This dramatically increases the shelf width within the southern North Sea and suggests that a huge amount of sediment became available as a result of the first major glaciation.

The paleoenvironmental reconstructions for each MIS 103-92 (2.58-2.35 Ma) indicate a single river dominated delta system, with an arcuate coastline, focused in the southern part of the Netherlands North Sea up to MIS 100 (~2.51 Ma). There is evidence for three separate depocentres by MIS 92, indicating at least three river-delta systems entering the basin, feeding a linear wave dominated shelf edge. This has implications for existing literature which describes the dominance of a single river delta system known as the "Baltic River System", or the "Eridanos Delta" draining Fennoscandia and the Baltic. This may be the case prior to MIS 100, but not for the majority of the Quaternary.

This study has implications for our understanding of the impact of the earliest large scale northern hemisphere glaciations on the North Sea and validates the repositioning of the base Quaternary to 2.58 Ma.

NOTES

Large-scale glacitectonism as a result of active retreat of the Fennoscandian Ice Sheetacross Dogger Bank during the Last Glacial Maximum

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Detailed analysis of high resolution seismic data from the Dogger Bank area in the southern North Sea has revealed that the Dogger Bank Formation records a complex history of sedimentation and penecontemporaneous, large-scale, ice-marginal to proglacial glacitectonism. These processes led to the development of a large, thrust-block moraine complex, in the order of 10 to 15 km across and over 30 km in length, which is buried beneath a relatively thin sequence of Holocene to recent sediments. This buried glacial landsystem comprises a series of elongate, arcuate ridges separated by low-lying linear basins and/or meltwater channels, which preserve the shape of the former ice sheet margin. Individual thrust moraines range from only 200 m across, up to more complex systems over 10 km in width. The lower boundary of the deformed sequence (up to 40-50 m thick) is marked by a laterally extensive décollement which also forms the base of the Dogger Bank Formation. Internally the moraines show evidence of locally intense SE-verging folding and thrusting, with the overall geometry of these glacitectonic structures being consistent with their formation in response to south- to southeast-directed ice-push. The internal architecture of the moraines has been divided into a number of structural domains which have aided in the interpretation of the constructional deformation history recorded by these glaciotectonic landforms. In the more ice-distal parts of the thrust-block moraine proglacial deformation led to open, upright to asymmetrical folding and thrusting consistent with the formation of a “forward” propagating imbricate thrust stack. Whereas in the more ice-proximal parts of the landsystem, the more complex folding and thrusting is thought to record the accretion of thrust slices of highly deformed sediment to the rear of the evolving moraine system as the ice repeatedly reoccupied this ice marginal position. Consequently, the internal architecture of the Dogger Bank thrust block moraine complex can be directly related to ice sheet dynamics, recording the former positions of an oscillating Fennoscandian Ice Sheet ice margin as it retreated northwards at the end of the Last Glacial Maximum.

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NOTES

Sediment failures within the Peach Slide (Barra Fan, NE Atlantic Ocean) and relation to the British-Irish Ice Sheet.

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The Barra Fan is a prograding shelf front glacigenic fan that is subject to cyclonic ocean circulation, with distinct differences between the circulation during stadial and inter-stadial periods. The fan has experienced growth since continental uplift during the mid-Pliocene, with the majority of sediments deposited during the Pleistocene when the fan was a major depo-centre for the British and Irish Ice Sheet. Surface and shallow-subsurface morphology of the fan is determined using archival paper pinger and deep towed boomer sub-bottom profile records (converted to SEGY format via drum scanning and digital conversion), sidescan sonar and multibeam echosounder data. This process has allowed the interpretation and mapping of a number of different seismic facies, including: contourites, hemipelagites and debrites. Other features such as fluid explusion and slide blocks are also visible in the data. Analysis of a number of core samples, some available in the literature and one analysed for this study, allow the development of an age model for the seismic stratigraphy. Gravity core 56/-10/239 identifies a debris flow containing material of glacial age and AMS ^{14}C dating of planktonic foraminifera constrain emplacement prior to 11.9 ka cal BP. Reference to the additional sediment cores located in the Barra Fan region (MD95-2006 and 56/-10/36) allows constraint of two periods of slope failure during the late Pleistocene: the first between 21 and 20 ka cal BP, shortly after the British ice sheet's maximum advance; and the second between 12 and 11 ka cal BP at the termination of the Younger Dryas stadial. Comparison with mass movement events on the Norwegian continental margin (in particular Storegga and Trænadjupet), which have a similar geological and oceanographic setting, suggests that events on the two margins may be controlled by similiar processes. Important roles seem to be played by contouritic and glacigenic sedimentation, deposited in inter-stadial and stadial periods respectively when different thermohaline regimes and sediment sources dominate. The effect of this switch in sedimentation is to produce low permeability glacigenic layers above contourite units: potentially producing excess pore pressure in the fan's sediments increasing the likelihood of sediment failure via reduced shear strength and potential liquefaction.

NOTES

Unravelling the North Sea Lobe; Extensive bathymetry and marine seismic data offer new perspectives

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The extent, pattern, and timing of late Pleistocene glaciation in the southern North Sea has long been discussed, not least due to the classic terrestrial field sites located along the adjacent Norfolk, Lincolnshire, and Yorkshire coasts. Despite this attention, and the eagerness of researchers to turn 'dashed lines' into 'solid lines' offshore (i.e. interpreted glacial limits), phases of glaciation in the North Sea remain poorly constrained, even for the LGM. This is somewhat ironic considering that this sector of the North Sea hosts perhaps the most regularly investigated seabed on the UK continental shelf due to the intense level of resource development (Oil & Gas, Offshore Wind, Aggregates, Fisheries), as well as further mapping for purposes such as Marine Protected Areas. These investigations however have often focussed on local, 'site-survey' scales (e.g. 5km x 5km), and investigators have not been required to examine regional-scale patterns of the seabed and shallow sub-seabed geology. Within this study we have utilised extensive bathymetric data together with existing 2D seismic data to examine the pattern, style, and relative chronology of glaciation in the southern North Sea during the last glacial cycle.

A series of broad glacigenic wedges and associated moraines observed on both the bathymetry and seismic data are interpreted as ice marginal landforms representing several terminal positions of the former North Sea Lobe of the British and Irish Ice Sheet (BIIS). These ice-marginal features also show clear affinities with geographically-defined groups of tunnel valleys, suggesting a genetic relationship between these landform suites. The sub-surface Bolders Bank Formation (subglacial till) has been subdivided into several seismostratigraphic units which correspond to the individual ice margins mapped at seabed from the bathymetry data. These observed members appear to correlate with onshore glacial diamicts (e.g. Skipsea and Withernsea tills). Across the study area this landform assemblage together with observations of the shallow geology are indicative of dynamic subglacial and ice-marginal glacial processes operating during the advance, occupation (and re-advance), and retreat over several phases of glaciation within the southern North Sea. This model provides a more detailed framework for understanding the offshore glacial geology, and should also enable improved correlation to terrestrial glacigenic features attributed to the North Sea Lobe of the BIIS.

NOTES

British-Irish Ice Sheet dynamics during the last glaciation and deglaciation and its influence on sedimentary processes in deep-water along the North Atlantic Passive Margin, North-West Ireland.

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The last British-Irish ice sheet (BIIS) during its maximum extension covered Ireland and part of Britain. Recently the BIIS has been defined as partially marine-based and highly dynamic with several advances and retreats on the continental shelf. The sedimentary processes in deep-water have been strongly influenced by the presence of the ice sheet on the outer shelf. Recent studies along the North Atlantic margin show that mass transport deposit, turbidites, plumites and Ice Rafted Debris (IRD) are all characteristic of a growing ice shelf and ice at its maximum extent, whilst contouritic and hemipelagic deposition are more common during interglacials. In this project, over 20 deep-sea sediment cores from the North Atlantic passive margin are investigated. The cores, retrieved from the Donegal Barra Fan, the Rockall Trough and along three transects on the Irish continental slope are used to reconstruct and chronologically constrain the variability of the BIIS in this specific deep-water sector. Microfossil and IRD contents will provide a reconstruction of BIIS dynamics; these proxies are strongly influenced by the location of the ice sheet margin. Moreover, the investigation of the sortable silt fraction (10-63 μm) will supply information about paleocurrents and the effects of the waxing and waning BIIS on the oceanic circulation.

Sedimentological analysis, x-radiographs, interpretation of physical properties (including shear strength, magnetic susceptibility, density and P-wave velocity), and microfossil and IRD counts provide information the depositional processes represented by the cores. Four different lithofacies, interpreted as contourites, turbidites, mass transport deposits and plumites, have been identified. The abundance of *Neogloboquadrina pachyderma* left coiling (NPS) and IRD concentration calculated at 20 cm sampling interval show the alternation of colder and warmer periods that can possibly be linked to a fluctuating BIIS margin. NPS and IRD contents show a direct relationship: high NPS abundance correspond to high IRD concentrations, suggesting an environment characterized by cold surface water temperature and floating icebergs. The NPS-IRD relationship will also be graphically tuned with the $\delta^{18}O$ from the Greenland Ice Core Record (GISP2) to set up a regional age model for the study area. Radiocarbon dates based on monospecific and mixed pick of foraminifera will provide a more robust chronology of the dynamism of the BIIS.

NOTES

Grounded glaciation in the central North Sea during the Calabrian (1.78 to 0.78 Ma)

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Evidence for glaciation in the North Sea region prior to the mid-Pleistocene transition (~0.8 Ma) has always been scarce. A combination of poor chronological control, a comparative lack of preserved glacial features and the need for good resolution 3D seismic data had created a bias in the literature towards the late Pleistocene and more specifically the LGM. Conventional wisdom has suggested that large marine-terminating ice sheets were unlikely to grow under the dominance of 41 kyr glacial-interglacial cycles and that glaciation from the onset of Northern Hemisphere glaciation was confined initially to highland areas over Norway. However a more detailed chronostratigraphy and a regional scale interpretation of 3D seismic data reveals a long history of glacial influence into the North Sea marine basin itself.
From the beginning of the Pleistocene at 2.58 Ma evidence of large scale iceberg scouring can be found on clinoform topsets indicating not just the occasional influx of ice but a large marine-terminating ice margin with repeated calving events. However more startling than this is that as the marine basin infills and shallows the ice sheets expand further. The first evidence for grounded glaciation into the marine basin has been found at approximately 1.7 Ma (MIS 60) in the form of several mega-scale glacial lineations coinciding with a sharp peak in estimates of average sedimentation rate. These features are initially infrequent, limited to only two small events at 1.7 and 1.53 Ma (MIS 52); however from 1.3 Ma (MIS 40) they increase in both frequency and extent until approximately 1.1 Ma (MIS 32). Between 1.1 Ma and the Bhrunes-Matuyama palaeomagnetic reversal at 0.78 Ma evidence for grounded glaciation is obscured on a regional scale by velocity effects from the Ling Bank Unconformity. However while MSGLs are no longer evident a large glaciotectonic complex can be observed during this period reaching over 280 km in length and clearly indicating an extensive grounded Norwegian ice margin.

Irrefutable evidence for grounded glaciation in the central North Sea during the early Quaternary questions our understanding of ice sheet growth and dynamics as well as having implications for many of our present day ice and climate models.

NOTES

Large-scale evolution of the central-east Greenland glaciated margin from late Miocene to Present

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The central-east Greenland margin runs from 71º to 68º N between two major fjords, the Kong Oscar Fjord to the north and the Kangerdlugssuaq Fjord to the south. It is considered as a passive margin bordered by Liverpool Land and Blosseville Kyst, which are separated by the most prominent fjord of east Greenland, i.e. the Scoresby Sund Fjord. Heavily glaciated hinterland and glaciers are found in this area, where the ice sheet repeatedly extended onto the shelf since Miocene times.

Morpho-structural and seismo-stratigraphic analyses have been made using available multichannel seismic data along the central-east margin of Greenland. Site 987 of the ODP Leg 162 is located in the abyssal plain offshore Scoresby Sund and has been used for age estimations of the major stratigraphic changes. Seven major stratigraphic discontinuities bound eight seismic units in the area. The areal distribution and internal facies of these units reveal the large-scale evolution of the glaciation over the central-east Greenland margin.
Before late Miocene times, the lower Unit 8 reveal signals of tectonic control of sedimentary processes and tentative fluvial influence in the valley area of Scoresby Sund Fjord. By late Miocene, the Unit 7 shows evidence of glacial advance onto the shelf off Scoresby Sund and north Blosseville Kyst. During early Pliocene, deposition of Unit 6 shows progradation building up the margin along Blosseville Kyst and the glaciation advanced all over the central-east Greenland margin. During late Pliocene times when Unit 5 was formed, the glaciation seems to retreat onshore. Around the Pliocene/Pleistocene boundary Unit 4 evidence a re-advance of the glaciation. It is formed by prograding sequences along the continental shelf edge and particularly well-developed off Scoresby Sund Fjord. Overall, the glaciation growth continued during the early Pleistocene. Unit 3 sedimentation shows a major advance off Scoresby Sund Fjord, whereas it is more regional during Unit 2. From late Pleistocene times onward the formation of Unit 1 indicates a period of glacial advance in particular along Scoresby Sund Fjord and Liverpool Land. The sedimentary growth patterns of the three upper units evidence a northward migration of glacial-controlled deposition along the central-east Greenland margin in course of the Quaternary.

NOTES

Subsurface heterogeneity in ice marginal deposits and its hydrogeological implications

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Quaternary ice marginal deposits are a common substrate in many parts of Canada and elsewhere around the world. The distribution of these materials is often complex as a result of the dynamic nature of these settings at the time of deposition, which in turn impacts modern groundwater recharge and contaminant transport. Hydrogeological studies of these deposits carried out in the context of resource management, source water protection or remediation of contaminated sites are often challenged by a lack of subsurface data that would allow sufficient characterization of subsurface heterogeneity. Here we present geomorphic, sedimentological and hydrogeological data from an ice marginal setting in Ontario Canada to demonstrate the scale of heterogeneity associated with different landscape elements (till plain, outwash and moraine) as well as the hydrogeological implications of that heterogeneity. The Paris Moraine is thought to have formed during the Wisconsinan glaciation during a temporary retreat of the Ontario ice lobe of the Laurentide ice sheet and is surrounded by outwash and till plain elements. The moraine's geomorphology was mapped using high resolution GPS transects, airphoto analysis and ground truthing. Nine sediment cores were recovered from various locations in each of the landscape elements and described in detail using standard sedimentological techniques. These data together with existing boreholes in the area were used to create cross sections through each element to further examine subsurface heterogeneity. Grain size analyses using sieves and the hydrometer method were carried out on over 150 samples to provide detailed grain size distribution for the various lithofacies encountered. These grain size distributions were then used to calculate saturated hydraulic conductivity based on the Kozeny-Carman empirical equation. In addition, the falling head permeameter method was used to measure saturated hydraulic conductivity on 104 disturbed samples. The findings show that different scales of sediment heterogeneity occur across the moraine itself and the associated till plain and outwash elements. In contrast, the hydraulic conductivity does not vary as much, though key units at specific depths that exhibit higher hydraulic conductivity are expected to play a significant role at the cm-100's of m scale.

NOTES

Subglacial gas hydrate regulation of ice stream flow

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The majority of ice, sediment and meltwater discharged from ice sheets drains through narrow areas of fast flow called ice streams. Observational data increasingly shows order of magnitude variations in the velocity of ice streams over very short temporal and spatial scales, which strongly affect ice sheet mass balance over a wide area. A comprehensive understanding of the process controlling such dynamics remains elusive, however friction at the ice bed interface is considered key, especially sticky spots- localised zone of high basal traction. Here we present evidence showing that subglacial gas hydrate can influence ice stream dynamics, by initiating and maintaining high basal traction conditions.

We present marine geophysical data from a palaeo-ice stream that drained the Barents Sea-Fennoscandian Ice Sheet. These show a large sticky spot that coincided with subsurface shallow gas accumulations, seafloor fluid explosion and a fault complex associated with deep hydrocarbon reservoirs. We propose that under high pressure, low temperature subglacial conditions, gas migrating from these reservoirs would have formed hydrates, critically altering the ice stream's basal regime. Gas hydrate formation would have desiccated, stiffened and hence strengthened the subglacial sediments, increasing basal frictional resistance and regulating ice stream flow. Deep hydrocarbon reservoirs are widespread in areas occupied by both palaeo and contemporary ice sheets. Thermogenic gas migrating from these will be stable as gas hydrates, providing a significant and previously unrecognised control on ice sheet dynamics and stability.

NOTES

Interactions between grounded ice sheets, deeper hydrocarbon reservoirs and methane emissions.

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Emissions of methane are an important driver of global climate change and, in marine settings, also affect chemosynthetic communities and ocean acidification. A potentially significant, but largely unconsidered source of methane is glaciated petroleum provinces, where grounded ice sheets play an important role in initiating and enhancing focused gas migration from deeper hydrocarbon reservoirs into large, shallow subsurface gas accumulations. Subsequent release of this gas when ice retreats leaves a range of geologic imprints. Here we document over 100 giant seafloor craters in the Barents Sea, inferred to have formed after the ice sheet retreated from the area at the end of the last glaciation. Associated with the craters are over 20 giant seafloor mounds, interpreted to be gashydrate pingos, formed by gas hydrate build-up in the shallow subsurface; and over 700 gas flares in the water, related to leakage from shallow gas hydrates and underlying hydrocarbon reservoirs. We propose a conceptual model for the formation of the assemblage of craters, mounds and gas flares in a marine-glaciated petroleum basin, discuss its relevance and the implication for gas leakage in a warming climate.

NOTES

Lille John oil field, Denmark: a glacially-driven trap and charge model

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In 2011 the Lille John well offshore Denmark was drilled on the flank of a prominent Zechstein salt diapir. Prior wells in the 1980's had encountered but overlooked oil and gas shows in Neogene clastics. 3D seismic interpretation and analysis of the historic well data suggested that liquid hydrocarbons might be responsible for a structurally-conforming seismic amplitude anomaly within the Miocene section targeted by the Lille John well.

The Lille John well penetrated oil-bearing Late Miocene sandstones and sampled 34° API oil of almost unprecedentedly slight biodegradation at c. -900 m TVDSS and low reservoir temperature of 40°C - 50°C. Subsequent appraisal drilling tested oil at rates upto 1,400 bopd and confirmed a column of c. 350m. The reservoir appears full to spill and coupled with minimal biodegradation implies an extremely short oil residence time. Stratal relationships show that the Lille John diapir was being passively onlapped during Late Miocene reservoir deposition. Trap formation is demonstrably due to re-commencement of diapir growth through Latest Miocene to Early Pleistocene (c. 6 – 2 Ma) and again in Late Pleistocene times (c. 0.5 Ma – c. 0.02 Ma).

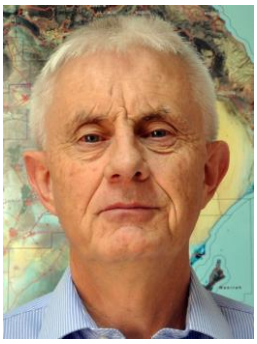
Glacial and de-glacial effects driven by ice loading and unloading act with a frequency, rate and magnitude that in combination are unlike anything normally experienced in a within-plate setting, including:

- Repeated, relatively long wavelength flexural tilting of the basin;
- Significant and fast-changing spatial and temporal fluctuations in the magnitude, orientation and sense of the prevailing stress field;
- Repeated fluctuations in pore pressure of the order of hundreds upto perhaps several thousand psi;
- Reduced stability of existing faults especially during interglacial and post-glacial periods, as accumulated stresses are released when pore pressure may remain elevated and fault reactivation thus facilitated;
- Repeated pulses of increased fluid flow due to sub-glacial groundwater injection and disequilibrium compaction;
- Increased probability of loss of seal integrity to hydrocarbon accumulations due to fault reactivation or reduced topseal capacity.

Reflecting timing of trap development relative to Late Miocene commencement of oil expulsion from Volgian source rocks, a two-stage charge model has been developed. An initial Late Miocene to Plio-Pleistocene oil accumulation ('motel') in the underlying, over-pressured Chalk reservoir is interpreted to have temporarily lost seal integrity during a Late Pleistocene to Holocene glacially-induced 'breach' phase, allowing oil re-migration to the reservoir. Furthermore, Late Pleistocene diapir growth may itself be attributable to glacially-driven compressive stresses acting on a shallow, weak salt stock.
The hydrocarbon exploration implications of glaciation, especially on stress, pore pressure and trap integrity are under-appreciated but potentially very significant and have wider implications for industry's understanding of North Sea hydrocarbon migration and charge.

NOTES

Oil in Permo-Carboniferous ice-marginal deposits in Oman.
Why oil accumulations occur and what makes them challenging.



Alan P. Heward, David B. Alsop, and Faisal Al-Abri

The Permo-Carboniferous Al Khlata Formation occurs widely in Oman. It is up to 800 m thick in the subsurface of the interior and much thinner in basin margin outcrops to the east. Large volumes of mainly heavy oil occur in these ice-marginal deposits in southern Oman.

Palynological evidence from hundreds of oil wells shows that these deposits are non-marine and span >20 Ma from the Carboniferous to the Permian. Seven intervals are distinguished by micro-floras that show progressively warming interglacial conditions. The oldest, is largely barren of Carboniferous taxa but yields Middle and Late Devonian spores that are presumed reworked. The Al Khlata overlies and reworks a thick sequence of Cambro-Ordovician sands.

Despite the presence of striated pavements at outcrop, the deposits in the subsurface are mainly glacio-lacustrine and show little, if any, evidence of grounded ice. Diamictites are the dominant lithofacies in southern Oman, comprising about 60% of the sequence in one 1750 km2 area where it has been analysed. Most sandstones are likely to have been deposited during glacial retreat phases. The oldest Al Khlata is the most sandy and the youngest the most shaly as sources of older sands were progressively covered-up. The oldest units are often dissected and eroded during later glacial periods. Large glacial valleys or channel-ways cut several of the oil fields and were eroded repeatedly at different periods. The deposits with the most continuity are those of the latest deglaciation and those preserved in basinal depocentres. Depocentres in southern Oman result from the removal of Infracambrian salt, probably accelerated by glacial meltwaters.

Oil occurs in these deposits by the chance coincidence of deeper source rocks, reservoir sands in the older units of the Al Khlata, a combination of glacio-lacustrine and younger seals, and salt movement to form anticlines. The Neoproterozic-Infracambrian source rocks have been generating oil from the Cambrian to the present, including during the Permian, where a clast of bitumen from a diamictite at outcrop provides an interesting glimpse of ice movement and lake biota. Most oil in South Oman is biodegraded and, given in-situ viscosities of tens to thousands of centipoise, Darcy permeability reservoirs are required for production. The extreme heterogeneity of these ice-marginal reservoirs presents challenges (and opportunities) for the exploration and production of oil.

NOTES

New insights into the Al Khlata to Lower Gharif succession of North Oman

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The Al Khlata to Lower Gharif succession of Oman records a transition from deposition in a glacially-influenced setting through to deglaciation at the end of the Permo-Carboniferous ice age and the development of fully marine conditions in the Lower Gharif.

Although extensively studied in South Oman and in the outcrops of the Huqf and Oman Mountains, information on the character of the Al Khlata deposits and the nature of the transition to the Lower Gharif across North Oman is sparse. Excellent quality core and borehole image data acquired by OOCEP in two wells from the Abu Butabul Field have been interpreted, age constrained and correlated with wireline log data from an additional three wells, providing an enhanced understanding of the nature of the succession in this area.

This succession consists initially of glacial outwash plain deposits confined into two separate palaeovalleys, separated by a potential palaeohigh, based on varied palaeoflow data. Once the valleys were infilled, E to NE-directed deposition on an outwash plain is inferred across the area, the upper part of which has been dated as HSAK-P1 in age. A fall in base level/increase in glacial melting resulted in a gradual change to lacustrine conditions, firstly in the form of potential fan deltas at the lake margins, followed by increasingly glacially-influenced conditions with the deposition of debrites and rare, varved mudrocks punctuated by dropstones.

A sudden draining of this lake resulted in a change to E-directed channelised deposits feeding into a delta/lake margin setting in the E/SE of the field; the presence of rare dropstones within these lacustrine deposits attesting to the ongoing influence of icebergs at this time. These deposits are dated as HSAK-P1 to HSAKR-equivalent in age.

Progradation of channelised deposits resulted in the eventual infilling of this lake and deposition of a southerly migrating channel-belt, crossing the Al Khlata-Gharif boundary and encompassing a shift to a NE-directed system. Whilst a laterally amalgamated channel system is envisaged, attributed to limited accommodation space, a discrete mudrock interval within these channels, bound by erosive surfaces, supports a marine-influenced incursion, potentially providing evidence of isostatic variations in base level.

The channels are overlain by a widespread change to marine-influenced deltaics of Lower Gharif age, followed by the regionally recognised onset of fully marine conditions.

This complex evolution has resulted in a complex depositional architecture which has implications for hydrocarbon prospectivity.

NOTES

Late-Wisconsinan grounding zone wedge systems off the Québec North-Shore (eastern Canada)

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Grounding-zone wedges (GZWs) are formed on high latitude continental shelves by the accumulation of subglacial sediments from fast flowing ice at the grounding zone of an ice-sheet during temporary stillstands. Swath bathymetry data and seismic profiles along the North Shore of the Gulf of St. Lawrence (eastern Canada) have revealed a series of wedge-shaped deposits interpreted as GZWs. Three GZW systems extend laterally along the same isobaths over a distance of >380 km, forming three ~20-30 m-high steps on the seafloor: (1) a first system at depth around 180 m located between 11 and 18 km from the coastline; (2) a second at depths around 120 m located between 10 and 17 km from the coastline; and (3) a third at depths around 80 m located <6 km from the coastline. Segments of the second and third GZW systems change locally to form morainal banks or submarine fans, reflecting changes in the nature of the ice-margin, i.e., ice-shelf or tidewater. In some sectors, segments of the third system also occur along the shoreline, where they have been generally washed out of fine sediments by waves and are visible on terrestrial LiDAR data and low elevation aerial photographs. The GZWs have a curvilinear geometry that reflects the general bathymetry of the continental shelf of the region. The three series of GZW systems were built during phases of stabilization of the marine-based southeastern margin of the Laurentide Ice Sheet following its rapid retreat over the Laurentian Channel in the Gulf of St. Lawrence after 14.8 cal ka BP. The occurrence of GZWs along three distinct isobaths indicates that bathymetry exerted a strong control on ice stabilization during deglaciation by reducing the relative water depth at the ice margin and thereby the rate of iceberg calving. However, climate-driven fluctuations of the ice margin are also suggested by the overprinting of a portion of the second wedge system by the third system due to a localized re-advance. Also, radiocarbon ages obtained from shells sampled in sediment cores collected in glaciomarine deposits 6 km south of the second GZW system indicate that the second phase of ice-margin stabilized shortly after the beginning of the Younger Dryas cold episode. The three GZWs observed along the shelf of the northwestern Gulf of St. Lawrence record a phase of episodic retreat of the Laurentide Ice Sheet margin following its rapid retreat in the deeper waters of the Laurentian Channel.

NOTES

Dynamics of and controls on post-Younger Dryas retreat of a Bothnian Sea ice stream

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The Gulf of Bothnia, a shallow basin in the heart of the terrain formerly occupied by the Fennoscandian Ice Sheet, has variably played host to interior portions of the ice sheet; the onset, trunk and retreat zones of Baltic and Finnish ice streams; and a major corridor of ice margin retreat under persistent marine/lacustrine conditions. These glacial dynamics and environments have, however, been hitherto inferred from almost exclusively terrestrial, peripheral evidence. The Gulf of Bothnia itself has been little investigated and its glacial geological archives are virtually unknown.

Recent acquisition of high resolution multibeam echo-sounding data across the Gulf of Bothnia reveals, for the first time, the glacial landforms associated with flow and retreat of ice through the basin. A late-stage ice stream flowed southward through the Bothnian Sea in a narrow corridor of fast flow. A vast field of crevasse squeeze ridges indicates ice flow under high extension, which likely enabled large supraglacial melt volumes to penetrate to the bed and develop the extensive, channelised and well-connected basal hydrological network that is recorded on the seafloor. Stimulated by our geomorphological observations, we use a physically-based numerical ice flowband model (Nick et al., 2010) to examine the sensitivity of ice retreat to surface process forcing and to marine forcing. We find that the rate and pattern of ice flow and margin retreat are most sensitive to surface mass balance change and crevasse propagation, while remarkably insensitive to submarine melting and sea level change. We suggest that surface meltwater production and its exploitation of a highly crevassed ice body triggered rapid deglaciation of the south-central sector of the post-Younger Dryas Fennoscandian Ice Sheet.

NOTES

Ice sheet dynamics of the western North Sea Basin: Shallow seafloor glacial landforms preserved offshore eastern Scotland and north-eastern England.

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Multibeam echosounder datasets have been combined with high-resolution topographic digital surface models (NEXTMap), 2D seismic reflection profiles and shallow cores to reveal strong evidence for onshore-offshore palaeo-ice streaming in eastern Scotland and north-eastern England, UK. The study area includes the catchments of the previously proposed, but only partly mapped, Strathmore, Forth–Tay, and Tweed palaeo-ice streams. Long suspected to terminate offshore, the full flow path and dimensions of this palaeo-ice stream system can now be reconstructed with some certainty using these new data. This paper presents the results from detailed mapping of the ice sheet glacial landsystem.

Digital terrain models were used in conjunction with derived layers of rugosity, slope, Bathymetric Positioning Index and aspect in undertaking geomorphological mapping. In addition, multibeam backscatter intensity data acquired in the western North Sea have been utilised as part of a semi-automated approach to identify areas of glacigenic deposits.
Drumlin fields, large arcuate moraine ridges, smaller-scale moraine ridges, grounding zone wedges and incised channels were mapped in detail. These ice streams extended at least 60 km offshore and probably accelerated across the transition from bedrock-dominated onshore terrain to the till-dominated North Sea Basin offshore. Of particular interest is the observation that the Forth–Tay palaeo-ice stream diverged, forming two glaciologically separate streams running parallel to the present-day coastline. One flowing north-east, merging with the Strathmore palaeo-ice stream, the other flowing south-east, forming a major component of the North Sea Lobe. Moraines preserved on the sea floor record in detail the stepped recession of the North Sea Lobe back to the Firth of Forth.

Spatial and morphological relationships between the landforms within this glacial landsystem allow inferences about the ice sheet history and behaviour to be reconstructed.

NOTES

The Holocene geomorphological and sedimentary record of Jakobshavn Isbræ, West Greenland

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Lithological and geophysical data from Disko Bay and the Vaigat Strait, marine embayments in central West Greenland, were investigated to obtain a better understanding of the long-term record of the dynamics of marine-terminating outlet glaciers from the Greenland Ice Sheet. These glaciers strongly influence the ice-sheet's mass balance, but although a number of studies have investigated their evolution and deglacial dynamics since the Last Glacial Maximum (e.g. Young et al., 2011; Jennings et al., 2013; Ó Cofaigh et al., 2013; Roberts et al., 2013; Dowdeswell et al., 2014; Lane et al., 2014), their Holocene glacimarine processes and the associated geomorphological and sedimentary records are still poorly known. Disko Bay is of particular interest, as it is strongly influenced by Jakobshavn Isbræ, Greenland's fastest-flowing outlet glacier, which currently drains ~7% of the ice sheet. The Vaigat Strait, a northern arm of the bay, is influenced by two smaller tidewater glaciers, Sermeq Avangnardleq and Sermeq Kujatdleq. Streamlined bedrock is visible on the bathymetry data and records the former expansion of glaciers through the bays and across the adjoining continental shelf. A small number of recessional moraines in Disko Bay further provide evidence that the retreat of Jakobshavn Isbræ was interrupted by occasional still-stands.

Nine vibrocores from Disko Bay and three from the Vaigat Strait demonstrate the importance of meltwater-related processes to glacier-controlled sedimentation in West Greenland fjords. The cores from Disko Bay contain a complex set of lithofacies, including laminated muds, sharp-based massive and graded sands, IRD-rich massive muds, and massive bioturbated muds. These facies suggest that suspension settling of fine-grained sediment from turbid meltwater plumes, sediment gravity flows and iceberg rafting were the principal sedimentary processes in the bay during and following the retreat of Jakobshavn Isbræ. Only the massive IRD-rich muds occur in the cores from the Vaigat Strait, suggesting that the sedimentary environment there was dominated by suspension rainout and ice-rafting.

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NOTES

Evolution in palaeo- ice stream behaviour during rapid retreat

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Concerns over the behaviour of unstable contemporary ice streams and associated onset of rapid collapse of the West Antarctic Ice Sheet (WAIS) are applications for the conceptual model presented here of the palaeo Irish Sea Ice Stream (ISIS) during rapid ice marginal retreat. Using a new unrivalled 2100 km^2 geophysical and geotechnical sea floor dataset collected on behalf of Celtic Array Ltd, the largest ice stream to drain the interior of the former British Irish Ice Sheet (BIIS) was investigated. We reveal the geomorphology and subsurface geology of this region and assess the ice flow dynamics and behaviour of a marine-terminating ice stream during rapid deglaciation over millennial timescales. The ice contact landforms and, in particular, subglacial bedforms of this submerged glacigenic landscape represent multiple and overprinted flow phases with changes in thermal regime, varying ice flow direction and indicative velocity. The successive flow phases document a scale reduction in the deglaciation processes as the ISIS down-wasted, thinned and the oscillating margins retreated, diminishing the erosive power of the ice mass. This conceptual model is developed as an analogue for the behaviour of rapidly declining ice streams with marine calving margins, and includes substantial re-organisation of flow within the ice stream, changes in thermal regime, repeated episodes of fast ice flow, and growing topographical moderation of ice flow. Forcing of this ice behaviour is likely a complex interplay of external drivers (e.g. climate warming, sea-level rise, mega-tidal amplitudes and reactivation of North Atlantic meridional circulation), but this study emphasises the critical importance of glaciological factors (e.g. bed topography, basin width, thermal regime of subglacial bed, over-extension of ice, ice flow reorganisation). We thus suggest that these factors need considerable attention in forecasting the behaviour of rapidly retreating ice streams in Greenland and the Antarctic.

NOTES

Poster Presentation Abstracts

The Port Askaig Formation of the Garvellachs islands, Scotland: a Neoproterozoic glacial succession with many diamictites and complex geometries

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The Cryogenian (720-635 Ma) glaciations produced a worldwide record of diamictite deposits on virtually every continent. The exposure quality of some of these successions, including those in Argyll, Scotland, rivals Quaternary successions in permitting detailed insight into the history of glacial events. Also, these Scottish rocks are a potential candidate for the Cryogenian GSSP (Global boundary Stratotype Section and Point). In the Garvellach islands, a total of six months fieldwork on the Port Askaig Formation has enabled a detailed analysis of the stratigraphy and geometry of beds. Previous studies have emphasised the layer cake nature of the stratigraphy. Detailed sedimentary logs have been measured over specific intervals to investigate the lateral variation in bed thickness and geometry. Results confirm the presence of ca. 50 diamictite beds in the Formation, but reveal the complex geometries of some of them. Facies analysis of the interbedded sediments between diamictite beds suggests shallow marine (often tidal), fluvial and debris flow environments. Periglacial conditions are recorded by horizons of sandstone wedges and frost-shattered clasts. Dropstone is evidence of ice rafting, but the predominantly massive diamictites record the presence of ice sheets in or near the Garvellachs. The formation records numerous glacial, periglacial and non-glacial events: the ice advanced and retreated many times.

Deglacial sequences and glacio-isostatic rebounds: Quaternary vs. Ordovician glaciations

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Along glaciated margins, post-LGM deglacial sequences are dominated by receding grounding zone wedges (GZWs) and ensuing deltaic and coastal successions. While the sediment entry points are essentially governed by the grounding line position in the early glaciomarine evolution, the isostatic rebound and associated forced regression have a major control on the sedimentary architecture of succeeding delta systems. Though their preservation potential may be a priori limited, field examples and numerical stratigraphic modelling show that forced-regressive ice-contact, deltaic and coastal deposits are an essential element of deglacial sequences, which thus should have their counterpart in the deep-time glacial record. Here, we will compare a late Pleistocene and an Ordovician deglacial sequences, in Quebec (St Lawrence North Shore) and Anti-Atlas (southern Morocco) respectively.

Throughout the Quebec North Shore, GZWs and ensuing glaciofluvial wedges, characterized by sandy cyclic step deposits to low-density turbidites and distal glaciomarine plume deposits, have been first emplaced. Then, a proglacial fluvio-deltaic wedge aggraded in fjord to inner shelf settings, owing to active sediment supply and despite effective RSL fall forced by the glacio-isostatic rebound. After the disconnection from the recessing ice fronts, river incision and offlapping beach ridges essentially remobilized glaciomarine and proglacial sediments deposited with lower sea-level fall rates. The resulting succession is a sand-dominated, 20-150 m thick, fining-then-coarsening upward sequence essentially deposited in less than 3kyr. The intermediate finer-grained interval represents the transition from retreating GZWs (subaqueous entry points) to prograding deltas (subaerial entry points). Coarsest deposits paradoxically relate to post-glacial meandering rivers and associated mouth deposits.

The latest glacial sequence preserved in southern Morocco shows such a stratigraphic pattern, superimposing a basal fining-upward stack (10-50 m) of individually thickening-upward, sand-dominated wedges with glacial influences (glaciomarine facies, outburst-flood deposits) and an overlying delta succession (40-70 m) without glacial influences. This sequence, severely truncated in places by postglacial transgressive ravinement, might be ascribed to a single deglacial sequence recording the decreasing influence of the glaciation, and the subsequent glacio-isostatic rebound. If true, one of the thickest sediment wedge constituting the archive of the Ordovician glaciation in Morocco only represents a few thousands of year of deposition within a much longer (>1Myr?) glaciation.

Comparison of glacigenic strata in northeastern Svalbard and Northeast Greenland: implications for dynamic glaciation in the Cryogenian Period

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Cryogenian glacial sediments (720 to 635 Ma) are widespread in the Arctic region. These sediments have been interpreted in terms of a Snowball Earth Model which postulates complete or near freezing of the Earth's surface during the Sturtian (717-659 Ma) and Marinoan (645-635 Ma) episodes of panglaciation.
The Polarisbreen Group in the Svalbard archipelago records some of the best-exposed and best-preserved examples of Neoproterozoic glaciation in the world. Two distinct glacigenic units, assigned to the Sturtian and Marinoan glaciations, are recorded in the Petrovbreen Member of the Elbobreen Formation (15-20 m) and in the Wilsonbreen Formation (~160 m), respectively. Recent work on the latter has shown that these deposits are characterized by an interplay of glaciolacustrine, subglacial and non-glacial conditions during repeated advance and retreat cycles (Benn et al., *Nature Geoscience,* 2015 and Fleming et al., *Sedimentology,* 2016), possibly in response to orbital forcing.

In Northeast Greenland, the Sturtian and Marinoan glaciations are recorded in the Tillite Group by the Ulvesø and Storeelv formations, respectively. These units are similar both lithologically and isotopically to those in northeastern Svalbard and despite their present-day spatial disparity, are considered to have formed in a contiguous sedimentary basin (Fairchild & Hambrey, *Precambrian Research* 1995).

In this study, the facies, petrographic and provenance characteristics of the glacigenic units of the two regions are compared. The fluvial and lacustrine limestones that characterize the Marinoan of northeastern Svalbard are not present in Northeast Greenland. However, a range of glacial-depositional environments are recorded (glaciomarine, glaciolacustrine and subglacial) as well as non-glacial (terrestrial, and fluvial) environments that share many similarities with the Polarisbreen Group. These results show that the two areas share similar facies architectures and suggest that the Storeelv Formation also records repeated glacial advance and retreat cycles.

The Kingston Peak Formation, California: A 720 Ma rifted glaciated margin and the challenge of distinguishing glacial from non-glacial deposits.

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The unzipping of Rodinia during the Cryogenian (720-635 Ma) occurred diachronously yet concomitantly with panglacial events. The close association between rifting (including basalt production) and glacial deposits in the Kingston Peak Formation is well established in the western part of Death Valley (Panamint Range), yet less well studied in the eastern outcrop belts of the area (Kingston Range and Silurian Hills). In the Kingston Range, previous outcrop work has highlighted clear evidence for extensional fault arrays of syn-sedimentary nature and an up to 2 km-thick olistostrome deposit, which bears up to km-scale megaclasts. Two intervals of diamictite occur within the stratigraphy. These rocks include stratified diamictites with clear dropstone textures, in places intercalated with dropstone-bearing turbidites and debrites. Given the historical challenges of discriminating diamictites deposited through glacial or mass flow origin, we propose criteria to distinguish those glacially-related parts of the stratigraphy from those of non-glacial (i.e. rift-related origin). These criteria include the 3D geometry of stratal packages across a 15 km long outcrop belt, the geometry and size of outsized clasts, and their composition. In the Silurian Hills, diamictites deposited as glaciogenic debris flows are intercalated with dropstone-bearing heterolithic strata. The former are dominated by crystalline basement clasts (gneiss, granitoid, quartzite): the latter contain these lithologies as outsized clasts. By contrast, olistostrome deposits, characterised by unsorted material and megablocks, are dominated by reworked material derived from Neoproterozoic cover rocks, including dolostone derived from sub-Kingston Range units (Crystal Spring Formation and the overlying Beck Spring Dolomite), Thus, discrimination between material fed into this rifted glaciated margin through the glacial conveyor belt can readily be distinguished from that produced by local slope foundering during the rifting process.

Did ‘Snowball Earth’ experience tropical levels of chemical weathering?

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Weathering in warm and humid conditions causes feldspars, the prime constituents of upper continental crust, to dissolve and reprecipitate as aluminium-rich clay minerals. Such alteration can be quantified by means of the ‘chemical index of alteration’ (CIA), the ratio of Al to the mobile elements Ca, Na and K plus Al. A large number of siliciclastic successions from the Palaeoproterozoic and Neoproterozoic have been analysed for major elements, enabling CIA values to be compared. A review of 20 such successions, including the Sturt Tillite (eponymous for the ‘Sturtian glaciation’), indicates that ‘glaciogenic’ sediments had undergone as much weathering as those supposedly weathered in temperatures up to 80° C higher. It is something of a trade secret amongst geochemists working in the Proterozoic that ‘CIA values in glacially influenced deposits are never as low as would be expected for sediments produced solely by mechanical erosion’ (Rieu et al. 2007). The paradigm that Precambrian diamictites formed in icehouse conditions is saved by supposing that the chemical alteration was inherited from a previous cycle of weathering and deposition. It can be tested by examining whether Zr/Sc ratios support such recycling.

An Early Permian sedimentary record of deglaciation from the Falkland Islands

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Glacigenic strata deposited during the extensive Early Permian glaciation of southern Gondwana are preserved in the Falkland Islands (52° South, 60° West) as the Fitzroy Tillite Formation. This unit is a close correlative of the better-known tillites from the South African Dwyka Group, and represents one of the last glacial records from Gondwana prior to the Earth's transition into the 'greenhouse' climatic state that persisted thereafter until the Neogene. Recent recovery of eight borehole core runs through the Fitzroy Tillite and overlying strata have enabled detailed analysis of the transition from glacial conditions through the ensuing deglaciation.

The Fitzroy Tillite Formation is between 700 m and 900 m thick and comprises a massive or weakly thick-bedded, sandy diamictite containing a variety of matrix-supported erratic clasts, most commonly of quartzite or granitic lithologies. At one locality an interbedded 5 m thickness of laminated sandstone with dropstones has been recorded, whilst in the extreme west of its outcrop the diamictite contains rare sandstone bodies that may have originated as eskers. A sub-horizontal fabric seen locally in the diamictite is probably a relict of an original stratification, modified by sub-glacial deformation.

Conformably overlying the diamictite is a distinctive, 7 to 10 m thickness of thinly interbedded diamictite, laminated mudstone, and sandstone with sporadic dropstones. This is the Hells Kitchen Member of the Port Sussex Formation, a transitional succession deposited during a fluctuating glacial regression that records waning cycles of re-advance superimposed upon an episode of overall glacial retreat. A complex facies interaction arose from a range of depositional processes: meltwater, release of glacial debris from ice, gravity flows, iceberg calving and current reworking. Statistical analyses of reflectance and XRF core-scanning data have identified possible Milankovitch periodicities, thereby allowing tentative time-scale modelling over the 'icehouse to greenhouse' transition. It is suggested that the transition may have spanned approximately 1.2 million years.

Strengthening the lithofacies similarities between the Fitzroy Tillite and the Dywka Group tillites of South Africa are unusual erratic clasts – Early Cambrian archaeocyath-bearing limestones – common to both stratigraphical divisions, and a similar age distribution of detrital zircon populations. These features have been used to support reconstructions of Gondwana in which a rotated Falklands microplate is placed close to the eastern continental margin of South Arica. Building on the regional correlation with the Dwyka Group succession, a Sakmarian age seems likely for the deglaciation recorded in the Falkland Islands.

The significance of glacial plough marks in the North Falkland Basin

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Offshore records of glaciation are relatively sparse in the southern hemisphere; this study documents the occurrence of iceberg plough marks and accompanying pits within the North Falkland Basin and discusses their significance in terms of glaciation history and ocean currents during the last glacial cycle. Morphological evidence of plough marks are observed at ~50 ° S on the Falkland Plateau, with scours reaching over 38 km long and 1 km wide. The area of study is situated in the northern area of the North Falkland Basin, using five high – quality seismic data sets covering a total area of 1500 km² in water depths of 300-500 m.
Iceberg plough marks are observed as erosional linear to curvilinear depressions, showing only one point of contact between iceberg and seafloor, with raised berms identified either side of the main depression. The maximum depth of plough marks is ~40 m and thickness of berms ~10 m. Rotation of the keel is seen shaping the furrow and results in the narrow to thicker width of scours. The sinusoidal character of these depressions can be extreme, with some features rotating over 180°. The cross sectional shapes of depressions are u to v shaped and occur in water depths of over 460 m (current sea level). Plough marks are irregular in distribution as the depressions cut across each other, with the most common orientations trending in a SW – NE direction.

Offshore and onshore landscape analysis is used to determine potential sources of icebergs, taking into consideration the Patagonian ice cap, Antarctic ice sheet, the South Georgian ice sheet and icebergs sourced directly from the Falkland Islands during the last glacial maximum. The results inform our understanding of southern hemisphere glaciation and ocean currents during the last glacial cycle.

Subglacial and glacimarine bedforms on the continental shelf of the SE Weddell Sea, Antarctica: New findings from hydroacoustic data acquired during RV "Polarstern" expedition PS96 (2015/2016)

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The glacial history of the continental shelf in the southern Weddell Sea, Antarctica, is poorly known. Sparse multibeam data collected on previous expeditions from the outer, middle and inner shelf parts of Filchner Trough and along the Filchner-Ronne Ice Shelf front revealed the presence of subglacial bedforms in the Filchner, Ronne and Hughes bathymetric troughs, while highly consolidated diamictons recovered in cores elsewhere from the Weddell Sea shelf were classified as subglacial tills. These findings were interpreted as evidence for the widespread presence of grounded ice both in the troughs and on shallower shelf banks during the younger geological past, probably at the Last Glacial Maximum (LGM; ca. 19-23 ka BP). In contrast, cosmogenic surface exposure ages of erratics collected from nunataks in the hinterland of the Weddell Sea embayment indicated that the LGM ice sheet could not have been thick enough to cause its grounding in the deeper parts of the Filchner and Ronne palaeo-ice stream troughs. Resolving these contradicting reconstructions is crucial, however, for a correct estimation of the ice volume stored in Antarctica during the LGM and for deciphering whether the Antarctic Ice Sheet was the main contributor for the rapid, drastic global sea-level rise of meltwater pulse 1A (MWP-1a; ca. 14.5 ka BP) during the last deglaciation.

In order to solve this problem multibeam swath bathymetry data (*ATLAS Hydrosweep DS3*), acoustic subbottom profiles (*ATLAS Parasound P-70*) and marine sediment cores were collected from the East and West Antarctic continental shelves in the southern Weddell Sea during RV "Polarstern" expedition PS96 in Dec 2015-Feb 2016. Despite severe sea-ice conditions that hampered multibeam surveys and coring operations a previously unknown grounding zone wedge (GZW) within the outer shelf part of Filchner Trough could be mapped and sampled with two gravity cores. Morphology and acoustic stratigraphy of the GZW suggest that this feature marks the maximum extent of the Filchner palaeo-ice stream at the LGM rather than the position of a grounding-line stillstand during ice stream retreat from the shelf edge. In addition, hydroacoustic data and seabed images (*Ocean Floor Observation System*) acquired from other areas of the continental shelf reveal the strong control of seabed substrate and tidal currents on the orientation and shape of iceberg furrows. Here we present a collection of the new geomorphological and geological data and discuss their significance for bedform genesis and Antarctic Ice Sheet history.

Sedimentary stacking pattern and evolution of the Antarctic Peninsula, Pacific Margin offshore of Adelaide Island

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A seismic stratigraphic analysis of multichannel seismic reflection profiles is presented from the continental margin offshore of Adelaide Island in the Antarctic Peninsula Pacific Margin (PMAP). We executed an integrated 'source to sink' study of the margin spanning the shelf to the continental rise, establishing novel chronologic constraints and offering new interpretations on tectonic evolution and environmental changes affecting the PMAP. The sedimentary stacking patterns record major shifts in the depositional style of the margin that outline three main intervals in its evolution. The first non-glacial interval (Early Cretaceous to middle Miocene) corresponds to a transition from an active to a passive margin (early Miocene). The second glacially-influenced interval (middle to late Miocene) is marked by pronounced aggradational sedimentary stacking and subsidence. Ice sheets advanced over the middle shelf of the margin at the end of this second interval, while the outer shelf experienced rare progradational events. The third, fully glaciated interval shows clear evidence of "glacially dominated" conditions on the margin. This interval divides into three minor stages. During the first transitional stage (late Miocene to the beginning of the early Pliocene), grounded ice began frequent episodic advances to the shelf break, depositing an initial progradational unit. A major truncation surface marked the end of this stage, which coincided with extensive mass transport deposits at the base of the slope. During the second progradational glacial margin stage (early Pliocene to middle Pleistocene), stacking patterns record clearly prograding glacial sequences. The beginning of the third aggradational glacial margin stage (middle Pleistocene to present) corresponded to an important shift in global climate known as the Mid-Pleistocene Transition. The study area specifically records not only the salient changes in depositional style, but also the relative temporal and spatial importance of persistent along- and down-slope sedimentary processes. Our study approach can be extended to other areas to understand the evolution and the global linkages of the Antarctic continental margin.

Grounding zone wedges, reverse bed slopes and the stability of the Coats Land ice margin

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The westernmost part of the East Antarctic Ice Sheet discharges into the Weddell Sea (WS) via the Coats Land ice margin between the Filchner and Riiser-Larsen ice shelves. A recent review of the evidence for glaciation in the region by Hillenbrand et al. (2014) proposed two possible scenarios for ice extent the WS during the last glacial cycle. Both scenarios include the advance of grounded ice from Coats Land and into the WS, however, little is known about how ice joined with flow through the Filchner Trough, or how and when the ice retreated during deglaciation. Today, the main glacial outlets on this margin consist of marine-terminating glaciers and ice shelves on the Luitpold and Caird Coasts.

During a research cruise of the RRS *James Clark Ross* in 2011 high-resolution multibeam-bathymetric data was acquired in six troughs along the Coats Land margin. These data were supplemented with sub-bottom profiler data, seismic surveys, sediment coring and previous surveys in the vicinity of the Brunt Ice Shelf. Results show that the glacial troughs have reverse-bed slopes with seafloor glacial geomorphological features including glacial lineations, drumlinised bedforms, moraines, over-deepened basins, and grounding-zone wedges. In some cases the surveys reveal medial moraines where the Coats Land glaciers merged with the palaeo-Filchner Ice Stream in Flichner Trough, indicating that these two systems were operating at the same time. The absence of iceberg ploughmarks in the troughs and the presence of grounding-zone wedges suggest rapid to episodic retreat of the glaciers following the southward migration of the Filchner Ice Stream. Subsequent retreat was then marked by periods of grounding-line stability and the formation of the grounding-zone wedges followed by lift-off and unstable retreat of glaciers or ice shelves on reverse-bed slopes devoid of pinning points.

Meltwater features on the western Antarctic continental margin: observations and modelling

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Geomorphic features thought to be related to subglacial meltwater erosion and (or) release have long been known from the western Antarctic continental margin. These features take on a variety of forms that range in scale from small, straight, cross-cutting channel segments and crescentic scours around drumlinised bedforms to huge, anastomosing channel systems, both typically incised in to bedrock in inner-shelf settings. Although it is widely accepted that the largest of these features likely formed over multiple glaciations of the Antarctic shelf, possibly in relation to large outburst events (cf. Nitsche et al., 2014), questions still remain regarding the exact timing of their formation and the sources of meltwater in an environment where the only sources of water are frictional heating and melting due to geothermal heat from below.

In this poster we show examples from the continental shelf offshore West Antarctica and the western Antarctic Peninsula to document morphological and size variations in these erosional features and to consider questions related to their mode of formation. We present high-resolution multibeam-bathymetric data from both Anvers Trough and Marguerite Trough, and seafloor photos and sediment-cores and from a large channel system in Marguerite Trough, the latter suggesting that the channels did not contain flowing meltwater during the Last Glacial Maximum (LGM) or at least since the last time grounded ice occupied the trough. Driven by the questions remaining regarding these enigmatic features we are also modelling basal meltwater generation and flow through the Marguerite Trough catchment area for two time slices since the LGM, 20 ka and 14 ka, using a modelled Antarctic Ice Sheet and the bathymetric data as inputs. The aim of this modelling is to determine how much meltwater can be generated in the Marguerite Trough catchment area, and how long it might take to pool enough water in inland areas in order to deliver the flow rates necessary to erode the huge channels following an outburst event.

Repeated advance and retreat of the East Antarctic Ice Sheet on the continental shelf during the early Pliocene warm period

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IODP Site U1358, located on the Antarctic continental shelf off the Adélie Coast, receives drainage from the East Antarctic Ice Sheet (EAIS) through the Wilkes Subglacial Basin. Diatom analysis of a sediment core recovered at site U1358 indicated that the lower section of the core contained an assemblage dating back to the Thalassiosira innura Zone of the lower Pliocene that ranges from 4.2 to 5.12 Ma. Based on lithological descriptions at both a macro- and micro-scale, four facies were interpreted from the diamictons representing the progressive advance and retreat of the grounding line over the site. Subglacial and grounding line proximal facies contain a distinct directional signal from the orientation of the a-axis of clasts with several phases of fabric development along with both brittle and ductile deformation features that are common in sediments that have been subglacially deformed. Grounding line distal to open marine facies are finely laminated. The four facies within the depositional model provide for the first time direct evidence for ice advancing across the shelf adjacent to the Wilkes Subglacial Basin on at least four occasions separated by three periods of open marine conditions indicating retreat of grounded ice inland of the site during a warmer than present early Pliocene. This has significant implications because firstly it suggests a dynamic EAIS that is probably far more sensitive to climatic and oceanic forcing even during relatively short time periods than had previously been thought. Secondly it suggests that proxies used to interpret the advance and retreat of the grounding line from the rise can be linked with direct evidence of grounding line migration from the shelf. Together with results from the rise, this study provides a crucial ice extent target for new ice sheet models of this region during the Pliocene.

Deglacial history of the Anvers Palaeo-Ice Stream Trough, western Antarctic Peninsula

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To predict the future behaviour of polar ice sheets in a warming world, it is important to understand how ice sheets and ice streams respond to changes in climate and sea level. By reconstructing the cause and style of ice stream retreat following the Last Glacial Maximum (LGM; ca. 23-19 ka BP), we can gain a greater insight into the future dynamics of modern day ice sheets. It is possible to achieve such reconstructions by investigating sedimentary sequences deposited during the LGM and the subsequent deglaciation on polar continental shelves. This project focuses on the deglacial history of the Anvers Palaeo-Ice Stream Trough, western Antarctic Peninsula shelf. A network of 23 sediment cores, collected along two transects, will allow us to constrain the style (i.e., fast, stepwise or slow) and rate of retreat of the Anvers Palaeo-Ice Stream from the outer to the inner shelf and the spatial variability of retreat along and across the trough. Sediment types deposited during ice stream retreat are difficult to interpret and, as a consequence, the reconstruction of the processes that led to their deposition is often challenging. This is due to the complex and highly variable processes occurring proximal to the grounding line of ice streams. This project will utilise a multi-proxy approach to refine the distinction between subglacial and glaciomarine facies and between seasonally open marine and sub-ice shelf facies. Preliminary results based on lithological investigations and measurements of physical properties suggest that the cores under investigation retrieved sediments deposited during the LGM, the subsequent deglaciation and under post-glacial, seasonally open-marine conditions. Sediment facies will be classified using a variety of data sets, including physical properties, geochemical parameters and micropalaeontological information. Radiocarbon ages obtained from calcareous microfossils and the acid-insoluble fraction of organic matter (AIO) will provide a chronological framework for the deposition of the identified facies types. The reconstruction of past changes in primary productivity, inferred from total organic and inorganic carbon and biogenic opal measurements, will enable an understanding of the depositional setting and environmental change at the time of ice stream retreat. Achieving these goals will ultimately help to test and improve ice-sheet models aiming to predict the future dynamics of ice sheets and resulting global sea-level change.

Continental slope records indicate a grounded ice sheet margin during past glacials, South Shetland Trench, Antarctica.

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The South Shetland Trench (SST) is located around 100 km northwest, and parallel to, the South Shetland Islands, located between the Antarctic Peninsula and South America. Although a number of studies examining glacial history have been undertaken in the Bransfield Strait located between the South Shetland Islands and the Antarctic Peninsula to the south, the authors believe this is the first study of the seafloor glacial geomorphology, and recent glacial history of the SST. This paper presents the results from a Eurofleets2 expedition to the SST that took place in December 2015.

There is evidence from other sub-Antarctic islands such as the South Orkney Islands and Elephant Island for glaciations that extended well onto their continental shelves although a lack of age constraint from marine cores means it cannot be tied to a specific glaciation
Multibeam echosounder data reveal the study area on the southern flank of the South Shetland Trench to host a system of linear downslope gullies and glacigenic debris flows. Downslope gullies have been observed on other glaciated margins such as the Scotian slope offshore Canada, Ross Sea Antarctica, north-western Barents Sea and West Shetland Margin offshore north-western UK. The gullies are inferred as being eroded by turbidity currents comprising cold, dense, sediment-rich meltwater released from an ice front located at or near the continental shelf break. Glacigenic debris flows are found to extend from the continental shelf break to the lower continental slope. Sub-bottom profiler data penetrated up to 150ms below seafloor in places and reveal a stacked sequence of debris flows suggestive of a fluctuating ice front that was grounded to, and retreated from, the shelf break on several occasions. The trench floor appears to be devoid of major geomorphological features as revealed by the multibeam echosounder data and comprise a relatively well layered sequence imaged by the sub-bottom profiler.

In addition 3 gravity cores up to 2.79 m in length and one core catcher sample were recovered from the study area. The cores will be analysed on their return to the UK and combined with the acoustic data to produce a shallow geological model specifically looking at the fluctuating ice margin located north of the South Shetland Islands.

Timing of methane release on the Norwegian margin after the Last Glacial Maximum

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Marine methane hydrates stored beneath grounded ice sheets on glaciated continental margins are susceptible to sudden dissociation if the ice retreats. The impact of hydrate dissociation events on global climate is controlled by the rate and water depth at which methane is released into the ocean. Methane fluxes from the geological record are difficult to quantify but U-Th dating of methane-derived authigenic carbonates (MDAC), which form in the shallow subsurface as a consequence of anaerobic methane oxidation, provides constraints on the timing and duration of past emissions.

The Norwegian margin, covered by the grounded Scandinavian Ice Sheet (SIS) during the Last Glacial Maximum, is a prime example of a regional hydrate system controlled by ice sheet dynamics. MDAC samples, documenting methane release after the collapse of the SIS, were recovered from five localities in the Norwegian and Barents seas, at water depths between 220 and 400 m (Crémière et al., 2016). Samples exhibited a range of mineralogical compositions and contexts: from carbonate-cemented silt, sand, and gravel, to cavities lined with relatively pure (>90%) late-stage aragonite. Microdrilled 2-40 mg carbonate samples were analyzed in tandem with carbonate-free sediment samples, with the latter used to establish the U-Th systematics of detrital material incorporated into the MDAC. 59 U-Th dates were obtained, mainly from cavity-filling late stage aragonite, providing minimum ages for the onset of methane emissions at each locality.

U-Th dates cluster between 17 and 7 ka indicating: (1) regional control of the main crust-forming methane release episode, which post-dates the deglaciation of the southwest Barents Sea at ca, 18–16 ka (Winsborrow et al., 2010); and (2) continuing methane efflux along the ice-free northern Norwegian margin for ca. 10 kyr. Post-SIS collapse, methane release was controlled by rising bottom water temperatures and rising relative sea-levels, with fluid pathway availability modulated by regional fault system re-activation through isostatic rebound. Consequently, although ice retreat along the Norwegian margin was fast (ca. 2 kyr) the protracted nature of the resulting methane emissions limited the impact of hydrate dissociation on greenhouse gas concentrations.

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Understanding Late Cenozoic glaciation and basin processes: implications for offshore CO_2 storage (North Sea). International Ocean Discovery Program (IODP) proposal #852-CPP.

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The North Sea Basin (NSB) has been suggested as a potential site for CO_2 storage [1,2,3], due to its favourable geological setting, its proximity to sources, and pioneering operational experience storing CO_2 at the Sleipner injection site [4,5]. The shallow Neogene and Quaternary sediments of the NSB form the overburden and seal to these underlying CO_2 reservoirs but are under-researched, even though the NSB is a mature petroleum system, penetrated by hundreds of wells. The up-to 1000 metre-thick Quaternary sediments are in general bypassed to reach the deeper, profitable hydrocarbon resources.
Over the last 2.6 Ma the NSB has been subject to repeated cycles of glaciation and deglaciation [6]. These Quaternary sediments have typically experienced rapid ice loading and unloading affecting the mechanical properties of the strata, fluid conductivity, and the effects of glacial erosion and deposition (e.g. incision by sub-glacial tunnel valleys). It is necessary to understand sedimentary architecture, compaction, cementation, and the role of connate fluids and microbial processes for CO_2 site characterisation. This increases confidence in secure containment of injected fluids.

The GlaciStore consortium comprises scientific, governmental and industrial partners formed with the purpose of submitting a proposal to the IODP addressing the following questions:

- Explore Earth's climate history over the last 2.6 Ma in an area where the most complete sequence is preserved.
- Better understand the geometry, dynamics, processes and wider impact of ice sheet development in the NSB.
- Understand fluid flow and its evolution (dissolved gases, salts and isotopes) during a period of fluctuating pressure conditions in shale-dominated basins and its implications for CO_2 storage.
- Understand the impact on the geomechanical properties of containment barriers (<1000 metres below sea floor) caused by cycles of glacial loading and unloading.
- Explore variations in microbial community within these shallow sedimentary sequences.

In this paper we will summarise the detailed analysis and selection process forming the basis for drill site selections.

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Were the Trænadjupet and Nyk Slides multi-staged?

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Submarine landslides originating from active and extinct trough mouth fans are some of the largest single mass movements evident on Earth. These landslides are capable of damaging offshore infrastructure and can also trigger far-reaching tsunamis. For these reasons understanding the timing, dynamics, and triggering mechanisms of large submarine landslides is important for regional geohazard assessment. The Trænadjupet Slide occurred 4,000 ca. years ago and originated from the Trænadjupet paleo-ice stream on the Central Norwegian margin. The Trænadjupet Slide partially buried the deposits of a previous slide originating from the same section of the Norwegian margin; the Nyk Slide, which occurred at 16,000 ca years ago. Although the Trænadjupet Slide had an estimated volume of 900 km3 and originated from a shallow water depth, it does not appear to have triggered a tsunami. This is in contrast to the comparably-sized Storegga Slide, which produced a tsunami that devastated coastal areas as far away as Scotland. The apparent absence of a tsunami suggests that the failure dynamics for the Trænadjupet slide were different to that of other large slides along the Norwegian Margin. The deposits of both the Trænadjupet and Nyk Slides consist of several blocky lobes extending out into the Lofoten Basin. The lobate morphology of the deposits may imply that both slides occurred in a number of different and possibly temporally-disparate stages. Importantly, multi-staged failures have a much lower tsunamigenic potential due to the lower initial volume displacement. These staggered failures consisting of smaller sediment volumes might explain why no contemporaneous onshore tsunami deposits are found on nearby coastlines, particularly in the case of the post-glacial Trænadjupet Slide. Here we present a new sediment core dataset collected from the previously un-sampled lobes of the Trænadjupet and Nyk Slides. These cores will help us better characterise the deposit types and facies associated with these landslides. We also present a suite of new AMS radiocarbon dates from each lobe to test the hypothesis that the slides occurred in multiple stages. Understanding landslide rheology and identifying multi-staged behaviour is important for both tsunami propagation modelling and future landslide risk assessment in the North Atlantic.

Lateral shear-moraines and marginal-moraines at the margins of palaeo-ice streams

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Significant sedimentary depocentres, termed ice-stream lateral moraines (ISLMs), can build up at the lateral margins of ice streams. A number of theories have been proposed for the formation of ISLMs; however, these theories are based on a relatively limited number of observations of these landforms in the geological record. An understanding of the nature of sedimentation at ice-stream lateral margins is important in reconstructing the dynamics of former ice sheets and modelling the mechanisms by which sediment is transported beneath contemporary ice streams.

We present an inventory of ISLMs that is compiled from available accounts of satellite and aerial imagery from the terrestrial environment, and bathymetric and shallow-acoustic data from formerly-glaciated continental shelves. Two-dimensional marine seismic-reflection data and OLEX and MAREANO bathymetry (http://www.mareano.no/en/maps/mareano_en.html) are also used to identify previously unreported ISLMs on the continental shelves of Greenland, Svalbard and Norway.

The locations of 70 ISLMs are presented, alongside a synthesis of their dimensions, geometry and acoustic character. Two different types of ISLMs are identified. Type 1 ISLMs maintain a constant width, thickness and cross-sectional shape along their length. They are up to 3.5 km wide and 60 m thick. Type 1 ISLMs are interpreted as ice-stream lateral *shear-moraines* that form subglacially in the shear zone between ice streams and slower-flowing regions of the ice sheet. In contrast, Type 2 ISLMs exhibit an increase in width and thickness along their length and their distal slopes become steeper in a seaward direction. They are up to 50 km wide and 300 m thick, and they are only identified close to the shelf break in the marine environment. Type 2 ISLMs contain internal dipping reflections that indicate sediment progradation away from the former ice stream. The identification of multiple downlap surfaces suggests that some of these landforms are composite features that built up over a number of successive ice-stream advances. Type 2 ISLMs are interpreted as ice-stream lateral *marginal-moraine*s that were formed at the outer-shelf lateral boundary between marine-terminating ice streams and terrain that was free of grounded ice at the time of lateral-moraine formation.

We suggest that it is possible to differentiate between ice-stream lateral shear-moraines and marginal-moraines in the geological record. This distinction is important for making inferences about the glaciological conditions that existed beyond the lateral ice-stream margin at the time of lateral-moraine formation and for understanding the mechanisms of sediment transfer beneath fast-flowing ice streams.

What controls the eastern sector of the British and Irish Icesheet?

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One of the more intriguing elements of the deglacial sequence of the British and Irish Icesheet is the appearance late on within the overall retreat of ice advances of the eastern sector. It is at this point (~19-17 ka) that ice extend up to 400 km south and maximal limits on the coast of Norfolk are thought to have been attained. Coupled with this, at least two tills are widely recognised on the Yorkshire coast indicating more than one ice fluctuation. Recent work (Bateman et al 2015) has shown a highly dynamic ice lobe in the eastern sector of the BIIS. This data combined with new data from the BRITICE-CHRONO project is used to evaluate whether the ice dynamics of this part of the BIIS can be correlated with large-scale climatic drivers or reflects other factors such as internal icesheet reorganisation, changes in sub-strate and/or interplay of ice lobes.

Bateman, M.D.[1*], Evans D.J,A.[2], Buckland, P.C.[3], Connell E.R.[4], Friend, R.J.[5], Hartmann D.[1], Moxon, H.[1], , Fairburn W.A.[1], Panagiotakopulu, E.[5],and Ashurst, R.A.[1]. (2015). Last Glacial dynamics of the Vale of York and North Sea Lobes of the British and Irish Ice Sheet. *Proceedings of the Geologist's Association* (in press).

Provenance investigations on the pre-glacial and the Elsterian tunnel valley deposits from the Dutch North Sea – new evidences on the glaciogenic origin of the TV infill

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This study aims to improve the comprehension of the origin and deposition history of the clinoforms-filled tunnel valleys (TV) in the Southern North Sea (SNS). The research is based on the compositional and geo-, thermo-chronological analyses of Early Pleistocene to post-Elsterian sediments recovered from the borehole K14-12, in the Dutch offshore. Methodology encompassed K-Ar dating of illite, QEMSCAN® heavy mineral identification as well as U-Pb and fission track dating on apatite grains. The integrated analytical approach used herein enabled identification and differentiation among the principal Quaternary drainage systems that substantially influenced the area of Southern North Sea along with the quantification of their influence on the TV sedimentary infill. The main portion of TV sedimentary succession is characterized by the presence of Scandinavia derived debris. The absence of an active drainage system from northeast Europe in Middle Pleistocene times suggests the majority of the succession is composed by the locally reworked Early Pleistocene deposits that accumulated in the Dutch offshore before the onset of the large-scale Middle Pleistocene glaciations. The meltwater flow transported and deposited the glacially eroded sediments at the retreating ice-sheet margin, during the formation of the glacial incision. The present results, coupled with detailed seismic-stratigraphic analysis of the TV sedimentary filling, clearly demonstrated a glaciogenic origin of analysed sediments and do not support its southern origin in post-glacial times from Europe-derived fluvial systems.

The retreat pattern of the Late Devensian ice sheet on the UK continental margin west of Shetland.

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The continental margin in the region west of Shetland forms a good example of a passive glaciated margin from a temperate latitude. During the Late Pleistocene, the continental shelf was subjected to repeated and extensive ice sheet advances which reached as far as the shelf edge. The ice transported large volumes of sediment to the shelf edge, where it was subsequently re-worked into glacigenic debris flows on the continental slope, and deposited a thin veneer of sediment across the shelf during the retreat phases.

A combination of geophysical, borehole core and published research data indicate that the retreat of the Late Devensian ice sheet, from the shelf edge to the inner shelf, was a complex process governed by factors such as water depth, seabed topography, bedrock type and provenance of the ice. The maximum extent of ice advance is marked by a series of terminal moraines and grounding line fans. Well developed concentrations of glacigenic debris flows on the upper and lower continental slope mark the probable outlets of former ice streams at the shelf edge.

A series of recessional moraines, identified from British Geological Survey seismic data, are interpreted as marking annual retreat phases and were buried by later deposition. The moraine banks and interbank zones show an internal structure which closely resemble theoretical models. Crest-to-crest measurements of these features indicate retreat rates of approximately 560m/year on the outer shelf, increasing to 800m/year as the ice retreated to the middle shelf.
A more restricted set of moraines are exposed at the seabed on the outer shelf to the northeast. These show similar crest-to-crest measurements of 550m - 600m.

Evidence of the ice retreat to the inner shelf is very limited and was largely removed by a late phase of re-advance. This appears to have been a series of lobate surges, which resulted in a series of large moraines up to 60 m thick and which reworked the underlying glacigenic sediments. The location and morphology of the moraines indicate that the ice may have become pinned on an extensive area of Precambrian gneiss on the inner shelf which was only overcome by ice driving from the east and by increased buoyancy through rising sea levels.

Late Glacial lake levels in the Vale of Pickering, Yorkshire UK – implications for the dynamics of the Last British-Irish Sheet in eastern England.

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During the Late Devensian, the Vale of Pickering to the west of Scarborough, Yorkshire is thought to have been the site of a large proglacial lake dammed by the North Sea Ice lobe of the British and Irish Ice sheet to the east (Evans et al., 2016). Based on field evidence, previous workers have suggested that the lake reached various levels between 70 and 30 m O.D. (Kendall, 1902; Edwards, 1978; Foster, 1985). But, controversy remains as to what levels were attained, how ice-damming of the lake occurred and how this evolved temporally and spatially. The evolution of proglacial Lake Pickering has implications for the whole eastern sector of the ice sheet and specifically links to internal (e.g. subglacial drainage) and external (e.g. climate change) mechanisms that drive ice sheet behaviour.

To explore the evolution of proglacial Lake Pickering, Digital Terrain Models (DTMs) adjusted for isostatic depression have been used in conjunction with ice limits from the BRITICE map (Clark et al., 2004) to construct a time-series of maximum lake levels that may have occurred within the basin. This work shows that very high lake levels (~69m O.D.) were possible provided ice in the Vale of York restricted outflow through the Kirkham Gap and ice from the North Sea Ice Lobe blocked the eastern end of the vale. Once the Vale of York Ice Lobe had retreated northwards leaving the Kirkham gap ice free (Bateman et al., 2015), Lake Pickering levels would have been limited to around 45 m O.D. Lake levels dropped to approximately 30 m O.D once the North Sea Ice Lobe retreated eastwards, leaving the lake dammed by the Filey moraine. Further work using LiDAR digital terrain imagery, geological mapping and 3D geological modelling seeks to further constrain the evolution of Lake Pickering as well as examine its relationship to the dynamics of the northeast portion of the British Irish Ice Sheet during the last glaciation.

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Seismic stratigraphy and sedimentary signature of Pleistocene glaciations in the western North Sea

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2D seismic profiles and multibeam bathymetry data collected by EGS for NAREC Ltd in the Blyth survey area (off NE Newcastle) provide new insights on the Pleistocene seismic architecture of the western North Sea. The research area is located on the former eastern margin of the British and Irish Ice Sheet (BIIS), which covered the UK, Ireland and the western North Sea multiple times during the Pleistocene, and was drained by numerous ice streams during the Last Glacial Maximum (LGM). Despite recent developments, the maximum extent, ice stream dynamics and nature of retreat of the BIIS are still poorly understood.

This research aims to: (1) provide an assessment of the seismic stratigraphy of the Blyth survey area and (2) link these findings to the wider Pleistocene glacial history of the region.
Six seismic units were identified in the research area and reveal the presence of pre-Quaternary strata overlain by two glacial units (Unit 4 and 5), which have been correlated to the Wee Bankie and St Abbs formations respectively (cf. British Geological Survey published literature). These units, located in the easternmost part of the survey, are 10 – 12 ms thick and are characterized by chaotic internal reflectors and undulatory upper boundaries. The Wee Bankie Formation is correlated to the Bolders Bank Formation to the east and to the Horden Till (mapped onshore in east County Durham). Its deposition is thought to be related to the onshore movement of the North Sea Lobe (NSL) during the Dimlington Stadial. Capping the glacial sequence is the St Abbs Formation; a deglacial glaciomarine unit.

Given that Unit 5 presents similar characteristics to Unit 4, a second scenario would infer Unit 5 to be also a till, deposited at a later stage. A third interpretation suggests that both seismic units could be older than Late Weichselian and could belong to previous Pleistocene glaciations.

Additional research based on 2D seismic profiles and sedimentological data collected during the Britice-Chrono JC123 survey, provides further information on the glacial geophysical and sedimentary signature in the western North Sea. Streamlined, exposed bedrock on the seafloor is overlain in places by distinctive till wedges which infer periodic standstills/re-advances of the NSL as it retreated north westwards parallel with the coast. It is hoped that new OSL/^{14}C dates will provide the first age controls on this late phase oscillatory behaviour of the NSL.

The style and intensity of deformation by the ploughing/scouring action of iceberg keels in diamicton offshore of East Greenland

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Icebergs are important as agents of deposition and reworking on polar and sub-polar continental margins. When the keel of an iceberg exceeds water depth it ploughs through soft sediments gouging out kilometre long ploughmarks, 100s of metres wide and sometimes tens of metres deep. Because the influence of iceberg keels on sediment is a critical factor when offshore structures (e.g. oil/gas pipelines, power cables) are installed, the surface morphology of iceberg scours on the seafloor is relatively well-documented. Less, however, is known about sub-scour deformation below the seafloor, particularly iceberg scoured diamicton (poorly sorted sediment comprising a variety of particle sizes), which is present in many high latitude fjords and continental shelves. The aim of this research is to examine directly (macroscopically and microscopically, through thin sections) the style and intensity of deformation by the scouring action of iceberg keels in diamicton offshore of East Greenland. Results show that a distinctive assemblage of deformation structures, dominated by planar shear (e.g. discrete shears) and sediment mixing (e.g. intraclasts type III and multiple domains), characterises iceberg scoured diamicton. This assemblage is different to the assemblages of structures seen in diamictons deformed by other processes (e.g. subglacial, mass-wasting). In addition, results show that diamicton from areas of high intensity iceberg scouring tends to show a wider variety of deformation structures indicative of high strain than diamicton from areas of intermediate and low intensity iceberg scouring. Characterising the effects of iceberg scour in diamicton is important more widely to inform i) reconstruction of glaciated margins such as ice sheet limits and dynamics (environmental value); and ii) installation and protection of offshore structures (e.g. pipelines) in diamicton where iceberg scouring presents a geohazard risk (economic value).

Palaeo-glaciology of the mid-Norwegian continental shelf through the Quaternary from 3D seismic data

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The mid-Norwegian continental shelf has repeatedly been inundated by the Fennoscandian Ice Sheet (FIS) through the Quaternary. During the Last Glacial Maximum, the FIS was drained by two major ice streams that eroded the mid-Norwegian continental shelf, forming Sklinnadjupet and Trænadjupet cross-shelf troughs. These ice streams acted as conduits for ice discharge from the adjacent sector of FIS. The seismic stratigraphy and architecture of the Trænadjupet-Sklinnadjupet sector of the mid-Norwegian continental margin are nvestigated using exceptionally extensive grids of marine 2D and 3D seismic reflection data that cover more than 30,000 km2 of the continental margin. Dense data coverage enables identification of buried glacigenic landforms and detailed examination of margin architecture and evolution throughout the Quaternary. At least 20 distinct palaeo-surfaces have been interpreted within the stratigraphy of the Quaternary Naust Formation on the mid-Norwegian shelf and slope. Multiple assemblages of buried glacigenic landforms are preserved within the Naust Formation across most of the study area, facilitating detailed palaeo-glaciological reconstructions. Seven surfaces within Naust sequence N (~2.6-1.5 Ma) show evidence of extensive iceberg activity, suggesting relative proximity of a calving ice front to the inner palaeo-shelf. Elongate, streamlined landforms resembling mega-scale glacial lineations (MSGLs) have been found within the Naust sequence A (~1.5-0.8 Ma). This may represent geomorphological evidence for the inception of fast ice-flow on the palaeo-shelf. MSGLs located on the base of palaeo-troughs identified within sequences U (~0.4-0.8 Ma), S (~0.2-0.4 Ma) and T (~0-0.2 Ma) demonstrate the presence of multiple ice streams reaching the palaeo-shelf break. Shifts in the location and direction of features indicative of fast ice-flow suggest that several reorganisations in the FIS draining pattern have occurred since ~1.5 Ma.

The most significant, almost 90 degree flow-switching, occurred during the last, Weichselian glaciation, resulting in the formation of the Trænadjupet cross-shelf trough. Detailed maps of sediment delivery suggest the migration of the depocentre from northeast to southwest, with ~38,000 km3 of sediments being delivered to the mid-Norwegian margin since the beginning of the Quaternary.

Modelling the effect of large submarine landslides on the ocean circulation

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Submarine landslide can be orders of magnitude larger than terrestrial landslide, moving up to thousands of kilometers of sediment. Submarine landslides have been suggested to play an important role in extreme climate events, such as through methane release hydrate-rich sediments, but this is currently uncertain.

The Storegga Slide is the biggest Holocene Slide mapped off the Norwegian Margin, with an estimated volume of 3,000 km^3. The slide failure is coincident with the last major rapid climate excursion, the 8.2k cold event. This presentation investigates potential links between the Storegga Slide and the 8.2k cold event. Our main focus is on the dense mud-cloud generated by release of the landslide, as it mixed with seawater. Previous work suggested that the mud-cloud may have had concentrations as high as 4% volume, and a height of 800m. Here we test the hypothesis that this dense mud-cloud interfered with the meridional overturning circulation and hence affected climate at around 8.2ka.

For this study, a regional Arctic coupled ocean-sea-ice model was set up using the MITgcm general circulation model. The mud cloud was simulated using salinity perturbation as a proxy for the increased density of the water column. Results indicate a strong response from the ocean currents to the perturbation. The dense water mass formed by the perturbation moves northward slowly infilling the Arctic and affecting the whole water column up to the top. The results so far exclude a direct effect of the Storegga Slide on the MOC via a perturbation of the dense water formation in the North Atlantic. However, given the response of the circulation to the perturbation, our results suggest that the Storegga Slide could have played a role in the 8.2k cold event. Ongoing work is assessing the magnitude of the impact of the landslide perturbation on ocean, and whether it tends to weaken or strengthen that circulation.

A Plio-Pleistocene record of glaciation offshore mid-Norway

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During the Plio-Pleistocene, repeated glaciations have acted as the primary control on the evolution of high-latitude continental margins. Whilst the global sea level records changes in total ice volume it provides little information as to where water was stored as ice during eustatic lowstands. The record of ice-rafted detritus (IRD) on the Vøring Plateau provides an insight into the Fennoscandian glacial history and shows that during the Plio-Pleistocene, ice cover grew large enough to reach the coast and beyond on multiple occasions.

Over 30 years of hydrocarbon exploration on the mid-Norwegian shelf has provided a large database of geophysical information from which we can investigate in better detail the glacial history of northwest Europe. When grounded ice retreats from the continental shelf it often leaves behind landform assemblages that can be used to reconstruct the characteristics of the ice sheet. Despite the wealth of seismic data available on the mid-Norwegian shelf, only a relatively small part of the glacial stratigraphy has been investigated and most studies have tended to focus on the most recent glaciations, which are relatively well known.

Here we present the results from an investigation using over 100,000 km^2 of 3D and over 200,000 line kilometres of 2D seismic reflection data from the mid-Norwegian shelf. We develop an archive of glacial landforms found in the seismic data that covers the entire glacial stratigraphy from its initial deposition at ~2.8 Ma, right through to the seafloor assemblage left behind after the Last Glacial Maximum. Landforms such as mega-scale glacial lineations, iceberg scours and grounding-zone wedges are found and described throughout the Naust Formation. This catalogue of landforms is used to develop an understanding of the long-term history of glaciation offshore mid-Norway.

Establishing the indicative meaning of ice-rafted detritus: ice sheet advance, collapse, or both?

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The Irish Sea Ice Stream (ISIS) was the largest ice stream that drained the British Irish Ice Sheet (BIIS) and as a consequence understanding its dynamic behaviour can help refine glaciological models of the BIIS (Patton et al. 2013). The ice stream had a large marine terminating margin with its limit the southernmost extension of the BIIS (Praeg et al. 2015). The ice stream was a major source of Ice Rafted Detritus (IRD) to the deep ocean but it is unclear whether these correlate with retreat or re-advance phases of the ice stream (Scourse et al. 2009). We determine the geochemical signature of proximal ISIS glacimarine sediments and their spatial variability using X-Ray Fluorescence with the aim of correlating these end members to the composition of the IRD flux in an adjacent deep sea core from the Goban Spur (MD04-2820CQ). We present initial results from the XRF analysis of ISIS end member sediments. Principle Component Analysis was used to characterise these end members into groups with similar geochemical composition to trace the source of the IRD flux record in the deep ocean and how this reflects the position of the calving margin of the ice stream.

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Late Pliocene-Pleistocene development of the central northern North Sea

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Based on new geochronological (amino acids and Sr-isotopes) and lithological data combined with analyses of 3D seismic data, the Pliocene-Pleistocene development of the central northern North Sea has been investigated. Close to the Late Pliocene Pleistocene transition the study area was dominated by a deltaic, shallow marine or tidal depositional environment with sediments mainly sourced from the west. These sand-rich sediments include green glauconitic grains that belong to the Utsira Sand with a local provenance. Directly above the Base Quaternary a 290 m thick layer of mud-rich sediments of glacimarine origin were rapidly deposited from the east between 1.68 to 1.18 Ma assumed to reflect glacial ice advancing to the Norwegian coastline. Sometime within 1.56 to 1.18 Ma, subaerial conditions allowed the formation of a >50 km long fluvial channel across the study area draining water from east to the south west. The earliest evidence of grounded ice in the investigated area comes from mega scale glacial lineations formed between 1.37 to 1.18 Ma. The high rate of deposition in the Early Quaternary occurred immediately before the initiation of the Norwegian Channel Ice Stream at ~1.1 Ma. Following this, a large part of the sediment input from Fennoscandia seems to have been directed away from the study area to the shelf break. A large hiatus of ~600 ka represented by a regional unconformity probably formed by grounded ice advancing across the North Sea Basin marks the boundary between the Early and Mid Quaternary. The Mid to Late Quaternary stratigraphy is dominated by glacimarine sediments and tills and is associated with multiple generations of tunnel valleys observed within the seismic data. A ten metre thick sand layer in the study area was deposited by drainage of ice dammed lakes in the southern North Sea during the last deglaciation (MIS2). This study shows that much of the Quaternary age sediments within the northern North Sea were deposited relatively rapidly during short periods of time leaving significant hiatuses within the stratigraphic record. This has implications for previous studies that use a chronological framework assuming a relatively continuous sedimentation rate and record for the Quaternary within the North Sea.

A Late-Glacial sedimentary sequence between Derryoge and Kilkeel, Co. Down, Northern Ireland: origins and wider significance

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This paper re-evaluates the nature and timing of a Late-Glacial ice sheet re-advance in the north western sector of the Irish Sea basin. The sedimentary archive in the region records the collapse of the Irish Sea Ice Stream, a major outlet glacier of the British-Irish Ice Sheet. The region documents the interplay between southerly flowing Scottish ice, ice flowing southeast from Lough Neagh and locally sourced Mournes ice.
We present the results of sedimentological analysis of a glacigenic sequence exposed in a modern cliff section ~3 km long between Derryoge and Kilkeel, Co. Down, Northern Ireland. The interaction between an advancing ice-sheet outlet lobe and rapidly changing sea levels are examined using facies analysis and micromorphology.

The section is composed of four lithofacies associations (LAs). These are, from the base, a laminated, fossiliferous and deformed silt (LA1) at least 4.5 m thick that contains lenses of diamicton and discontinuous rafts of sandy gravel. Marine shells form the axis of a fold hinge, part of a lightly tectonised channel fill within the raft. LA1 is overlain by a sandy diamict (LA2) up to 14 m thick containing mainly local clasts with some of northern provenance. Within LA2 are wide channel structures infilled by laminated clayey silts (LA2b). These form deposits up to 14 m thick and contain small-scale folds, discrete shear zones and ball-and-pillow structures. LA2b forms a lithofacies association with LA2, consisting of a lower subfacies of sheared and deformed silts, overlain by sandy diamicton, capped by a striated boulder pavement. These are interpreted to represent retreat/advance cycles of a marine terminating ice margin. Up to five such cycles are identified. LA2 is widely punctuated by fissures and conduits infilled by loose sands and gravels. These are inferred to be emplaced by subglacial meltwater during the final stages of ice sheet advance. Covering both LA2 and LA2b, LA3 is a unit of glaciofluvial outwash, composed of cross-trough stratified sandy gravels, with flame structures indicative of syn-depositional loading. The entire sequence is capped by loose interbedded sands and gravels (LA4) representing a Late-Glacial raised beach.

Evidence of a marine terminating ice margin provides support for high relative sea levels in the north western sector of the Irish Sea during deglaciation. Forthcoming dates from shells with the rafted subaqueous fan deposits underlying LF2 provide the opportunity to constrain either: a) sea-level rise prior to the onset of Irish Sea Basin glaciation, or, b) Late-Glacial sea level rise following deglaciation of the Irish Sea and prior to the re-advance of local ice masses.

Onshore-offshore correlations on the western margin of the last British-Irish Ice Sheet

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Ice sheets grow and decay in response to climate change and can leave a rich geological record of their former behaviour and extent after retreat. Although the British-Irish Ice Sheet (BIIS) has been investigated for over 100 years, it is only in recent years that we are beginning to unravel the history of the glaciated margin that surrounds Britain and Ireland. For example, recent studies conducted about ice extent show that the western Irish shelf has undergone major glacial advances at least since the earliest Pleistocene. The aim of this study is (1) to investigate the extent and timing of major glaciations and their influence on sedimentary processes on the western Irish continental shelf throughout the Quaternary period and (2) to correlate the onshore and offshore glacial record in western Ireland.
To achieve this a multi-proxy approach is adopted and includes the investigation of marine geophysical data, analysis of glacial material deposited in marine and terrestrial settings, as well as cosmogenic nuclide (CN) and radiocarbon dating. The study area stretches from nearshore to the outer shelf, from west of Donegal Bay (55°N) to the Porcupine Ridge (51°N).

A Cenozoic stratigraphy, with a focus on the Quaternary, was produced from borehole data and a marine geophysical dataset of 69 seismic lines, including airgun, sparker and pinger data of varying vertical resolution. The lithology, radiocarbon dating, and micropalaeontology of sediment cores allowed for the interpretation of depositional processes and palaeoevironmental changes on the shelf. A transition from stiff towards soft diamicton and an increasing planktonic to benthic foraminifera ratio suggest a change from glacial proximal to glacial distal environments. These sediments are overlain by gravel and Holocene marine sand. Some cores were collected on a set of moraines at southern Donegal Bay, representing a glacial re-advance after the last glacial maximum (LGM) ice sheet retreated. Radiocarbon dates should provide a chronology for this re-advance that can be traced back onshore and linked to a northward-flowing ice stream. Age estimates of ice retreat onshore will be obtained through CN analysis of 22 erratics, sampled at key sites around southern and eastern Donegal Bay, and should provide ice landfall chronology for both the LGM ice sheet and the post-LGM re-advance.
This presentation will discuss the main results of this multi-proxy approach and their implications for future detailed reconstructions of the BIIS dynamism during the Quaternary and more specifically during the last glacial period.

Glaciotectonic deformations of Quaternary sediments in the margin zone of Lodz moraine upland

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The poster presents the margin zone of Lodz moraine upland, an area which extends from upper Bzura river stretch from Zgierz town, via Lodz in the direction of Rawa Mazowiecka town. An alternate of wide glacial plain, separated by steep margins, characterizes the relief of this region.

The structural analysis and lithofacies research were conducted in operate exposure located in Celestynów and Kotowice – katarzynowski level of the margin zone. The area of study conveys multiple examples of glaciotectonic structures visible under several centimetres of massive diamicton.

The fold mesostructures, overthrusts, structures from squeezing and also numerous reverse faults are dominant in the researched disturbances. Fine deformational structures of few to several centimetres are represented by the complex of normal faults, minor reverse faults and drag folds. Thus, the structural analysis was compiled in the spherical diagrams with the reconstruction of local ice flow. The examination of local stress poles on the basis of orientations and vergences measurements allowed me to evaluate the main stress directions (glaciotectonic transport).

The obtained results indicate that the origin of glaciotectonic deformation in Celestynów and Kotowice stems from subhorizontal compression. The direction of this compression is oriented from NNE to SSW and from NE to SW. The convergence of the directions of glaciotectonic transport was taken from the analysis of compressive mesostructures and vergences of minor disturbances. Hence, it can be assumed that the origin of high plain step in Celestynów region (katarzynowski level) results from the stagnation of Wartian ice-sheet (Late Saalian) in its recession and brief ice sheet transgression that sheared and deformed glaciomarginal fans.

Glaciotectonic deformations of the Late Saalian ice sheet foreland in the North of Łódź (central Poland)

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The so-called margin zone of Lodz moraine upland with a specific relief represented by four levels descending to the Warsaw – Berlin ice-marginal valley is located to the North of Lodz. Sediments in the particular levels have numerous glaciotectonic structures which have been associated with the Wartanian (Late Saalian) ice sheet transgression (Klatkowa 1972). The ice sheet travelled towards the South in stages. Each time it was moving over the obstacles of sediments stacked up in the foreland shearing and levelling their uppermost sections.

Currently, on the Dąbrówka-Strumiany site located within the second (Stryków) level lithofacial investigation of the sediments have been conducted along with mezostructural analysis of glaciotectonic deformations that were seen in the number of walls of the outcrop. Archive boreholes profiles have been also analysed.

The involvement of the Neogene deposits in the glaciotectonic structures and a small thickness of the Quaternary (5-11 m) represented by glaciofluvial sediments characterizes the side area. However, the thickness of the Quaternary deposits in the nearby boreholes reaches from 50 to 60 meters.

The asymmetric fold of axis from NW to SE observed in the walls of the outcrop along approximately 300 meters was recognized. This structure consist of Neogene carbonaceous sands, silts, carbonaceous clays and also Quaternary sands, gravels and silts. The layers of SE limb descended 65-88° S, whereas NW limb which is gentle fall 14-52° N. Furthermore, in the analysed outcrop the number of secondary Riedel shears, reverse faults, cleavage and system of dense conjugate normal faults occurred.

Local ice flow direction were determined from NW to SE. Moreover, it has been asserted that the transgression of the ice sheet contributed to the process of formation of glaciomarginal fans whose sediments are partly involved in disturbances.

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Mid-Pleistocene thin-skinned glaciotectonic thrusting of the Aberdeen Ground Formation, Central Graben region, central North Sea

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The results of a high-resolution 2D seismic survey of mid-Pleistocene glaciogenic sediments in the Central Graben region of the central North Sea have revealed that they have undergone major glaciotectonic thrusting and folding associated with the repeated southerly advance of a mid-Pleistocene ice sheet. The total observed length of the thrust-stacked section is approximately 5 to 6 km, comprising a series of discrete thrust slices, which range in length from < 300 m to > 700 m. The basal detachment of the thrust complex occurs at a depth of c. 220 m below sea bed within the upper Aberdeen Ground Formation. A thin-skinned glaciotectonic model involving proglacial to ice-marginal glaciotectonic thrusting followed by post-tectonic deposition is proposed. Initial ice advance led to the over-pressurising of groundwater within a laterally extensive sand sheet in the upper Aberdeen Ground Formation, promoting the formation of a major décollement surface at the base of the developing thrust stack. Over-pressurisation of the ground water system is thought to have occurred in response to rapid ice advance, suggesting that the development of large-scale thrust complexes may be associated with surge-type behaviour. The proposed model evidences complex dynamics of mid-Pleistocene ice sheets within the central North Sea.

Late Quaternary retreat of the British-Irish Ice Sheet on the continental shelf offshore of NW Ireland.

Kasper Weilbach, Colm O'Cofaigh, Jerry Lloyd, Sara Benetti, Paul Dunlop and John Howe

Traditional reconstructions of the British-Irish Ice Sheet (BIIS) in North-West Ireland, have predominantly been based on terrestrial evidence, and show an ice sheet that did not extend beyond the present coastline. This reconstruction of a restricted ice sheet has, in recent decades, been replaced by that of a more dynamic and extensive ice sheet, which during the Last Glacial Maximum (LGM) advanced to the NW-Irish shelf edge. Investigating the dynamic history of marine-terminating ice sheets is important for a wider understanding of the role that ocean forcing plays in controlling ice sheet advance and retreat.
Multibeam swath bathymetric and acoustic sub-bottom profiler data supplemented by transects of sediment cores across Donegal Bay and the adjoining NW Irish continental shelf were acquired as part of the Irish National Seabed Survey programme and, more recently, the 2014 Britice-Chrono JC106 cruise. These data were used to identify sediment thicknesses, acoustic facies and landforms. Vibro cores from two east-west transects across the shelf have been used to help understand the timing and nature of retreat of this sector of the BIIS. X-Ray imagery and MSCL scans of the sediment cores have been used along with sedimentological analysis to identify lithofacies associated with the glacial retreat from the shelf. These sediment cores have also been used to ground truth the acoustic facies. Taxonomic analysis of foraminifera from the sediment cores has been used to reconstruct depositional environments. Twenty-one radiocarbon dates from foraminifera and macrofossils sampled from the sediment cores constrain the timing of retreat of the BIIS from the shelf edge to Donegal Bay.

Collectively the data confirm an extensive ice sheet, grounded to the shelf edge at the LGM. Radiocarbon dates and lithofacies indicate that initial retreat across the shelf was rapid and occurred in a glacimarine setting, but was punctuated across the mid-inner shelf by stillstands and minor readvances building a series of arcuate moraines.

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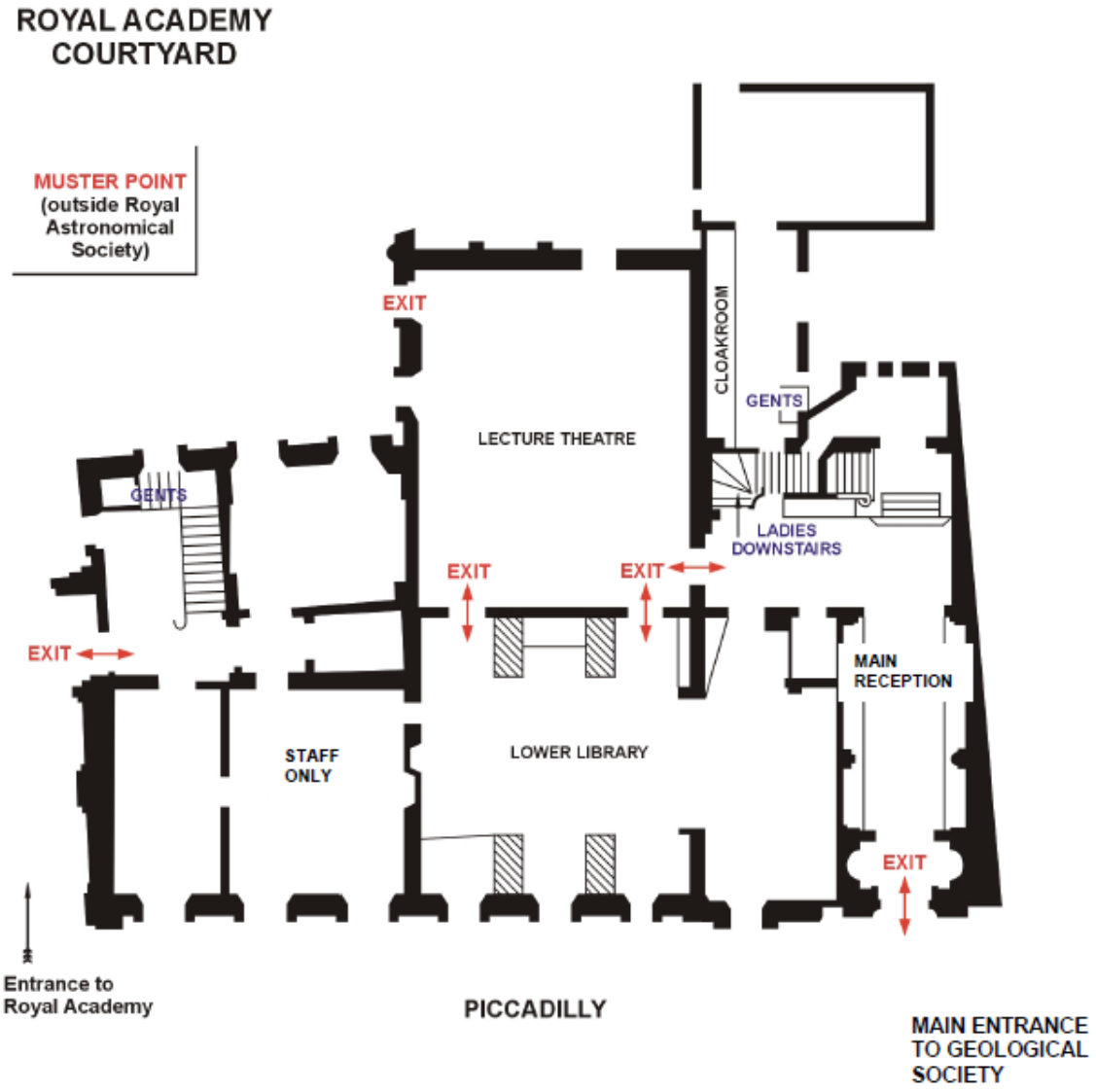
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