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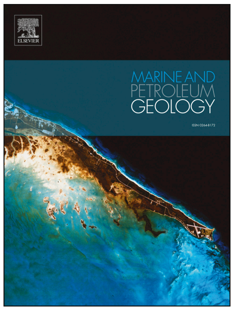

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A conceptual model for glaciogenic reservoirs: from landsystems to reservoir architecture

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Abstract

Glaciogenic sediments are present in many hydrocarbon-producing basins across the globe but their complex nature makes it difficult to characterise the reservoir-quality sedimentary units. Despite this, Ordovician glacial deposits in North Africa, and Carboniferous-Permian glaciogenic sequences in the Middle East, have been proven to host significant, economical, hydrocarbon accumulations. Additionally, discoveries have been made in the shallow (<1000 m below seabed), glacial, Pleistocene sedimentary succession of the North Sea (e.g. Peon and Aviat). This paper provides a predictive exploration framework in the form of a conceptual model of glaciogenic sediment-landform distributions. The model is based on the extensive onshore glacial sedimentary record integrated with available offshore data. It synthesises the published knowledge, drawing heavily on glacial landsystem models, glacial geomorphology and sedimentology of glaciogenic deposits to provide a novel conceptual model allowing for the efficient description and interpretation of glacial sediments and landforms in the subsurface. Subsequently, land-terminating and water-terminating ice sheet depositional systems are described and discussed, with respect to ice advance and retreat cycles. This detailed description focuses on the macro-scale stratigraphic organisation of glacial sediments with relation to the ice margin, aiding the prediction of glaciogenic sediment distributions, and their likely geometry, architecture and connectivity as reservoirs.

1 Introduction

Glacial sediments and landforms have long been studied but, to date, a comprehensive overview of their properties and characteristics from a hydrocarbon reservoir perspective has been lacking. Sediments of glaciogenic origin have been targeted during hydrocarbon exploration and, in some cases, have demonstrated good reservoir properties (e.g. South Oman Salt Basin, Ghadames-Illizi Basin, North Africa, Murzuq Basin in Libya) (e.g. Forbes et al., 2010; Huuse et al., 2012; Klett, 2000). Shallow gas accumulations in the Pleistocene succession of the North Sea, previously viewed as drilling hazards, are now being considered an attractive target for relatively low cost/low risk fuel for infrastructure (Aviat gas field) and, when large enough, for full scale production (Peon discovery)

(Huuse et al., 2012; Ottesen et al., 2012; Rose et al., 2016). Improvements in geophysical methods and analytical techniques over the last two decades resulted in multiple publications describing glaciogenic sequences. Especially worth mentioning are Special Publications and Memoirs from The Geological Society, London including: “Glaciogenic reservoirs and hydrocarbon systems” (Huuse et al., 2012); “Glaciated margins: the sedimentary and geophysical archive” (Le Heron et al., 2019); “Glacier influenced sedimentation on high-latitude continental margins” (Dowdeswell and O'Cofaigh, 2002); “Engineering Geology and Geomorphology of Glaciated and Periglaciated Terrains: Engineering Group Working Party Report” (Griffiths and Martin, 2017); “Atlas of Submarine Glacial Landforms” (Dowdeswell et al., 2016a). From these, and other, publications it is clear that the distribution and nature of glaciogenic sediments is more complex, and less predictable, than more traditional clastic sequences. As a result, glaciogenic packages are less well understood and often underexplored for their reservoir potential than sediments associated with more “typical” depositional environments. Although glaciogenic sediments can be complex, there are some general rules and/or characteristics that can be of use in petroleum exploration.

This paper bridges the gap between the academic and the applied perspective, by providing a framework for investigating the distribution and characteristics of ice sheet sediments and landforms, with a specific focus on their identification in the subsurface and subsequent assessment of their hydrocarbon reservoir potential. While this paper presents some general glaciology as background in the first few sections, it assumes a degree of *a priori* knowledge regarding glacial processes, landforms and sediments and is not focused on detailed descriptions thereof. For such information readers are referred to specialist publications mentioned throughout the text or textbooks (e.g. Glaciers and Glaciation by Benn and Evans (2010)). Here, a conceptual model of glaciogenic deposition relevant to the subsurface and hydrocarbon exploration potential is developed.

2 Glaciations and glacial Processes

Ice sheets are masses of ice larger than 50,000 km^2 (Benn and Evans, 2010). During a single glaciation an ice sheet will typically experience multiple phases of advance and retreat, leaving a highly complex sedimentary record and assemblage of landforms, often referred to as a glacial mosaic (Bennett and Glasser, 2009; Evans et al., 2006). Here, we introduce some key concepts related to glaciation to provide the necessary background to understand ice sheet sediment and landform distribution.

2.1 Timescales of glaciation

The rock record shows that during the last 2.5 billion years, Earth has undergone multiple shifts in climate between periods of relatively high ice cover (icehouse) and periods where glaciers were either missing or present in small isolated pockets (greenhouse) (e.g. Craig et al., 2009; Eyles, 2008, 1993; Le Heron et al., 2009; Strand, 2012). From a geological point of view, the Earth, at present, is in an icehouse which began around 37 Ma ago, during the Late Cenozoic, with the first glaciation of Antarctica (Anderson et al., 2011). Within this icehouse, ice sheets have advanced and retreated many times, but never disappeared completely at a global scale (Eyles, 2008). The Pleistocene (2.58 Ma to 11.5 ka), part of the Late Cenozoic, is the best understood and temporarlly-resolved icehouse period (e.g. Ehlers et al., 2011; Farmer and Cook, 2013). During this time, ice sheets periodically expanded and retreated, following a cyclical orbital climatic forcing that is well-recorded in benthic foraminifera oxygen isotope ratios ($\delta^{18}O$) (Figure 1), recovered from marine sediments (Lisiecki and Raymo 2005). Lower $\delta^{18}O$ is linked to warmer periods and interglacials (i.e. marine isotope stage odd numbers), while higher $\delta^{18}O$ indicates colder periods and glacials (i.e. even-numbered marine isotope stage) (Figure 1). Glacial – interglacial changes are attributed mainly to cyclical Milankovitch orbital forcing (100 ka eccentricity cycles, 41 ka obliquity cycles and 21 ka precession cycles) (Eyles, 1993). Pleistocene glaciations are further subdivided into relatively colder (stadials) and warmer (interstadials) periods, where ice sheets advance and retreat. They are forced by internal dynamics within the coupled Earth climate systems (Bradley, 2015; Lisiecki and Raymo, 2005; Spratt and Lisiecki, 2016).

2.2 Ice motion, glacial erosion, transport and deposition

Ice moves from the ice sheet interior (ice divide) outwards, towards the ice margin via three possible mechanisms: internal deformation, basal sliding and subglacial deformation of the underlying bed (sediments) (Benn and Evans, 2010). The prevailing mechanism depends on the thermal regime at the ice-bed interface, the type of bed and presence or absence of meltwater (Benn and Evans, 2010).

The thermal regime of an idealised circular ice sheet, at a given time, can be described in a tripartite subdivision (Boulton, 1996; Jamieson et al., 2008). Cold based (frozen to the bed) and slow moving, via internal deformation, in the ice sheet centre proximal to the ice divide. A transition zone (polythermal zone), where fast-flowing corridors of ice, known as ice streams, are initiated. Towards the margin the thermal regime is warm-based (ice is at the pressure melting point) with lubricating water at the ice-bed interface. This tripartite zonation is transgressive during ice advances, and regressive during ice retreat, and the rate of change is dependent on the climate forcing mechanisms and internal ice dynamics (Benn and Evans, 2010). When ice accumulation outpaces ablation, ice masses expand and advance. When the opposite is true, the ice margin steps back as ice masses shrink and retreat.

Basal sliding and/or subglacial deformation causes areas of bedrock and pre-existing sediments to be eroded. Rock fragments and/or sediments are then incorporated into the basal ice and/or advected in a layer coupled to the ice sheet bed, ultimately being transported towards the ice sheet margin (Evans et al., 2006; Powell and Cooper, 2002). At some point down flow, more sediments are melted out from the ice than are eroded/incorporated into the ice, due to meltout and increased friction at the ice/bed interface. As a result, the environment becomes dominated by depositional rather than erosional processes (Evans et al., 2006; Spagnolo et al., 2016). Some of the sediment is transported inside (englacially), or on top of (supraglacially) the ice and melts out directly at the ice margin. Other sediment may be transported by subglacial meltwater, which drains the bed of the ice sheet (Kleman et al., 2008; Krüger et al., 2009; Lønne, 1995; Thomas and Chiverrell, 2006). Glaciofluvial (meltwater) sediments may be deposited in subglacial and englacial meltwater conduits (Burke et al., 2015; Storrar et al., 2014) or beyond the ice margin as ice marginal or proglacial sediments (Glückert, 1986; Zielinski and Van Loon, 2003; Zieliński and van Loon, 1998).

2.3 Glacial isostatic adjustment, eustatic and relative sea levels

Sea level changes are one of the major controls on the sediment distribution within most sedimentary basins (Emery et al., 1996) and sedimentary systems typically respond to sea-level changes. Ice sheets have a unique ability to change sea-level, both on local and global scales. There are three major mechanisms by which ice sheets affect sea level fluctuations (Figure 2) (Lambeck, 1998; Milne et al., 2009; Peltier, 2002):

1. Ice sheets store vast amounts of water causing the eustatic sea level to fall during ice sheet growth and rise during retreat when the stored water is released, via melting and iceberg calving.
2. The weight of an ice sheet causes an isostatic depression of the pre-existing topography resulting in a relative sea level rise in the vicinity of an ice sheet and a sea level fall where the forebulge is present in front of the ice sheet.
3. The ice sheet mass locally perturbs the geoid and therefore affects the equipotential surface of the ocean. As a result, the ocean surface rises proximal to the ice sheet.

Eustatic sea level rise and fall is most pronounced (Milne et al., 2009) when associated with both ice sheet growth (glacials) and decay (interglacials), while lower amplitude oscillations of global and local sea level may occur across stadials and interstadials (Spratt and Lisiecki, 2016).

2.4 Accommodation, and sediment supply

It is generally accepted that accommodation is essential for preservation of a sedimentary sequence in the rock record (Jervey, 1988). Sedimentary basins provide this, and are affected, variously, by an interplay between eustatic sea level and subsidence rate (Catuneanu, 2002; Catuneanu et al., 2011). This relationship only partially holds in glacially-affected regions (Zecchin et al., 2015). Sedimentary basins influenced by ice sheets may be intermittently (during a glaciation) affected by anomalously high sediment fluxes resulting in rapid (in geological time scale) basin filling and increased subsidence rates due to both sediment and ice loading, in comparison to other non-glacial depositional environments (Eyles et al., 1993; Eyles, 1993). Moreover, sediment transport directions and input points in glacially-affected sedimentary basins will change substantially over hundreds to thousands of years as a response to ice advance and retreat (Nielsen and Rasmussen, 2018). The efficacy with which ice and meltwaters erode, transport and deposit sediments in a basin will most likely overprint other contemporary changes, including short wavelength sea level oscillations and changes in fluvial input into the basin (Lawson, 1981).

3 Glacial landsystems

Glacial processes described in the previous section ultimately exert a controlling influence on the distribution of glaciogenic sediments and landforms. A systematic approach to glacial landform-sediment associations exists in the form of glacial landsystems (Benn and Evans, 2010; Evans, 2006). To date, the application of the landsystems approach has mainly focused on qualitative landscape characterisation (Evans, 2006) to develop landform-process associations in order to reconstruct the dynamics of palaeoglaciations (Davies et al., 2013; Evans, 2006; Ingólfsson et al., 2016). A key benefit of the landsystems methodology, from an exploration perspective, is the ability to divide depositional environments into zones, with associated landforms and sediment types.

Ice sheet landsystems, which are the primary focus of this paper, describe processes, landforms and sediments associated with continental scale ice masses. Modern analogues are the Antarctic and Greenland Ice Sheets, although it must be stressed that these do not represent the full suite of ice sheet landsystems that occur in the geological record. Specifically, they cannot act as analogues of continental scale ice sheets that covered present day epicontinental seas (North Sea, Baltic), large terrestrial terminating margins (e.g. Fennoscandian Ice Sheet (FIS), Laurentide Ice Sheet (LIS)) or ice streams extending to the continental shelf edge (Margold et al., 2015; Patton et al., 2016; Rea et al., 2018; Velichko et al., 1997).

Multiple landsystem models have been constructed (Evans, 2006), but the majority are limited to surficial, short timeframe/snapshots, characterising a depositional system in a certain state, rather than its full evolution over space and time (i.e. the landsystem observed at the earth surface and the associated stratigraphy below, be it terrestrial or marine). It is important to note that a landsystem can be described at different scales. For example, a fjord landsystem can be part of a bigger, subaqueous landsystem when an ice sheet enters a water body. The landsystem models developed from the investigation of relatively recent glacier dynamics, are of limited use when multiple, stacked, deposits from glacial-interglacial cycles are analysed. When investigating ancient glaciations from outcrops, well data or seismic surveys, it may be impossible to define a landsystem in the way contemporary glacial landsystems are described. This is due to data limitations combined with the complicating effects of post depositional reworking, compaction and diagenesis, varying ice sheet thermal regimes and geometries and even transitions from submarine to terrestrial environments.

Sequence stratigraphy and the concept of system tracts is of practical use when interpreting glaciogenic deposits (Boulton, 1990; Catuneanu, 2006; Lee, 2017; Pedersen, 2012; Powell and Cooper, 2002; Zecchin et al., 2015). Unlike in traditional sequence stratigraphy, accommodation is not linked to relative sea level changes. Instead it is the ice margin position that exerts the primary control on accommodation and on mode of deposition (Boulton, 1990; Zecchin et al., 2015). In such scenarios ice advance and retreat controls marine regression and transgression. The picture is complicated further by glacial isostatic adjustment, forebulge collapse and eustatic sea level changes, all of which have an effect on the final sedimentary assemblage (Powell and Cooper, 2002; Zecchin et al., 2015). Finally, the erosional nature of glacial processes results in multiple, stacked glacial erosional surfaces (known as GES) leading to difficulties in correlating glaciogenic packages based on their stratigraphic relationships - the concept upon which the classical sequence is built (Catuneanu et al., 2009; Lee, 2017; Van Wagoner et al., 1988). High lateral variability of deposition requires an integrated interpretation approach utilizing high resolution, preferably 3D, seismic data and wells (Zecchin et al., 2015).

4 Glaciogenic Deposition

Glaciogenic sedimentary sequences, whether ancient or contemporary, can be summarized using the following key characteristics:

1. High flux and rapid deposition of sediments (decadal to millennial time scales) (Bellwald et al., 2019; Ottesen et al., 2012).
2. Multiple erosional and depositional episodes, and frequent post-depositional reworking of sediments (e.g. Boulton, 1979; Hodgson et al., 2014; Kleman et al., 2008).

3. Abrupt changes from subaqueous to subaerial conditions and sharp facies contacts (decadal to millennial time scales) (e.g. Lamb et al., 2017; Thomas and Chiverrell, 2006).
4. Uneven distribution of glacial sediments through a glaciated terrain (e.g. Lopez-Gamundi and Buatois, 2010; Marks, 2012; Martin, 1981).
5. distribution of sediments and landforms governed by the position of the ice margin (annual to millennial time scales) (e.g. Ely et al., 2016; Lønne, 1995; Palmu, 1999).
6. High magnitude, extreme events (days to decades) (e.g. lake outburst floods, jökulauhps; Gupta et al., 2017; Maizels, 1997).
7. Presence of large scale landforms/features characteristic of glacial processes only (e.g. Ely et al., 2016; Haavik and Landrø, 2014; Kristensen et al., 2007; Ó Cofaigh et al., 2003).

All of the above elements may complicate evaluations of the reservoir potential of glaciogenic successions and construction of a predictive facies model, when compared to those commonly constructed for marine, fluvial or aeolian successions (e.g. Catuneanu et al., 2011; Kocurek, 1993; Nichols and Fisher, 2007; Zecchin et al., 2015). However, some fundamental classifications are possible and are presented here in a conceptual model to facilitate the interpretation of glacial sediments (and landforms) that might act as oil and gas reservoirs.

5 Glaciogenic Reservoir Distribution – A Conceptual Model

5.1 Model framework

Multiple authors have presented glaciogenic depositional models (e.g. Brodzikowski and Loon, 1991; Eyles et al., 1985; Lønne, 1995), describing in fine detail the distribution of landforms and sediments over a specific area (Boulton, 1972) or related to a specific aspect of glaciogenic sedimentation (e.g. sandar, grounding zones; Pisarska-Jamrozy, 2006; Powell and Alley, 1996).

The conceptual model of glaciogenic landforms and their sediments distribution presented here (Figure 4) builds on these, and an extensive literature review of ancient and Pleistocene-to-contemporary glaciogenic deposits (Tables 2, 3 and 4).

Glaciogenic deposition can be divided into three depositional zones controlled by the ice margin position (1st order control on deposition):

1. Subglacial zone where glacial erosion and deposition is responsible for the formation of a unique landform and sediment assemblage. It can be further subdivided in areas of slow-moving and fast-moving ice.
2. Ice marginal zone, where a mix of subglacial and proglacial processes occur.

3. Proglacial zone, where no direct influence of ice contact on sediment deposition can be seen.

Glaciogenic sedimentation is also affected by, and interacts with, the gross depositional environment in which the ice sheet terminates (2^{nd} order control) i.e. sedimentation in the ice marginal zone of a marine grounded ice sheet will be significantly different to one terminating on land. These depositional environments include:

1. Terrestrial - subaerially exposed land surface (including kettle hole and small proglacial lakes).
2. Large proglacial lacustrine – continental-scale lakes.
3. Shallow marine – from the shore to the shelf break.
4. Deep marine - beyond the shelf break.

Finally, deposition is also controlled by ice sheet dynamics and can be further subdivided into:

1. Deposition during Ice advance when sediment incorporation and advection is dominant, and less meltwater is released.
2. Deposition during Ice retreat when sediment release and meltwater processes are dominant.

The influence of ice dynamics on sediment and landform assemblages is described and discussed in detail below.

5.2 Landforms, sediments and their identification

Glacial landforms and their sediment associations are often described by their surface morphological expression and studied to elucidate the glacial processes responsible for their formation (Hughes et al., 2014; Klages et al., 2016; Phillips et al., 2002). The focus of this paper is on the reservoir potential of glacial sedimentary sequences, so the abundance of landforms and the variations of nomenclature was critically reviewed and re-grouped in our model, based on the potential to be: 1 - preserved in the rock record and 2 - recognized in the subsurface. For example, landforms that have been previously referred to as: grounding line fans (Powell, 1990), turbiditic outwash fans (Hirst, 2012), glaciomarine fans (Lajeunesse and Allard, 2002), subaqueous esker deltas (Thomas, 1984), ice proximal fans (Batchelor and Dowdeswell, 2015), esker-fan complexes (Brennand, 2000); will be described in our model as ice-contact subaqueous fans (Lønne, 1995). In all instances these will be composed of sediments deposited at the ice margin (in the ice-marginal depositional zone in a marine or lacustrine environment - Figure 3 and Figure 4) by channelized meltwater entering a water body (ocean or lake). An alias table (Table 1) providing a synthesis of terms used to describe similar glacial features, landforms and sediments from the published literature is provided to simplify the terminology and enable easier use of Figures 3 and 4 (Table 1). A qualitative description of the reservoir potential, based on published literature, wells and outcrop studies, of the landforms and sediments assigned to the model is provided (Table 2, Table 3 Table 4). A traffic light system (green: good/known reservoir; yellow: potential reservoir; red: non-reservoir/seal) is used to indicate the potential reservoir quality. This simple scheme should improve predictability of reservoir quality sediments within the glaciogenic depositional system.

It is crucial to emphasize that our conceptual model is a generalization which aims to represent the majority of glaciogenic deposits found in nature. Therefore, there may be site-specific sediments or landforms that do not conform to the reservoir quality assigned to them.

A systematic description of the major glaciogenic sediments and landforms, and their hydrocarbon potential, with respect to depositional zones (subglacial, ice-marginal and proglacial) followed by depositional environment (terrestrial/lacustrine/shallow marine/deep marine) and subdivided into ice dynamic stages (ice advance and retreat), is now provided.

6 Subglacial zone

The bed in the interior of an ice sheet is generally marked by an erosional unconformity which expands outwards as the ice advances. This is the subglacial erosional zone. Towards the ice margin, under a warm-based ice sheet, the erosional unconformity is overlain by traction till composed of mixed, unsorted material derived from overridden, pre-existing sediments, or eroded bedrock (Table 2) (Clarke, 1987). Such sediments described from the ancient (pre-Quaternary) rock record are sometimes referred to as glacial diamictite. The diamictite category, however, comprises a broad spectrum of sediments with bimodal or polymodal grainsize distributions, deposited by multiple processes (e.g. mass wasting, rainout (dropstones) etc.). All the above processes need to be carefully considered before interpreting diamicton/diamictite as a subglacial traction till or tillite. A broad grainsize spectrum, lack of clear sedimentary structures and alignment of elongated clasts are characteristics of subglacial traction tills (Evans et al., 2006). Micromorphology may also prove useful when trying to distinguish between subglacial till and other similar-looking deposits (Busfield and Le Heron, 2018).

Processes governing the subglacial depositional zone of a marine-terminating ice sheet (Figure 3 and Figure 4) are similar to the subglacial depositional zone of a land terminating ice sheet, resulting in similar landforms and sediments (Table 2, Table 3 and Table 4). A clear morphological division between cross-shelf troughs eroded by ice streams and adjacent inter-ice stream areas is visible in submarine settings (Ó Cofaigh et al., 2003).

6.1.1 Advance stage

Traction till could be deposited widely across the subglacial depositional zone or be confined to specific topographic settings resulting in distinct landforms (e.g. Graham et al., 2009; Hughes et al., 2014). Deposition may occur under the ice to form elongated landforms, although the genesis of some of these is disputed. Amongst such landforms, the most common are (Table 2): drumlins and Mega Scale Glacial Lineations (MSGL) – elongated to extremely elongated features that are usually found in areas of fast-flowing ice streams(Bingham et al., 2017; Clark et al., 2009; Spagnolo et al., 2014; Stokes and Clark, 1999) . These landforms are easy to recognise in the subsurface records because of their distinct shape and spatial arrangement. Well-sorted lenses and thin layers of sands and gravel are often found between thick till sequences where subglacial meltwater flowed at the ice-bed interface. Ice sheets advance and override landforms and deposits associated with either, other sedimentary environments or, a previous stage of glaciation, reinitiating subglacial erosion and deposition. All or part of the sediments deposited earlier will be cannibalized by the advancing ice sheet and redeposited, down flow, as traction till (Table 2) covering older sediment packages (Boulton, 1996). Preservation of pre-existing sedimentary packages largely depends on the depth of glacial erosion (as a function of the duration of ice cover) and/or accommodation generated during and since the previous retreat (e.g. Knutz et al., 2019).

Older, pre-existing bedforms are overridden and streamlined (Benn and Evans, 2010). In marine environments, part of the sedimentary package will be eroded, entrained and transported more distally to be deposited as traction till or released at the ice margin as meltout or carried off as ice rafted debris in icebergs (IRD- Table 3) (Dowdeswell and Fugelli, 2012; Powell and Alley, 1996). Some bedforms may survive overriding if they are sufficiently resistant to subglacial erosion or protective material overlies them (Bellwald et al., 2019). In both cases, they can be only partially eroded or streamlined and are preserved under a traction till carapace acting as a seal for fluid accumulation (Ottesen et al., 2012). Such a mechanism is described for the Peon gas discovery (Ottesen et al., 2012), where a large gas accumulation was found in a Pleistocene subaqueous outwash fan complex (Figure 4 and Table 3). The ice-contact subaqueous fan deposit was subsequently overridden by the fast-flowing Norwegian Channel ice stream which deposited an overlying traction till.

Glaciotectonic deformation (thrusting, folding and fracturing), erosion and streamlining of pre-existing sediments occurs as the ice advances and the subglacial zone expands outwards (Krüger et al., 2009; Phillips et al., 2002). If organic rich sediments are overridden by an advancing ice mass and capped by traction till, they can be biologically (methanogens) or thermally (if burial depth is sufficient) altered to produce gas accumulations (Holmes and Stoker, 2005; Laier et al., 1992).

From a petroleum reservoir perspective, sediments deposited in the subglacial zone during the ice advance mostly have poor reservoir characteristics but may be considered as potential seals (Figure 4) (Bellwald et al., 2018; Clarke, 2018). However, careful evaluation is required when considering traction till as a regional seal. A patchy or discontinuous distribution can hinder its sealing capacity as can lenses of intra-till sand and gravel, deposited by subglacial meltwater drainage (Boulton, 1996). Cross-shelf troughs (ice stream corridors) form elongated sub-basins which will most likely have a distinctive sedimentary assemblage from parts of the shelf covered by a slow-moving ice (Knutz et al., 2019; Ó Cofaigh et al., 2003; Stokes and Clark, 2001). This implies that reservoir properties will vary between the two areas introducing regional scale heterogeneity as more erosion, but also more meltwater derived sedimentation can be expected within the trough. Moreover, erosion of cross-shelf troughs can juxtapose older, underlying sediments with the glaciogenic package and provide fluid migration pathways. Present-day bathymetric data shows that cross shelf-troughs remain largely underfilled following deglaciation (Batchelor and Dowdeswell, 2014; Hodgson et al., 2014; Rüther et al., 2013; Swartz et al., 2015). Anoxic conditions and preservation of organic matter (source rocks) may be facilitated in such settings during the post-glacial marine transgression (Le Heron and Craig, 2012; Lüning et al., 2000).

6.1.2 Retreat stage

During ice retreat the subglacial zone migrates inwards, uncovering sediments and landforms generated during the advance. As the ice sheet retreats, the warm-based subglacial zone migrates in towards the ice divide where previously the ice sheet was cold-based and frozen to its bed. The switch from a cold- to a warm-based thermal regime facilitates initiation of proximal subglacial erosion and distal deposition of traction till (Table 2 and Figure 4). Rising atmospheric temperatures generate melting and runoff, increasing ice and sediment fluxes. As a result, larger volumes of glaciofluvial sediments will be deposited subglacially in meltwater conduits in the form of eskers (Table 2, Figure 4 and Figure 5) - elongated, often curvilinear ridges, comprising silts, sands and granule to boulder-sized gravels (Burke et al., 2015). Otherwise, the processes taking place in the subglacial depositional zone (Figure 4) during retreat are similar to those during the ice advance. Eskers, although having potential to be good reservoirs are rarely continuous and/or large enough to constitute a stand-alone target. Anastomosing (amalgamated) eskers may provide significantly greater reservoir volume and improve connectivity between otherwise discontinuous reservoirs.

7 Ice marginal zone

The ice marginal depositional zone migrates outwards as an ice sheet advances and inwards as it retreats. It is relatively narrow but by far the most dynamic zone, with the most abrupt changes in facies over relatively short distances. An interplay of subglacial and proglacial deposition, glaciotectonic processes, large variations in meltwater energy and ice margin oscillations provide the potential for complex sediment assemblages (e.g. Batchelor and Dowdeswell, 2015; Pedersen, 2014; Vaughan-Hirsch and Phillips, 2017; Zieliński and Van Loon, 1998).

7.1 Terrestrial

Large moraine complexes (Table 2) are deposited where the ice margin stabilises for a sufficient period (e.g. a stadial or glacial maxima), allowing sediments to accumulate in a relatively narrow zone (e.g. Bennett, 2001; Krüger et al., 2009; 2016; Van der Wateren, 1995). Push moraines comprise bulldozed and reworked sub-glacial to proglacial zone sediments and may include glacifluvial outwash, paraglacial and non-glacial sediments (Bennett, 2001). Thrust blocks can also form large moraine complexes, sometimes even in bedrock (Pedersen, 2014; Phillips et al., 2018), but are generally composed of proglacial outwash sands and gravels. Some of the largest examples have a vertical relief of 150 m or more (Benn and Evans, 2010). Their composition may vary greatly along the ice front depending on the available sediments (Bennett, 2001; Huuse and Lykke-Andersen, 2000; Krüger et al., 2009; Le Heron et al., 2005). Moraine ridges may, in places, be dissected by meltwater channels emanating from the ice sheet. Where meltwater exits the ice front through portals, ice-contact fans (Table 2) may be formed (Zieliński and van Loon, 2000, 1999, 1998). They are characterised by proximal cobble to boulder gravels, with sands and silts deposited distally and laterally from the efflux location (Krzyszkowski and Zielinski, 2002).

7.1.1 Advance

During an advance stage, ice-contact fans, moraines and sandar, or parts thereof, will be overridden and at least partially cannibalized by the advancing ice sheet margin. Reservoir properties of land terminating ice marginal deposits mainly depend on the type of sediment available for remobilisation (Figure 4). Thrust-block moraines can have relatively good reservoir properties if composed of proglacial outwash sands and gravels (van der Wateren, 1994; Van der Wateren, 1995). Push moraines will typically exhibit poor reservoir quality as a result of mixing and homogenisation during the bulldozing of the sediments by the ice margin (Phillips et al., 2002; Pisarska-Jamrozy, 2006). Ice-contact fans will have moderate to poor reservoir quality depending on the sediment supply, stability of the ice margin and transport distance of the material (the longer the meltwater transport the better the sorting and reservoir quality) (Zieliński and van Loon, 2000). Meltwater deposited, ice marginal and proglacial sediments will generally be smaller in volume in this phase than their retreat-stage counterparts, due to the lower meltwater discharge during the advance (van der Wateren, 1994).

7.1.2 Retreat

Moraines (Table 2) composed of bulldozed outwash deposits and slope-failure/slump/meltout sediments delineate back-stepping ice margin positions as the ice sheet periodically stabilises/stillstands. Ice-contact fan size (Table 2) is a function of duration of the stillstand, the size of the meltwater portal, subglacial catchment area, meltwater discharge and sediment availability. If an ice-contact lake develops in a topographic low, subaqueous/ice-contact sediments will be deposited. These landforms are described in section 7.2 and in Table 3. Reservoir properties of moraines formed during retreat stillstands (de Geer moraines-Table 3) are poor (Figure 4) because they are predominantly composed of traction till and gravity flow deposits (e.g. Reinardy et al., 2013). During this stage occurrences of better sorted, meltwater-derived sediments increase in volume and spatially coverage. The reservoir potential of ice-contact fans can be highly variable depending upon, the sediment source and other factors (see above) (Zieliński and van Loon, 2000).

7.2 Water terminating

The style of deposition for a marine or freshwater terminating ice sheet largely depends on the water depth in which the ice is grounded (i.e. ice is resting on the bed) (Glückert, 1995; Koch and Isbell, 2013; Visser et al., 2003). If deposition occurs on the continental shelf, sediments delivered to the ice front form a subaqueous analogue of a frontal moraine (Table 3) (Dowdeswell and Fugelli, 2012; Powell, 1990). Most of the sediments are deposited as gravity flows (debrites/turbidites) due to slope instabilities at the ice front generated by a constant supply of water saturated sediments and ice front oscillations. Grounding zone wedges (GZW) (Table 2, figure 4 and figure 6) are deposited in cross-shelf troughs (figure 4) when ice stream grounding lines are stationary for a period of time (Dowdeswell and Fugelli, 2012; Powell, 1990). GZWs are often transparent in subsurface geophysical data (seismic), indicating little or no acoustic impedance (sediment bulk density x sonic velocity) contrast, reflecting glaciotectonic homogenisation of sediments (Dowdeswell and Fugelli, 2012). Their geometries and location in ice stream troughs suggest that glaciofluvial processes may play some role in the formation of GZWs (L. R. Bjarnadóttir et al., 2017; Koch and Isbell, 2013), along with the deposition and reworking of traction till at the grounding line (Table 3).

7.2.1 Advance

Most of the sediments deposited during an ice advance on the continental shelf have relatively low preservation potential. The advancing ice sheet will most likely override and cannibalise ice marginal deposits. Subaqueous ice-contact fans may be relatively well-sorted in comparison to sediments bulldozed, melted out, squeezed and/or lodged by the ice movement (Table 3 and Figure 4). During the ice advance, because of the lower supply of meltwater, the fans are likely to be small, short lived and often overridden and/or eroded. When a fast-moving ice stream reaches the shelf edge, deposition occurs primarily in the form of trough mouth fans (TMF) (Table 3, Figures 4 and 6), which are very large, fan-shaped, debris flow complexes extending from the shelf edge down towards the abyssal plain (Figure 4) (Dowdeswell et al., 2008; Gales et al., 2019; Ó Cofaigh et al., 2003; Vorren and Laberg, 1997). Sediments are deposited by a mixture of mass wasting and glaciofluvial processes. TMFs can extend for up to 200 km down the slope towards the abyssal plain with the proximal thickness of sediments reaching 5 km offshore Alaska (Powell and Molnia, 1989). Numerous examples, including the West Antarctica Belgica Fan (Dowdeswell et al., 2008), North Sea Fan (Nygård et al., 2005; Ó Cofaigh et al., 2003) and the Barents Sea Bjørnøyerenna Fan (Laberg and Dowdeswell, 2016; Vorren and Laberg, 1997), are clearly visible in bathymetry and seismic surveys of formerly glaciated shelf margins.

From a reservoir perspective, large, subaqueous clastic fans are considered as a reservoir target, but this might not apply to TMFs for three main reasons: (1) Most of the sediment is transported to the shelf edge subglacially as a diamicton with limited selective sorting by meltwater; and (2) high sedimentation rates and ice sheet oscillations result in oversteepening of slopes leading to reworking of the material in gravity flows (Table 3); (3) Seismic data shows abundance of uniform or chaotic seismic facies within the TMFs interpreted as landslide sediments which indicates mixing and homogenisation. (Table 3 and Figure 6) (e.g. Bellwald et al., 2019; Olsen et al., 2013; Taylor et al., 2002).

7.2.2 Retreat

Retreat of a grounded ice sheet margin, in response to climate warming involves intensified calving, iceberg production and increased meltwater discharge. Higher basal meltwater pressure at the ice/bed interface will facilitate faster ice flow, especially along ice streams (Benn and Evans, 2010; Boulton et al., 1995), but recent observations from Greenland and arctic Russia suggest that this picture may be more complex (Lane et al., 2014; Lea et al., 2014; Stokes et al., 2007; Zheng et al., 2019) Sediment flux and deposition increases concomitantly as a response to the increase in meltwater discharge.

Where ice is moving more slowly, in the inter-stream areas, morainal banks (ice-marginal moraines-Table 2) usually delineate ice margin positions. They can be composed of older, cannibalised sediments, traction till, well sorted proglacial subaqueous outwash and ice-contact delta deposits (depending on water depth). Thin-skinned thrusting and glaciotectonic deformation (Table 3) of underlying sediment has been reported from the Pleistocene succession in the North Sea and from onshore Denmark and Germany (Vaughan-Hirsch and Phillips, 2017).

Densely spaced recessional moraines defined as sediment ridges delineating positions of short-lived (possibly annual) re-advances during ice retreat (Dowdeswell et al., 2016b; Todd, 2014), are frequently found on the seabed but are unlikely to be identifiable in the subsurface.

Grounding line fans are deposited where meltwater exits a portal across the grounding line and enters a standing water body (Table 3 and Figure 4) (Mackiewicz et al., 1984; Powell and Molnia, 1989). Such fans form important reservoirs in the glaciogenic Ordovician succession in North Africa (Lang et al., 2012; Le Heron et al., 2006). Powell (1990) described a relationship between the size of the meltwater conduit, meltwater discharge, flow type (axi-symmetric or planar) and sediment concentration. Gradual decrease in efflux jet energy (deceleration), distally from the meltwater portal, results in proximal deposition of coarse fractions (boulders and cobbles). Sands and gravels will be deposited along the length of the jet runout. From laboratory experiments it is known that a high pressure jet may deposit most of its sediment load between the grounding line and a distance up to 200 times the conduit diameter, where rapid flow deceleration occurs (Powell, 1990). Laminations in glaciomarine sediments often reflect pulses (diurnal and/or seasonal) of meltwater (Benn and Evans, 2010). Cyclopels (laminated clays and silts) and cyclopsams (laminated silts and sands) (Powell and Cooper, 2002) are products of settling from turbid overflows and/or interflows. Laminae are usually normally graded (fining upwards) reflecting density settling of suspended sediments. Cyclopsams are usually deposited proximal to the efflux point (within 1 km from the source) whereas cyclopels can be distributed over larger areas (several kilometres) (Mackiewicz et al., 1984; Powell and Molnia, 1989). In lacustrine conditions laminated or varved sediments indicate the transition between the warm season with meltwater input (bright and coarser laminae) and the cold season with a frozen water surface, decreased sediment supply and temporary anoxia (dark, finer laminae).

When an ice sheet is grounded in relatively shallow marine or lacustrine waters (10's of meters rather than 100's) and meltwater transports abundant sediment to the ice margin, multiple subaqueous fans and/or deltas may be constructed (Table 3 and Figure 4). Their location and size will depend mainly on the period of ice margin stillstand (longer = bigger) and subglacial drainage pattern. It appears that interlobate zones (confluence between ice lobes) can be associated with the volumetrically largest sediment accumulations (Gruszka et al., 2012; Saarnisto and Saarinen, 2001).

Most of the well-sorted sediments will be deposited during this stage at, or proximal to, the ice margin, as ice-contact deltas or fans (Table 3, Figure 4 and Figure 6)(Dietrich et al., 2017; Fyfe, 1990; Lønne, 1995; Powell and Molnia, 1989). Large, reservoir-quality, sediment accumulations are usually associated with periods when the ice margin stabilizes for longer during overall retreat. The well-sorted sediments will most likely be blanketed by glaciomarine muds as the ice margin becomes more distal. Glaciomarine and glaciolacustrine muds, often varved, have similar properties. These lithotypes have a high seal capacity (Dahlgren et al., 2005; Eyles et al., 1985; Powell and Cooper, 2002). Some of the geotechnical properties of glaciomarine and deglacial muds have been discussed in the context of slope stability by Kvalstad et al., (2005) and applied in a numerical model by Bellwald et al., (2019).

8 Proglacial zone

8.1 Terrestrial

In the proglacial zone, deposition occurs mainly through glaciofluvial processes. After exiting the ice sheet through portals, sediment-laden meltwater deposits broad sand and gravel-rich braidplains – sandar (singular: sandur (Table 2)) (Magilligan et al., 2002; Maizels, 2007; Pisarska-Jamrozy, 2015; Zielinski and Van Loon, 2003). Multiple meltwater input points, no identifiable fan apex and frequent avulsions are characteristic of sandar (Zielinski and Van Loon, 2003). If the terrain constrains the meltwater, a valley train, i.e. a valley-filling sediment belt, may be deposited. If the topography rises away from the ice margin a proglacial lake may form (Martin et al., 2008). If a sandur is not in direct connection with a water body, an ice marginal spillway network will ultimately drain the meltwater away from the ice margin towards the nearest basin depocentre (Brodzikowski and van Loon, 1987). Examples of both settings are known from Pleistocene glacial landsystems in Germany and Poland (Pisarska-Jamrozy, 2015; Rinterknecht et al., 2012).

8.1.1 Advance

During the initial advance rivers may incise their valleys re-mobilising and removing part of the sedimentary sequence of the proglacial zone as a response to sea level fall. It is important to re-emphasize that meltwater discharge is lower during advance than retreat and will result in a reduced area of active sandar deposition (Table 2). The proglacial drainage network will be re-arranged if ice advances beyond an earlier terminal moraine. Vegetated areas in the proglacial deposition zone may be partially blanketed by outwash sands and gravels. With decreasing distance from the ice margin to the next sediment sink and a falling sea level, the angle of depositional slope increases, resulting in upward coarsening facies and/or fluvial incision into the shelf and low stand delta progradation. Proglacial glaciofluvial sediments have the best reservoir properties of all identified glaciogenic landforms and sediments (Figure 4). They will likely reach their maximal lateral extent but not maximal thickness during this stage. In general, glaciofluvial sediments of sandar deposited during the ice advance can have good reservoir properties but they are often overridden by the advancing ice sheet, which results in deformation and at least partial erosion of the sequence. Thin, sheeted reservoir geometries are to be expected.

8.1.2 Retreat

As the melt increases and the ice margin retreats, a large amount of sediment is transported and deposited by meltwater into the proglacial zone (Figure 4) as sandur deposits (Girard et al., 2012; Le Heron, 2007; Magilligan et al., 2002; Pisarska-Jamrozy and Zieliński, 2014). Pitted sandar (Table 3) develop where blocks of ice are completely, or partially, buried by glaciofluvial outwash and subsequently melt away leaving a pitted kettle hole surface (dead ice topography)(Fleisher, 1986; Thwaites, 1926). Some sandar may be deposited, or augmented, by periodic, high magnitude, flooding events (jökulhlaup/glacial lake outburst floods) rather than by seasonal surface-melt driven meltwater discharge (Girard et al., 2012; Gomez et al., 2000; Winsemann et al., 2016). An erosional base and very large scale bedforms characterise deposits from such events (Marren, 2005). The spatial extent and catastrophic nature of jökulhlaup deposits may be used to establish an isochron for, at least part of, a glacial sedimentary sequence in the proglacial zone (Hanson and Clague, 2016). One, or a series of, sub-basin/s may have been created between the moraine/s deposited during the first stadial maximum advance, which are exposed on retreat providing accommodation space for glaciofluvial sediments. This backfilling pattern is typical for glacial environments when space, previously occupied by the ice sheet, is infilled by sediments released after the ice front retreats. Ice-contact lakes, often developed between the ice margin and a moraine ridge/complex (García et al., 2015), are typically infilled with sediment derived from a mixture of paraglacial and glaciofluvial processes (Table 3 and Figure 5). Glacier-fed deltas (Table 3) may also develop in places where a sandur terminates in a proglacial lake. The size the delta largely depends on landscape topography, ice sheet geometry, and spillway elevations and size of the lake (a spillway is a pathway developed when water from an ice-contact lake overflows the lowest point of the constraining topography) (Benn and Evans, 2010). The seasonal nature of meltwater discharge (low in the winter and very high in the summer) results in a large annual variation in the volume and grainsize of sediments being deposited in proglacial lakes. When such a lake becomes infilled by outwash sediments sandur deposition will re-commence (Pisarska-Jamrozy and Zieliński, 2014). On newly deglaciated terrain, large exposures of fine-grained unconsolidated sediments, with little to no vegetation cover, are highly susceptible to aeolian reworking (Chewings et al., 2014; Derbyshire and Owen, 2017; Mountney and Russell, 2009). Fine fractions are entrained, transported and deposited by wind, filling depressions from the small scale all the way up to large scale regional loess covers(Derbyshire and Owen, 2017). Major sand dune systems may be present on sandur plains and other proglacial areas (Ballantyne, 2002; Ballantyne, 2002; Maizels, 1997).

Distally, where the ice sheet had no direct influence on landform genesis, the only indication of ice retreat may be found in deltaic or shoreline sedimentary records (Figure 5). During this time sea level will generally rise, resulting in marine transgression. The regional sea level will be a function of the eustatic sea level change, isostatic rebound, forebulge collapse (the kinematic response of the lithosphere to off-loading following ice sheet retreat) and reduction in gravitational attraction. The crest of the decaying Fennoscandian ice sheet forebulge, post Last Glacial Maximum at 15,000 ka BP was estimated by Fjeldskaar (1994) to be 100 km beyond the ice margin and elevated by 60 m, decreasing to 40 m by 11,000 years BP. High-discharge glacial rivers can transport large volumes of sediment resulting in rapid progradation of marine and lacustrine deltas even at a significant distance from the ice sheet margin (e.g. Pleistocene Mississippi River delta (Fildani et al., 2018)).

8.2 Marine/Lacustrine

Distal from the grounding line, beyond direct deposition from meltwater jets, muds and marine diamictons are dominant (Table 3 and Figure 4, Figure 6)(Ó Cofaigh, 1996). Deposition occurs from density currents and suspension settling, creating a fine grained, often laminated, package with outsized clasts (dropstones, iceberg rafted debris (IRD - Table 4)) supplied by, and melted out from, floating icebergs. This glacimarine diamicton (Table 3) is diagnostic for the presence of grounded ice in the basin. Localised mass-wasting and slope processes associated with over-steepened slopes occur (Clerc et al., 2013; Evans et al., 2012; Koch and Isbell, 2013). Proglacial muds often preserve iceberg plough marks (Table 3) (Benn and Evans, 2010), which are formed when grounded icebergs are pushed by the wind and ocean currents. They are typically v-shaped, linear or curvilinear furrows in the seabed. In extreme cases, iceberg ploughing of sediments can destroy all primary sedimentary structures leaving behind a structureless marine diamicton (Table 3 and Figure 4) (Benn and Evans, 2010). Length and depth of an individual plough mark largely depends on the water depth and iceberg size (Dowdeswell and Bamber, 2007). The presence of iceberg plough marks preserved in sediment packages requires grounded ice within the marine or lacustrine setting (Figure 4 and Figure 6).

8.2.1 Advance

Proglacial deposition occurring during ice advance has a limited preservation potential as it will be subsequently overridden by the advancing ice sheet (Figure 6). Sedimentary packages will either be eroded subsequently, creating an upper erosional unconformity, or deformed by overriding ice. Some sediments may, however, be preserved if deposited in seabed depressions or larger basins.

Proglacial deposition occurs on the continental slope and into the abyss if the ice sheet extends all the way to the continental shelf break and the grounding line is approximately collinear with the shelf edge(Figure 4 and Figure 6) (Elmore et al., 2013; Ó Cofaigh et al., 2003; Powell and Alley, 1996). Greater water depth, steep depositional slope and high accommodation, with respect to the continental shelf, aids dispersal of the sedimentary package delivered by glaciofluvial processes (Dowdeswell and Dowdeswell, 1989). Settling from suspension, mass-flows with long run-out distances (distal turbidites from TMFs) and slope failures are the dominant depositional processes on the slope. The final sediment assemblage in the abyss will consist mostly of laminated marine shales with dropstones and iceberg dump deposits sometimes interbedded with density current deposits and slump facies (Table 3) (Brodzikowski and van Loon, 1987). Sorted sandy sediments may be deposited and/or reworked by contour currents forming contourites (Table 3) (Camerlenghi et al., 2001; Lucchi and Rebesco, 2007; Stuart and Huuse, 2012). There is little potential for reservoir quality packages to be deposited apart from TMFs and contourites (Figure 4) (Dowdeswell et al., 2008; Laberg and Dowdeswell, 2016; Vorren and Laberg, 1997). Glaciomarine muds can be considered as a good sealing lithology. Influence of iceberg plough marks on the pre-existing sediments should be carefully considered; their keels can deform sediments to a significant depth. The sealing properties of the glaciomarine muds may be degraded if ploughmarks are of sufficient depth and are subsequently filled with more permeable sediments (Figure 4).

8.2.2 Retreat

The depositional zones (Figure 4) are linked to the grounding line/ice margin position, which changes over the lifespan of the ice sheet (e.g. Andreassen *et al.*, 2014). As deglaciation commences, the grounding line/ice margin retreats, revealing the seabed that was previously in the ice marginal or subglacial depositional zone. The stratigraphic change in deposition from ice marginal to proglacial may be gradual up-section if the ice margin retreat is slow (continuous annual retreat at a similar rate), or abrupt, if retreat is rapid/catastrophic and it occurs over a significant distance (Sejrup et al., 2016; Stokes et al., 2015). If the retreat is gradual Ice-contact deltas may transitions into glacier-fed deltas (Table 3 and Figure 4, Figure 5 andFigure 6) as the ice sheet retreats and the ice margin emerges from the water(Dietrich et al., 2017, 2016; Dietrich and Hofmann, 2019). Glacier-fed deltas are one of the most prospective reservoir candidates as the sediments are commonly sand dominated and the depositional processes are efficient at sorting and portioning the different grainsizes, resulting in thick, laterally extensive packages with good reservoir properties.

In the marine proglacial zone, sediments may be transported offshore either in suspension or trapped in icebergs that move with the ocean currents and winds. Sediments encased in icebergs are subsequently melted out as dropstones and iceberg rafted debris (IRD -Table 3) (Benn and Evans, 2010), sometimes many hundreds of kilometres away from where they detached from the ice sheet. The grain size distribution in glaciomarine sediments deposited from iceberg rainout varies greatly. It is dependent upon the iceberg calving rate, debris concentrations in the ice sheet, meltwater discharge, particle size of the parent sediment (lithology of the source area) and oceanographic conditions including, but not limited to, water column density and bottom current winnowing, transport and deposition (e.g. contourites –Table 3) (Benn and Evans, 2010). Dropstone concentration appears to decrease with distance from the grounding zone (Dowdeswell and Dowdeswell, 1989; Dowdeswell *et al.*, 2016). A bimodal grainsize distribution is a common characteristic of glaciomarine diamicton (Table 3) where suspension settling, from buoyant sediment plumes, is accompanied by coarser IRD deposition. Layers containing higher proportions of coarser material may indicate increased calving due to rapid retreat of ice during deglaciation (Bond et al., 1992; Hodell et al., 2017). Dropstones and iceberg dump deposits are commonly used as a diagnostic indicator of the proximity of ice sheets in the sedimentary basin (Bennett et al., 1996). However, the presence of dropstones in fine-grained sediments may also be explained by non-glacial processes including deposition from floral mats (coarse material entangled in roots), volcanic bombs and outrunner clasts from from debis flows (Bennett et al., 1996). Therefore, care must be taken when investigating sediments of Carboniferous and younger age when flora was widespread. The presence of iceberg dump deposits, in the form of massive, unsorted and structureless diamicton or boulder/gravel lenses in otherwise fine marine muds allows for a more confident interpretation of proximal glacial conditions. Sealing (rather than reservoir) lithologies can be expected to be deposited in this zone. If ice flux is sufficiently high icebergs can locally supply coarser, moderately sorted material into the marine environment. This iceberg-supplied package can be considered to have moderate reservoir potential. Other than that, glaciomarine muds can be considered as a regional seal candidate over a deglaciated area (Figure 4). The longevity and magnitude of the highstand, coupled with the sediment supply, control probability of a regional seal being deposited. Following the deglaciation of the Ordovician ice sheet in North Africa, such highstand conditions led to the deposition of the Silurian hot shales, which act both as a source rock and a regional seal for hydrocarbon accumulations in the region (Le Heron et al., 2009; Lüning et al., 2000).

8.2.3 Littoral reworking

The interplay of interglacial/postglacial sea level rise and glacial isostatic rebound often results in marine/lacustrine regression and/or a transgression causing emergence or submergence of deglaciated landscapes (Mitrovica and Milne, 2002). Partial erosion and re-deposition of glacial sediments and modification of glacial landforms by wave action and currents can be expected in both cases (Dowdeswell and Ottesen, 2016) and a degree of postglacial reworking and re-deposition of landforms and sediments is almost inevitable following deglaciation and should be considered a normality rather than an exception. However, numerous examples of submerged or emerged glacial landscapes with limited reworking are reported from the North Sea (Emery et al., 2019b, 2019a), North America (Barrie and Conway, 2016; Ward et al., 2019) and Europe (Glückert, 1986; Rinterknecht et al., 2004), suggesting that, in many instances, this has had little impact. This may be due to the rapidity of relative sea level rise. Sorting related to littoral reworking may improve reservoir properties of glaciogenic deposits.

8.2.4 Extreme scenarios

A melting ice sheet has the potential to produce very large volumes of water, that can be released in a controlled manner through the subglacial drainage system, gradually supplying the marine, proglacial zone. If meltwater is stored in an ice dammed lake, it may be released in a catastrophic event which has the potential to scour the topography, erode and transport large volumes of sediments far offshore. Examples include; breaching of the land connection between present-day France and Great Britain, through the English Channel, sculpting large sandur areas in NE Poland and breaching a topographic high in Germany (Gupta et al., 2017; Meinsen et al., 2011; Weckwerth et al., 2019). An even more extreme example can be found between Labrador and Greenland in the Labrador Sea; submarine channels originate at the shelf edge and extend all the way to the abyssal plain in water depths of 3 - 4 km. A large submarine channel with a 200 m high levee complex is present in the area. Outside the channel a coarse-grained braid plain with linguoidal bar forms has been described by Hesse et al. (2001). The shape of the channel and barforms indicate extremely high magnitude flows originating from the area of Hudson Bay and are linked to deglaciation of the Laurentide ice sheet.

8.2.4.1 Tunnel valleys

Tunnel valleys (Table 4, Figure 4, Figure 5 and Figure 6) are elongated depressions eroded by meltwater into underlying deposits and are best known from Pleistocene successions in the North Sea, Western and Eastern Europe, Canada and ancient glacial deposits in Australia and North Africa (Andersen *et al.*, 2012; Sandersen and Jørgensen, 2012). They can range from several to tens of kilometers long, may be several kilometers wide and usually up to a couple of hundred meters deep. The architecture of their infill is intimately linked to the landsystem in which they were created. Some tunnel valleys, eroded beneath land terminating ice sheets, are subsequently infilled with outwash sediments while others remain under-filled and become lakes following the ice margin retreat (Thomas, 1984). When eroded at the seabed, they are subsequently infilled by either subaqueous outwash sediments, glaciomarine diamicton, distal glaciomarine or marine muds, associated with deglacial and interglacial conditions (L. R. Bjarnadóttir et al., 2017; Fichler et al., 2005; Ghienne and Deynoux, 1998; Livingstone and Clark, 2016; Stewart et al., 2013; van der Vegt et al., 2016). Slump deposits associated with wall collapse have been reported from several tunnel valleys (van der Vegt et al., 2016). Tunnel valley fills may, or may not, be of glacial origin (Clerc et al., 2013; Moreau and Huuse, 2014; Praeg, 2003) testifying to the complexity of processes governing their infilling (e.g. Forbes et al., 2010; Stewart et al., 2013). Subglacial to proglacial tunnel valleys (Table 3 and Figures 4, 5 and 6) are reported both from the Pleistocene section of the North Sea and the Barents Sea (L. R. Bjarnadóttir et al., 2017; Praeg, 2003; van der Vegt et al., 2016). In the North Sea they seem to be mainly of Middle to Late Pleistocene in age. Ancient tunnel valleys in marine settings are reported from the Illizi Basin in Algeria where the Ordovician age reservoirs host significant hydrocarbon reserves (Dixon et al., 2010; Hirst, 2012).

9 Discussion

The purpose of this paper is to provide an overview of current understanding of glacial sedimentology from a hydrocarbon reservoir perspective. Glacial systems are extremely dynamic and highly transient. The models described above are snap-shots of specific times in the history of an idealised system and the final product that ends up in the rock record is a product of significant reworking and over printing (Figure 7). In the following discussion we focus on the aspects of the systems that produce the key components of hydrocarbon reservoir systems, especially the architectural elements that have the potential to act as reservoirs for hydrocarbon, as aquifers for water or sites for CO_2 storage.

9.1 Implications for hydrocarbon exploration

The description of landforms and sediments summarized in the conceptual model (Figures 3 and 4) have a number of implications for hydrocarbon reservoir distribution: (1) the majority of subglacial sediments and landforms, both in terrestrial and marine environments have poor reservoir properties and are most likely to provide sealing lithologies on top of reservoirs or intraformational barriers and baffles to fluid flow within reservoirs, (2) subglacial traction till is rarely continuous and should not typically be considered as a regional seal, (3) in each ice sheet advance the subglacial zone is marked by an extensive erosional surface which does not necessarily have to be overlain by traction till. This implies that older, reservoir quality sediments may be partially or fully eroded (Figure 7). When only partially eroded, they do not necessarily have to be covered (sealed) by a traction till carapace. Lack of a sealing till layer on top results in older glacial sediments being in connection with a subsequent, deglaciation sediment package (Figure 7) (4) eskers can add to the volume of, and/or provide reservoir connectivity between, isolated, larger reservoir quality sediment accumulations (ice-contact deltas, subaqueous outwash fans) deposited during ice margin retreat, (5) sediments and landforms in the ice marginal zone have the most diverse composition and show rapid changes over very short distances along the ice margin and their reservoir properties depends on the mode of deposition (glaciofluvial may have moderate to good reservoir properties, material bulldozed by ice or deposited from gravity flows at the ice margin will have poor to non-reservoir properties), (6) proglacial zone sediments in terrestrial environments (sandar) have the best reservoir properties and can be very extensive but their preservation over geological timescales is uncertain if deposition occurs above the erosional baseline, (7) ice marginal-to-proglacial glaciofluvial deposits (ice-contact deltas, glacier-fed deltas, subaqueous ice-contact fans) have both good reservoir properties and high potential to be preserved in the rock record, and their deposition is strictly associated with the ice margin(Figures 4 and 7), (9) glacimarine or glaciolacustrine diamicton has the potential to provide a regional seal if an ice sheet is marine or lake terminating (Figures 4 and 7).

Some of the above points can be illustrated by hydrocarbon discoveries made in glaciogenic sequences. In the North Sea the Peon gas discovery is interpreted to be hosted in a subaqueous outwash fan deposited during ice margin retreat, which was subsequently overridden by ice margin re-advance and sealed by a traction till carapace (Ottesen et al., 2012). The Aviat gas field, which has also been interpreted as a subaqueous outwash fan is sealed by a thick package of glaciomarine diamictons and marine muds (Rose et al., 2016). Gas fields in North Africa, including In Amenas and Elephant fields, are hosted in glaciogenic rocks (Mamuniyat Formation) deposited over a glacial erosional surface (GES) (e.g. Bataller et al., 2019; Hirst, 2012; Le Heron et al., 2009, 2006; Lüning et al., 2000). The reservoir intervals show a broad spectrum of grainsizes, multiple minor internal erosional contacts and at least two extensive GESs indicating two or more ice sheet re-advances (Heron et al., 2015; Le Heron et al., 2009). They also fill valleys incised into older strata either, by meltwater (tunnel valleys) or, ice streams (cross shelf troughs) (El-Ghali, 2005; Le Heron et al., 2018). Recent studies indicate that ice streaming in ancient deposits is more common than previously thought and can be recognized from glaciogenic successions of Ordovician and Late Palaeozoic age (Andrews et al., 2019; Assine et al., 2018; Elhebiry et al., 2019; Heron, 2018). Identification of such features in the subsurface can aid understanding sediment transport mechanisms, mode of deposition, resulting reservoir distribution and fluid migration pathways. Moreover, some interpretations which describe large scale glaciogenic, erosional features as glacial valleys or palaeo-valleys from ancient deposits may require re-evaluation (e.g. Clark-Lowes, 2005; Hirst et al., 2002; Powell et al., 1994; Vaslet, 1990). The troughs may represent either palaeo-ice stream corridors or tunnel valleys (Kehew et al., 2012; Ottesen et al., 2002; Stokes and Clark, 2001; van der Vegt et al., 2016). The ability to discern them has significant implications for the understanding of their position within the glacial environment and expected reservoir distribution. A careful morphometric study of modern and ancient examples remains to be completed.

Sediments of the Hirnantian glaciation in North Africa are anomalous in that they are almost entirely composed of sandy fractions (Deschamps et al., 2013; Hirst, 2012; Le Heron et al., 2009). This phenomenon has been attributed to the Hirnantian ice sheet advecting, reworking and re-depositing sandy shoreface sediments present in the region prior to the onset of glaciation (Le Heron et al., 2009). For this reason, North African outcrops may be somewhat different to glaciogenic sequences in the subsurface elsewhere. In Saudi Arabia the Hirnantian aged glaciogenic rocks are an important target for gas exploration (Craigie et al., 2016; Ehlers et al., 2011; Melvin, 2019; Michael et al., 2018, 2015). In the south the Sanamah Formation includes sandar, glacier-fed deltas and/or ice-contact deltas deposited over traction tills. In the north the Sarah Formation is comprised of marine, ice marginal and proglacial deposits described as glacier-fed deltas, prodelta muds, shallow shelf and deep marine facies (Michael et al., 2018). Time- equivalent facies in Jordan consist of subglacial, glaciofluvial and glaciodeltaic deposits and proglacial turbidites and “sheet like lobe deposits” (possible subaqueous outwash fans) in the south (Hirst and Khatatneh, 2019; Michael et al., 2018). Common characteristics of all these areas is the occurrence of cross-cutting, incised valley networks testifying to multiple phases of ice advance and retreat which can also be observed from Pleistocene glaciations e.g. in the North Sea (Craigie et al., 2016; Kristensen et al., 2007; Le Heron, 2007; Lonergan et al., 2006; Michael et al., 2018; Stewart and Lonergan, 2011). Here the glaciogenic sequence is capped regionally by glaciomarine diamicton facies, with abundant dropstones, illustrating deglaciation and post-glacial sea level rise (Fortuin, 1984; Ghienne, 2003; Le Heron et al., 2010; Lüning et al., 2000). In Oman, the glaciogenic Al-Khlata Formation (late Carboniferous - early Permian) forms an important reservoir target in the South Oman Salt Basin (e.g. Al-Abri et al., 2018; Forbes et al., 2010; Hadley et al., 1991; Levell et al., 1988; Millson et al., 1996). It has been interpreted to have been deposited by land terminating ice sheets as sandar, glacier-fed deltas and ice-contact deltas deposited in glaciolacustrine environments during multiple phases of the ice sheet advance (erosion and diamictic facies deposition) and retreat (reservoir quality glaciofluvial and glacio-deltaic facies capped by glaciolacustrine muds) (Al-Abri et al., 2018; Heward and Penney, 2014; Osterloff et al., 2004b).

The conceptual model presented here offers a 2D, bird's eye view of a glaciated landsystem at any given time. From this it is it is possible to trace the relative movement of the depositional zones in response to ice sheet advance and retreat by plotting glacial sediments/landforms identified in vertical succession from outcrops, wells or seismic data on the diagram (Figure 4). This allows reconstruction of the depositional zones (subglacial, ice marginal and proglacial) and the depositional environment (terrestrial, lacustrine, shallow marine, deep marine). This will aid in correlation and ultimately prediction of potential reservoir-quality sediments up or down the depositional dip.

9.2 Other considerations

Glaciogenic deposition is extremely dynamic (in relation to geologic time scales). An ice sheet margin migrates in response to climate forcing and ice sheet dynamics, which may result in rapid spatial and temporal changes of both the mode and location of deposition. A depocenter which was initially in the ice-marginal depositional zone on land can be overridden by an advancing ice margin relatively quickly and moved into the subglacial depositional zone. Alternatively, the subglacial zone may rapidly give way to the proglacial depositional zone as the ice margin retreats. During retreat a land terminating ice sheet margin can quickly become grounded in water due to rising sea level and/or development of a large proglacial lake. This leads to different sediment and landform assemblages being deposited, over the same area, in a very short period of time. It is crucial to emphasize that such changes can be repeated multiple times in a vertical sedimentary succession. Although dynamic, the basic geological laws of superposition (Steno) and lateral and vertical facies succession (Walther), still hold true (Steno, 1671; Walther, 1893). Nonetheless, the series of events leading to the deposition of a given succession maybe much more difficult to unravel.

The characteristics of the sedimentary sequence depends upon the sediment/bedrock present in the subglacial zone, from where most of the sediment is advected. For example, an Ordovician marine glaciogenic sediment sequence is described by Le Heron et al. (2009) as particularly sandy, as a result of entrainment of overridden sandy aeolian and shoreface sediments, present in abundance at that time on the northern margin of the palaeo-African continent. Alternatively, Pleistocene ice sheets entering the North Sea basin from the W/NW (Shetland Platform and UK mainland) and E/NE (present day Norway and Sweden) cannibalised fine grained sediments of deltaic and paralic origin (Lamb et al., 2017; Rea et al., 2018; Stoker et al., 2011), re-working and re-depositing them as a finer grained sediment package further into the basin. The diversity of sediment types emphasizes the necessity to investigate glacial sedimentary sequences holistically, with respect to underlying and overlying non-glacial sequences and available sediment sources in the area/region. Identification of individual facies associations or morphological elements may not be sufficient to confidently recognize glaciation. However, there are several diagnostic, non-depositional features and landforms that have been included in the model (tunnel valleys, mega-scale glacial lineations, ploughmarks etc., (Table 3, Figures 4, 5 and 6) explicitly to aid identification of a glacial succession.

An ice sheet is deemed land terminating when the majority of the ice margin is located on an emerged surface above the mean sea level (Figure 4 and Figure 6) (Benn and Evans, 2010). If accommodation is available terrestrially this will be filled with glaciofluvial and glaciolacustrine deposits depending on: 1) meltwater discharge; 2) sediment availability; 3) topography; 4) ice sheet geometry and 5) distance from the ice margin to the basin depocenter. Examples include Ordovician sediments in intracratonic basins in Northern Africa and Carboniferous-to-Permian sediment basin-fills in Oman and Saudi Arabia (Khalifa, 2015; Le Heron et al., 2009; Levell et al., 1988; Martin et al., 2012). Glacial deposition may occur on land even when no accommodation is available by creating positive topography or filling features eroded by the ice into the underlying bedrock and/or sediments (Bennett, 2003; Deschamps et al., 2013; Le Heron et al., 2009; Swartz et al., 2015). This can be seen, for example, from Pleistocene ice marginal and proglacial deposits associated with the Fennoscandia ice sheet in Germany, Denmark, Poland, Latvia and Estonia (e.g. Andersen et al., 2012; Marks, 2005; Rinterknecht et al., 2012). On longer timescales, the preservation of positive topography is, at best, uncertain (Figure 6). Ice-contact and proglacial lake deposits are also included in this depositional system. The distribution of sediments and landforms (Figure 4 and Figure 5) associated with a land terminating ice sheet can be highly complex (Figure 6). Traction tills deposited during ice advances dominate the subglacial depositional zone. During deglaciation, back stepping of the ice front may result in partial erosion and remobilization of subglacial deposits and/or blanketing by glaciofluvial deposits (sands and gravels). Backfilling of accommodation created by ice retreat is a key characteristic of land terminating ice sheets (Figure 5). Subsequent ice sheet re-advance can remove parts, or all, of the sediment packages deposited during previous glacial episodes, as well as interglacial deposits. However, it has been demonstrated by Bellwald et al. (2019) that, under favourable conditions, landforms associated with multiple ice flow episodes can be preserved in the sedimentary record. In terms of reservoir potential, glaciofluvially sorted sediments in the proglacial zone (sandur - Table 2, Figure 4 and Figure 5) most likely have the best reservoir quality. Sands and gravels deposited in topographic lows have also the highest preservation potential. Finally, sediments deposited during the final deglaciation are more likely to be preserved due to lack of subsequent subglacial erosion and postglacial eustatic sea level rise.

Landforms and sediments associated with Pleistocene and older ice sheets indicate that, in many instances, they extended across the continental shelf terminating in the ocean or terminated in a large, fresh water body, for at least a part of their existence (Figure 6) (Dowdeswell et al., 2016b; Eyles et al., 1985). Marine terminating ice sheets cannot extend beyond the shelf break. It is the ultimate boundary, beyond which no ice sheet can remain grounded because of the increased calving flux and submarine melting (Benn and Evans, 2010). This means that the ice flux can never be high enough to sustain an advance into the ever-increasing water depths. In certain circumstances ocean-scale ice shelves can form, which are up to a kilometre thick and ground on bathymetric highs e.g. the Central Arctic Ocean on the Lomonosov Ridge (Jakobsson et al, 2010). Evidence of this is widespread at high latitudes across the world (e.g. Dowdeswell et al., 2008; Ó Cofaigh et al., 2003), where the bathymetry and sedimentology of continental shelves, all the way out to the shelf break, reveals a rich assemblage of glacial landforms and sediments associated with proximal grounded ice (e.g. Andreassen and Winsborrow, 2009; L. R. Bjarnadóttir et al., 2017; Bjarnadóttir and Andreassen, 2016; Dowdeswell and Fugelli, 2012; Esteves et al., 2017; Greenwood et al., 2018; Hodgson et al., 2014; King et al., 2016; Kurjanski et al., 2019) (Bjarnadóttir and Andreassen, 2016; Greenwood et al., 2018; Hodgson et al., 2014; King et al., 2016; Kurjanski et al., 2019). However, large volumes of sediments delivered subglacially to the shelf break and deposited on the continental slope during glaciation can cause the shelf to prograde basinward (Figure 6) (Eyles et al., 1985; Knutz et al., 2019; Ottesen et al., 2012). This can be observed in seismic data on the north Norwegian continental margin as well as the Norwegian, Danish, Dutch and German sectors of the North Sea (Ottesen et al., 2012; Rea et al., 2018). Most coarse-grained sediments are deposited in the ice marginal zone (Figure 4), proximal to the grounding line. Since ice can be grounded at depths exceeding several hundred meters it is possible that coarse grained sediments will be deposited directly into deep water. Sediment distribution in glaciomarine environments (Figure 4 and Figure 6) appears to be a function of sediment input location, oceanographic conditions and distance from the grounding line.

Ice sheets terminating in, and interacting with, large lacustrine basins are also common (Carrivick and Tweed, 2013; Murton et al., 2010; Patton et al., 2017). Generally, the interplay between crustal isostatic response beneath, and beyond, an ice sheet margin promotes the formation of proglacial lakes (Figure 2) (Carrivick and Tweed, 2013). For example, during the last glaciation (MIS 2-4, the

Wisconsinian) the Laurentide ice sheet was partially grounded along its southern margin in Lake Agassiz and Lake Ojibway (Carrivick and Tweed, 2013; Levson et al., 2003; Thorleifson, 1996). The lakes had a combined water volume of up to 163 000 km^3 (Leverington et al., 2002), which equals two times the volume of the, present-day, Caspian Sea and seven times the volume of the, present day, Lake Baikal. In the South Salt Basin in Oman, the upper part of the Permo-Carboniferous Al Khlata formation is interpreted as a large proglacial lake system (Martin et al., 2008; Osterloff et al., 2004b). These large proglacial lakes may be intermittently connected to seas or oceans. For example, the southern margin of the Fennoscandian ice sheet, during retreat from the Last Glacial Maximum was grounded in the Baltic ice lake, which, at the time, had no connection to the global ocean (Houmark-Nielsen, 2007; Uścinowicz, 2004; Vassiljev and Saarse, 2013).

It is crucial to emphasise that all the above environments can be interchangeably present over the same area during the lifespan of one icehouse. Moreover, the final sediment assemblage is most likely a result of multiple ice advance and retreat stages (glacial-interglacial cycles) superimposed on each other with multiple erosional episodes (ice advance) removing a part or even a whole section deposited during a previous glaciation. As a result, it is unlikely that the full sedimentary package associated with an icehouse period will be preserved (Figure 6).

9.2.1 Improved imaging workflows, techniques and equipment

The typical offshore hydrocarbon workflow commences with gravity and magnetic surveys followed by several widely spaced, long regional 2D (older standard) or large-scale 3D surveys aiming to uncover the general structure of the basin (Alsadi, 2017; Nanda, 2016; Sengbush, 1983). Subsequently a more targeted, densely spaced 2D (older standard) survey was performed or, more likely now, part of a 3D cube is selected and often reprocessed over a prospective area. If the prospective area is deemed worthy , a high-resolution, shallow-looking (higher frequency,) 2D or 3D site survey, aiming to identify potential geotechnical and drilling hazards is contracted (Camargo et al., 2019; Lane and Taylor, 2002; Shmatkova et al., 2015; Zhang et al., 2016).

This workflow, is not optimal for exploration in glaciogenic sequences for several reasons: (1) lower frequencies resulting in poorer vertical resolution cannot image subtle, glaciogenic features (MSGL, iceberg ploughmarks etc.) that are crucial for identification of a glaciogenic package and for understanding its position within the glacial landsystem (Bellwald et al., 2018; Bellwald et al., 2019; Bellwald and Planke, 2019). (2) Site-surveys of the shallow subsurface are almost exclusively focused on identifying hazards and are not evaluating potential opportunities associated with shallow gas accumulation (Huuse et al., 2012; Ottesen et al., 2012; Rose et al., 2016). The division between an exploration survey versus a site-survey may result in missed opportunities.

Recent technological advances in processing workflows and equipment can often allow for a better preservation of frequency bandwidth and better signal to noise ratio in seismic data (Brookshire et al., 2015; Firth and Vinje, 2018; Soubaras and Whiting, 2011). Alternatively, surveys can be performed with higher frequencies and smaller bin sizes resulting in better horizontal and vertical resolution (Bellwald and Planke, 2019; Brookshire et al., 2015; Lebedeva-Ivanova et al., 2018). In both cases imaging of the shallow (and deeper if frequencies are preserved) targets is improved. Such high-resolution data can be used both for exploration and site risk assessment. The improved imaging of the shallow section can yield additional, otherwise missed exploration opportunities and contextualise it within a working petroleum system.

9.2.2 Shallow gas - a hazard or a missed opportunity?

Identification of shallow gas hazards in the subsurface is crucial to safely execute drilling operations. Hazards, if volumes of hydrocarbons are sufficient, can be readily transformed into exploration opportunities as demonstrated by the Aviat and Peon discoveries (Huuse et al., 2012; Ottesen et al., 2012; Rose et al., 2016). In seismic data the interpretation of shallow gas in glaciogenic deposits found offshore on glaciated continental margins is a direct indication of reservoir properties (Bellwald and Planke, 2019; Haavik and Landrø, 2014). However, the complexity of these sequences and limited/poor quality sealing lithologies requires improved understanding of the distribution and properties of porous, permeable and impermeable packages within glaciogenic sequences. This is crucial to ensure safe well abandonment, decommissioning and proposed carbon capture and storage (CCS) activities. The conceptual model presented in this paper aims to support interpretation efforts in all the above activities.

10 Conclusions

The conceptual model presented in this paper (Figure 3) is a synthesis and simplification of what can be an extremely variable and complex depositional environment (Figure 4 and Figure 5). Therefore, it should be used as a framework tool, enabling a first-pass interpretation of glacial landforms. Subsequently, more detailed, interpretations to consider specific local conditions are required.

Several conclusions can be drawn:

1. Glaciofluvial sediments have the best reservoir properties since they are deposited by meltwater, the implications for hydrocarbon exploration is that deglacial sediments (sands and gravels) should be primarily targeted.
2. Landforms and sediments marked in yellow (potential reservoirs) in Figure 4 should be investigated in further detail as they can comprise good reservoir quality sands and gravels, fine sediments or a mixture of both. Local changes in the energy of the depositional system, available sediments, substratum or local topography can all have a significant impact on their composition e.g. moraines (push or thrust) can be composed of either, outwash sands and gravels, or muds and diamictites, depending on the available substratum. A grounding zone wedge could be either, predominantly composed of traction till (diamictite), or have a significant proportion of well sorted sands and gravels, depending on meltwater discharge at the grounding line and the distribution of meltwater portals (point sources).
3. Oscillations of the ice front can aid deposition of sealing lithologies on top of reservoir facies. Reservoir quality sediments can be either overridden during ice advance and, if not eroded, capped by a traction till carapace (e.g. Peon field) or, when ice retreats during deglaciation, sea level rise may result in flooding of reservoir facies and deposition of a marine mud seal on top.
4. Retreat of the ice front in a land terminating system can result in the deposition of triplets of stacked subglacial tills and proglacial sandy and gravely outwash followed by a non-glacial sediment assemblage, associated with interglacials.
5. Identification of characteristic glaciogenic landforms and/or sediments is crucial to improving predictability of reservoir facies distribution and quality, within any basin.
6. The landsystem approach, is applicable for hydrocarbon exploration but may be of limited use in development and production cases, where local complexities in sedimentary systems become more important. All glaciogenic landsystems describe a “snapshot” view of a glacial landscape rather than its evolution over time. Moreover, the landsystem approach is mainly focused on ice dynamics (the processes) rather than the landforms and sediments (the products).
7. Size, distribution and controls on emplacement of reservoir quality landforms in glaciogenic depositional systems requires further research, of both modern and ancient analogues, with the concept of preservation potential providing the, often overlooked, link between the modern and ancient.

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References

Aber, J.S., Croot, D.G., Fenton, M.M., 1989a. Large Composite-Ridges, in: Glaciotectonic Landforms and Structures. pp. 29–46. https://doi.org/10.1007/978-94-015-6841-8_3

Aber, J.S., Croot, D.G., Fenton, M.M., 1989b. Small Composite-Ridges, in: Glaciotectonic Landforms and Structures. pp. 47–69. https://doi.org/10.1007/978-94-015-6841-8_4

Al-Abri, F.G., Heward, A.P., Abbasi, I.A., 2018. Regional 3D Modeling of the Permo-Carboniferous Al Khlata Formation in the Rima Area, Eastern Fflank of the South Ooman Salt Basin. J. Pet. Geol. 41, 29–46. https://doi.org/10.1111/jpg.12691

Alsadi, H.N., 2017. Seismic Hydrocarbon Exploration, Advances in Oil and Gas Exploration & Production. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-40436-3

Andersen, T.R., Huuse, M., Jorgensen, F., Christensen, S., 2012. Seismic investigations of buried tunnel valleys on- and offshore Denmark. Geol. Soc. London, Spec. Publ. 129–144. https://doi.org/10.1144/SP368.14

Anderson, J.B., Warny, S., Askin, R.A., Wellner, J.S., Bohaty, S.M., Kirshner, A.E., Livsey, D.N., Simms, A.R., Smith, T.R., Ehrmann, W., Lawver, L.A., Barbeau, D., Wise, S.W., Kulhenek, D.K., Weaver, F.M., Majewski, W., 2011. Progressive Cenozoic cooling and the demise of Antarctica's last refugium. Proc. Natl. Acad. Sci. U. S. A. 108, 11356–11360. https://doi.org/10.1073/pnas.1014885108

Andreassen, K., Winsborrow, M., 2009. Signature of ice streaming in Bjørnøyrenna, Polar North Atlantic, through the Pleistocene and implications for ice-stream dynamics. Ann. Glaciol. 50, 17–26.

Andreassen, K., Winsborrow, M.C.M., Bjarnadóttir, L.R., Rüther, D.C., 2014. Ice stream retreat dynamics inferred from an assemblage of landforms in the northern Barents Sea. Quat. Sci. Rev. 92, 246–257. https://doi.org/10.1016/j.quascirev.2013.09.015

Andrews, G.D., McGrady, A.T., Brown, S.R., Maynard, S.M., 2019. First description of subglacial megalineations from the late Paleozoic ice age in southern Africa. PLoS One 14, e0210673. https://doi.org/10.1371/journal.pone.0210673

Ashley, G.M., 2002. Glaciolacustrine environments, in: Modern and Past Glacial Environments. Elsevier, pp. 335–359. https://doi.org/10.1016/B978-075064226-2/50014-3

Assine, M.L., de Santa Ana, H., Veroslavsky, G., Vesely, F.F., 2018. Exhumed subglacial landscape in Uruguay: Erosional landforms, depositional environments, and paleo-ice flow in the context of the late Paleozoic Gondwanan glaciation. Sediment. Geol. 369, 1–12. https://doi.org/10.1016/j.sedgeo.2018.03.011

Ballantyne, C.K., 2002. A general model of paraglacial landscape response. The Holocene 12, 371–376. https://doi.org/10.1191/0959683602hl553fa

Ballantyne, Colin K., 2002. Paraglacial geomorphology. Quat. Sci. Rev. 21, 1935–2017. https://doi.org/10.1016/S0277-3791(02)00005-7

Barrie, J. V., Conway, K.W., 2016. Glacier-fed outwash plain on the Pacific margin of Canada. Geol. Soc. Mem. 46, 225–226. https://doi.org/10.1144/M46.54

Bataller, F.J., McDougall, N., Moscariello, A., 2019. Ordovician glacial paleogeography: Integration of seismic spectral decomposition, well sedimentological data, and glacial modern analogs in the Murzuq Basin, Libya. Interpretation 7, T383–T408. https://doi.org/10.1190/INT-2018-0069.1

Batchelor, C.L., Dowdeswell, J.A., 2016. Lateral shear-moraines and lateral marginal-moraines of palaeo-ice streams. Quat. Sci. Rev. 151, 1–26. https://doi.org/10.1016/j.quascirev.2016.08.020

Batchelor, C.L., Dowdeswell, J.A., 2015. Ice-sheet grounding-zone wedges (GZWs) on high-latitude continental margins. Mar. Geol. 363, 65–92. https://doi.org/10.1016/J.MARGEO.2015.02.001

Batchelor, C.L., Dowdeswell, J.A., 2014. The physiography of High Arctic cross-shelf troughs. Quat. Sci. Rev. 92, 68–96. https://doi.org/10.1016/j.quascirev.2013.05.025

Bellwald, B., Planke, S., 2019. Shear margin moraine, mass transport deposits and soft beds revealed by high-resolution P-Cable three-dimensional seismic data in the Hoop area, Barents Sea. Geol. Soc. London, Spec. Publ. 477, 537–548. https://doi.org/10.1144/sp477.29

Bellwald, Benjamin, Planke, S., Lebedeva-Ivanova, N., Piasecka, E.D., Andreassen, K., 2019. High-resolution landform assemblage along a buried glacio-erosive surface in the SW Barents Sea revealed by P-Cable 3D seismic data. Geomorphology 332, 33–50. https://doi.org/10.1016/j.geomorph.2019.01.019

Bellwald, B., Planke, S., Polteau, S., Lebedeva-Ivanova, N., Hafeez, A., Faleide, J.I., Myklebust, R., 2018. Detailed Structure of Buried Glacial Landforms Revealed by High-resolution 3D Seismic Data in the SW Barents Sea. https://doi.org/10.3997/2214-4609.201801161

Bellwald, B., Urlaub, M., Hjelstuen, B.O., Sejrup, H.P., Sørensen, M.B., Forsberg, C.F., Vanneste, M., 2019. NE Atlantic continental slope stability from a numerical modeling perspective. Quat. Sci. Rev. 203, 248–265. https://doi.org/10.1016/J.QUASCIREV.2018.11.019

Benediktsson, Í.Ö., Iongólfson, Ó., Schomacker, A., Kjaer, K.H., 2009. Formation of submarginal and proglacial end moraines: implications of ice-flow mechanism during the 1963-64 surge of Brúarjökull, Iceland. Boreas 38, 440–457. https://doi.org/10.1111/j.1502-3885.2008.00077.x

Benn, D.I., Evans, D.J.A., 2010. Glaciers and Glaciation, 2nd ed. Hodder Education.

Bennett, M.R., 2003. Ice streams as the arteries of an ice sheet: Their mechanics, stability and significance. Earth-Science Rev. 61, 309–339. https://doi.org/10.1016/S0012-8252(02)00130-7

Bennett, M.R., 2001. The morphology, structural evolution and significance of push moraines. Earth Sci. Rev. 53, 197–236. https://doi.org/10.1016/S0012-8252(00)00039-8

Bennett, M.R., Doyle, P., Mather, A.E., 1996. Dropstones: Their origin and significance. Palaeogeogr. Palaeoclimatol. Palaeoecol. 121, 331–339. https://doi.org/10.1016/0031-0182(95)00071-2

Bennett, M.R., Glasser, N.F., 2009. Glacial Geology: Ice Sheets and Landforms, Journal of Chemical Information and Modeling. https://doi.org/10.1017/CBO9781107415324.004

Bennett, M.R., Huddart, D., McCormick, T., 2000. An integrated approach to the study of glaciolacustrine landforms and sediments: a case study from Hagavatn, Iceland. Quat. Sci. Rev. 19, 633–665. https://doi.org/10.1016/S0277-3791(99)00013-X

Berkson, M.J., Clay, C.S., 1973. Microphysiography and Possible Iceberg Grooves on the Floor of Western Lake Superior. Geol. Soc. Am. Bull. 84, 1315. https://doi.org/10.1130/0016-7606(1973)84<1315:MAPIGO>2.0.CO;2

Bingham, R.G., Vaughan, D.G., King, E.C., Davies, D., Cornford, S.L., Smith, A.M., Arthern, R.J., Brisbourne, A.M., De Rydt, J., Graham, A.G.C., Spagnolo, M., Marsh, O.J., Shean, D.E., 2017. Diverse landscapes beneath Pine Island Glacier influence ice flow. Nat. Commun. 8, 1618. https://doi.org/10.1038/s41467-017-01597-y

Bjarnadóttir, L.R., Andreassen, K., 2016. Ice-stream landform assemblage in Kveithola, western Barents Sea margin. Geol. Soc. London, Mem. 46, 325–328. https://doi.org/10.1144/m46.145

Bjarnadóttir, L.R., Winsborrow, M.C.M., Andreassen, K., 2017. Large subglacial meltwater features in the central Barents Sea. Geology 45, 159–162. https://doi.org/10.1130/G38195.1

Bjarnadóttir, L.R.R., Winsborrow, M.C.M.C.M., Andreassen, K., 2017. Large subglacial meltwater features in the central Barents Sea. Geology 45, 159–162. https://doi.org/10.1130/G38195.1

Bogen, J., Xu, M., Kennie, P., 2015. The impact of pro-glacial lakes on downstream sediment delivery in

Norway. Earth Surf. Process. Landforms 40, 942–952. https://doi.org/10.1002/esp.3669

Bond, G., Heinrich, H., Broecker, W., Labeyrie, L., McManus, J., Andrews, J., Huon, S., Jantschik, R., Clasen, S., Simet, C., Tedesco, K., Klas, M., Bonani, G., Ivy, S., 1992. Evidence for massive discharges of icebergs into the North Atlantic ocean during the last glacial period. Nature 360, 245–249. https://doi.org/10.1038/360245a0

Boulton, G.S., 1996. Theory of glacial erosion, transport and deposition as a consequence of subglacial sediment deformation. J. Glaciol. 42, 43–62. https://doi.org/10.3189/S0022143000030525

Boulton, G.S., 1990. Sedimentary and sea level changes during glacial cycles and their control on glacimarine facies architecture. Geol. Soc. Spec. Publ. 53, 15–52. https://doi.org/10.1144/GSL.SP.1990.053.01.02

Boulton, G.S., 1979. Processes of Glacier Erosion on Different Substrata. J. Glaciol. 23, 15–38. https://doi.org/10.3189/S0022143000029713

Boulton, G.S., 1972. Modern Arctic glaciers as depositional models for former ice sheets. J. Geol. Soc. London 128, 361–393. https://doi.org/10.1144/gsjgs.128.4.0361

Boulton, G.S., Caban, P.E., Van Gijssel, K., 1995. Groundwater Flow Beneath Ice Sheets : Part I - Patterns. Quat. Sci. Rev. 14, 545–562. https://doi.org/10.1016/0277-3791(95)00039-r

Boulton, G.S., Deynoux, M., 1981. Sedimentation in glacial environments and the identification of tills and tillites in ancient sedimentary sequences. Precambrian Res. 15, 397–422. https://doi.org/10.1016/0301-9268(81)90059-0

Bradley, R.S., 2015. Climate and Climatic Variation. Paleoclimatology 13–54. https://doi.org/10.1016/B978-0-12-386913-5.00002-8

Brennand, T.A., 2000. Deglacial meltwater drainage and glaciodynamics: inferences from Laurentide eskers, Canada. Geomorphology 32, 263–293. https://doi.org/10.1016/S0169-555X(99)00100-2

Brodzikowski, K., Loon, A.J. van, 1991. Glacigenic sediments. Elsevier Science.

Brodzikowski, K., van Loon, A.J., 1987. A systematic classification of glacial and periglacial environments, facies and deposits. Earth Sci. Rev. 24, 297–381. https://doi.org/10.1016/0012-8252(87)90061-4

Brookshire, B.N., Landers, F.P., Stein, J.A., 2015. Applicability of ultra-high-resolution 3D seismic data for geohazard identification at mid-slope depths in the Gulf of Mexico: Initial results. Underw. Technol. 32, 271–278. https://doi.org/10.3723/ut.32.271

Burke, M.J., Brennand, T.A., Sjogren, D.B., 2015. The role of sediment supply in esker formation and ice tunnel evolution. Quat. Sci. Rev. 115, 50–77. https://doi.org/10.1016/J.QUASCIREV.2015.02.017

Busfield, M.E., Le Heron, D.P., 2018. Snowball Earth Under the Microscope. J. Sediment. Res. 88, 659–677. https://doi.org/10.2110/jsr.2018.34

Camargo, J.M.R., Silva, M.V.B., Júnior, A.V.F., Araújo, T.C.M., 2019. Marine geohazards: A bibliometric-based review. Geosci. https://doi.org/10.3390/geosciences9020100

Camerlenghi, A., Domack, E., Rebesco, M., Gilbert, R., Ishman, S., Leventer, A., Brachfeld, S., Drake, A., 2001. Glacial morphology and post-glacial contourites in northern Prince Gustav Channel (NW Weddell Sea, Antarctica). Mar. Geophys. Res. 22, 417–443. https://doi.org/10.1023/A:1016399616365

Canals, M., Amblas, D., Casamor, J.L., 2016. Cross-shelf troughs in Central Bransfield Basin, Antarctic Peninsula. Geol. Soc. Mem. 46, 171–172. https://doi.org/10.1144/M46.138

Carrivick, J.L., Tweed, F.S., 2013. Proglacial Lakes: Character, behaviour and geological importance. Quat. Sci. Rev. 78, 34–52. https://doi.org/10.1016/j.quascirev.2013.07.028

Catuneanu, O., 2006. Principles of sequence stratigraphy. Elsevier.

Catuneanu, O., 2002. Sequence stratigraphy of clastic systems: Concepts, merits, and pitfalls. J. African Earth Sci. 35, 1–43. https://doi.org/10.1016/S0899-5362(02)00004-0

Catuneanu, O., Abreu, V., Bhattacharya, J.P., Blum, M.D., Dalrymple, R.W., Eriksson, P.G., Fielding, C.R., Fisher, W.L., Galloway, W.E., Gibling, M.R., Giles, K.A., Holbrook, J.M., Jordan, R., Kendall, C.G.S.C., Macurda, B., Martinsen, O.J., Miall, A.D., Neal, J.E., Nummedal, D., Pomar, L., Posamentier, H.W., Pratt, B.R., Sarg, J.F., Shanley, K.W., Steel, R.J., Strasser, A., Tucker, M.E., Winker, C., 2009. Towards the standardization of sequence stratigraphy. Earth-Science Rev. https://doi.org/10.1016/j.earscirev.2008.10.003

Catuneanu, O., Galloway, W.E., Kendall, C.G.S.C., Miall, A.D., Posamentier, H.W., Strasser, A., Tucker, M.E., 2011. Sequence Stratigraphy: Methodology and Nomenclature. Newsletters Stratigr. 44, 173–245. https://doi.org/10.1127/0078-0421/2011/0011

Chewings, J.M., Atkins, C.B., Dunbar, G.B., Golledge, N.R., 2014. Aeolian sediment transport and deposition in a modern high-latitude glacial marine environment. Sedimentology 61, 1535–1557. https://doi.org/10.1111/sed.12108

Clark-Lowes, D.D., 2005. Arabian glacial deposits: Recognition of palaeovalleys within the Upper Ordovician Sarah Formation, Al Qasim district, Saudi Arabia. Proc. Geol. Assoc. https://doi.org/10.1016/S0016-7878(05)80051-3

Clark, C.D., Hughes, A.L.C., Greenwood, S.L., Spagnolo, M., Ng, F.S.L., 2009. Size and shape characteristics of drumlins, derived from a large sample, and associated scaling laws. Quat. Sci. Rev. 28, 677–692. https://doi.org/10.1016/j.quascirev.2008.08.035

Clark, C.D., Spagnolo, M., 2016. Glacially eroded cross-shelf troughs surrounding Iceland from Olex data. Geol. Soc. Mem. 46, 165–166. https://doi.org/10.1144/M46.86

Clarke, B.G., 2018. The engineering properties of glacial tills. Geotech. Res. 5, 262–277. https://doi.org/10.1680/jgere.18.00020

Clarke, G.K.C., 1987. Subglacial till: A physical framework for its properties and processes. J. Geophys. Res. 92, 9023. https://doi.org/10.1029/JB092iB09p09023

Clerc, S., Buoncristiani, J.F., Guiraud, M., Vennin, E., Desaubliaux, G., Portier, E., 2013. Subglacial to proglacial depositional environments in an Ordovician glacial tunnel valley, Alnif, Morocco. Palaeogeogr. Palaeoclimatol. Palaeoecol. 370, 127–144. https://doi.org/10.1016/j.palaeo.2012.12.002

Craig, J., Thurow, J., Thusu, B., Whitham, A., Abutarruma, Y., 2009. Global Neoproterozoic petroleum systems: the emerging potential in North Africa. Glob. Neoproterozoic Pet. Syst. Emerg. Potential North Africa 326, 1–25. https://doi.org/10.1144/sp326.1

Craigie, N.W., Rees, A., MacPherson, K., Berman, S., 2016. Chemostratigraphy of the Ordovician Sarah Formation, North West Saudi Arabia: An integrated approach to reservoir correlation. Mar. Pet. Geol. 77, 1056–1080. https://doi.org/10.1016/J.MARPETGEO.2016.07.009

Dahlgren, K.I.T., Vorren, T.O., Stoker, M.S., Nielsen, T., Nygård, A., Petter Sejrup, H., 2005. Late Cenozoic prograding wedges on the NW European continental margin: their formation and relationship to tectonics and climate. Mar. Pet. Geol. 22, 1089–1110. https://doi.org/10.1016/j.marpetgeo.2004.12.008

Davies, B.J., Glasser, N.F., Carrivick, J.L., Hambrey, M.J., Smellie, J.L., Nyvlt, D., 2013. Landscape evolution and ice-sheet behaviour in a semi-arid polar environment: James Ross Island, NE Antarctic Peninsula. Geol. Soc. London, Spec. Publ. 381, 1–43. https://doi.org/10.1144/SP381.1

Derbyshire, E., Owen, L.A., 2017. Glacioaeolian Processes, Sediments, and Landforms, Past Glacial Environments: Second Edition. Elsevier Ltd. https://doi.org/10.1016/B978-0-08-100524-8.00008-7

Deschamps, R., Eschard, R., Roussé, S., 2013. Architecture of Late Ordovician glacial valleys in the Tassili N'Ajjer area (Algeria). Sediment. Geol. 289. https://doi.org/10.1016/j.sedgeo.2013.02.012

Dietrich, P., Ghienne, J.-F., Normandeau, A., Lajeunesse, P., 2016. Upslope-Migrating Bedforms In A Proglacial Sandur Delta: Cyclic Steps From River-Derived Underflows? J. Sediment. Res. 86, 113–123. https://doi.org/10.2110/jsr.2016.4

Dietrich, P., Ghienne, J.-F.F., Normandeau, A., Lajeunesse, P., 2017. Reconstructing ice-margin retreat using delta morphostratigraphy. Sci. Rep. 7, 16936. https://doi.org/10.1038/s41598-017-16763-x

Dietrich, P., Hofmann, A., 2019. Ice-margin fluctuation sequences and grounding zone wedges: The record of the Late Palaeozoic Ice Age in the eastern Karoo Basin (Dwyka Group, South Africa . Depos. Rec. 5, 247–271. https://doi.org/10.1002/dep2.74

Dixon, R.J., Moore, J.K.S., Bourne, M., Dunn, E., Haig, D.B., Hossack, J., Roberts, N., Simmons, C.J., 2010. Petroleum Geology Conference series Integrated petroleum systems and play fairway analysis in a complex Palaeozoic basin : Ghadames-Illizi Basin , North Africa Integrated petroleum systems and play fairway analysis in a complex Palaeozoic basin : Ghadames. Pet. Geol. Conf. Ser. 7, 735–760.

https://doi.org/10.1144/0070735

Domack, E.W., 1982. Sedimentology of glacial and glacial marine deposits on the George V-Adelie continental shelf, East Antarctica. Boreas 11, 79–97. https://doi.org/10.1111/j.1502-3885.1982.tb00524.x

Domack, E.W., Lawson, D.E., 1985. Pebble Fabric in an Ice-Rafted Diamicton. J. Geol. 93, 577–591. https://doi.org/10.1086/628982

Dowdeswell, J.A., Bamber, J.L., 2007. Keel depths of modern Antarctic icebergs and implications for sea-floor scouring in the geological record. Mar. Geol. 243, 120–131. https://doi.org/10.1016/j.margeo.2007.04.008

Dowdeswell, J.A., Canals, M., Jakobsson, M., Todd, B.J., Dowdeswell, E.K., Hogan, K.A., 2016a. Introduction: an *Atlas of Submarine Glacial Landforms*. Geol. Soc. London, Mem. 46, 3–14. https://doi.org/10.1144/M46.171

Dowdeswell, J.A., Canals, M., Jakobsson, M., Todd, B.J., Dowdeswell, E.K., Hogan, K.A., 2016b. The variety and distribution of submarine glacial landforms and implications for ice-sheet reconstruction. Geol. Soc. London, Mem. 46, 519–552. https://doi.org/10.1144/M46.183

Dowdeswell, J.A., Cofaigh, C.Ó., 2002. Glacier-influenced sedimentation on high-latitude continental margins: introduction and overview. Geol. Soc. London, Spec. Publ. 203, 1–9. https://doi.org/10.1144/GSL.SP.2002.203.01.01

Dowdeswell, J.A., Dowdeswell, E.K., 1989. Debris in Icebergs and Rates of Glaci-Marine Sedimentation: Observations from Spitsbergen and a Simple Model. J. Geol. https://doi.org/10.2307/30065541

Dowdeswell, J.A., Fugelli, E.M.G., 2012. The seismic architecture and geometry of grounding-zone wedges formed at the marine margins of past ice sheets. Bull. Geol. Soc. Am. 124, 1750–1761. https://doi.org/10.1130/B30628.1

Dowdeswell, J.A., Ó Cofaigh, C., Pudsey, C.J., 2004. Continental slope morphology and sedimentary processes at the mouth of an Antarctic palaeo-ice stream. Mar. Geol. 204, 203–214. https://doi.org/10.1016/S0025-3227(03)00338-4

Dowdeswell, J.A., Ottesen, D., 2016. Current-modified recessional-moraine ridges on the NW Spitsbergen shelf. Geol. Soc. Mem. 46, 255–256. https://doi.org/10.1144/M46.68

Dowdeswell, J.A.A., Bamber, J.L.L., 2007. Keel depths of modern Antarctic icebergs and implications for sea-floor scouring in the geological record. Mar. Geol. 243, 120–131. https://doi.org/10.1016/j.margeo.2007.04.008

Dowdeswell, J.A.A., O'Cofaigh, C., Noormets, R., Larter, R.D.D., Hillenbrand, C.-D.D., Benetti, S., Evans, J., Pudsey, C.J.J., 2008. A major trough-mouth fan on the continental margin of the Bellingshausen Sea, West Antarctica: The Belgica Fan. Mar. Geol. 252, 129–140.

https://doi.org/10.1016/j.margeo.2008.03.017

Dunlop, P., Clark, C.D., 2006. The morphological characteristics of ribbed moraine. Quat. Sci. Rev. 25, 1668–1691. https://doi.org/10.1016/j.quascirev.2006.01.002

Ehlers, J., Gibbard, P.L., Hughes, P.D., 2011. Quaternary glaciations - extent and chronology : a closer look. Elsevier.

El-Ghali, M.A.K., 2005. Depositional environments and sequence stratigraphy of paralic glacial, paraglacial and postglacial Upper Ordovician siliciclastic deposits in the Murzuq Basin, SW Libya. Sediment. Geol. 177, 145–173. https://doi.org/10.1016/j.sedgeo.2005.02.006

Elhebiry, M.S., Sultan, M., Abu El-Leil, I., Kehew, A.E., Bekiet, M.H., Abdel Shahid, I., Soliman, N.M.A., Abotalib, A.Z., Emil, M., 2019. Paleozoic glaciation in NE Africa: field and remote sensing-based evidence from the South Eastern Desert of Egypt. Int. Geol. Rev. https://doi.org/10.1080/00206814.2019.1636416

Elmore, C.R., Gulick, S.P.S., Willems, B., Powell, R., 2013. Seismic stratigraphic evidence for glacial expanse during glacial maxima in the Yakutat Bay Region, Gulf of Alaska. Geochemistry, Geophys. Geosystems 14, 1294–1311. https://doi.org/10.1002/ggge.20097

Ely, J.C., Clark, C.D., Spagnolo, M., Stokes, C.R., Greenwood, S.L., Hughes, A.L.C., Dunlop, P., Hess, D., 2016. Do subglacial bedforms comprise a size and shape continuum? Geomorphology 257, 108–119. https://doi.org/10.1016/j.geomorph.2016.01.001

Emery, A.R., Hodgson, D.M., Barlow, N.L.M., Carrivick, J.L., Cotterill, C.J., Mellett, C.L., Booth, A.D., 2019a. Topographic and hydrodynamic controls on barrier retreat and preservation: An example from Dogger Bank, North Sea. Mar. Geol. 416. https://doi.org/10.1016/j.margeo.2019.105981

Emery, A.R., Hodgson, D.M., Barlow, N.L.M., Carrivick, J.L., Cotterill, C.J., Phillips, E., 2019b. Left High and Dry: Deglaciation of Dogger Bank, North Sea, Recorded in Proglacial Lake Evolution. Front. Earth Sci. 7. https://doi.org/10.3389/feart.2019.00234

Emery, D., Myers, K., Bertram, G.T., 1996. Sequence stratigraphy. Blackwell Science.

Esteves, M., Bjarnadóttir, L.R., Winsborrow, M.C.M., Shackleton, C.S., Andreassen, K., 2017. Retreat patterns and dynamics of the Sentralbankrenna glacial system, central Barents Sea. Quat. Sci. Rev. 169, 131–147. https://doi.org/10.1016/J.QUASCIREV.2017.06.004

Evans, D.J.A., 2006. Glacial Landsystems, in: Glacier Science and Environmental Change. Blackwell Publishing, Malden, MA, USA, pp. 83–88. https://doi.org/10.1002/9780470750636.ch18

Evans, D.J.A., Hiemstra, J.F., Cofaigh, C.O., 2012. Stratigraphic architecture and sedimentology of a Late Pleistocene subaqueous moraine complex, southwest Ireland. J. Quat. Sci. 27, 51–63. https://doi.org/10.1002/jqs.1513

Evans, D.J.A., Phillips, E.R., Hiemstra, J.F., Auton, C.A., 2006. Subglacial till: Formation, sedimentary characteristics and classification. Earth-Science Rev. 78, 115–176. https://doi.org/10.1016/j.earscirev.2006.04.001

Evans, D.J.A., Thomson, S.A., 2010. Glacial sediments and landforms of Holderness, eastern England: A glacial depositional model for the North Sea Lobe of the British-Irish Ice Sheet. Earth-Science Rev. 101, 147–189. https://doi.org/10.1016/j.earscirev.2010.04.003

Eyles, C.H., Eyles, N., Franca, A.B., 1993. Glaciation and tectonics in an active intracratonic basin: the late Palaeozoic Itarare Group, Parana Basin, Brazil. Sedimentology 40, 1–25. https://doi.org/https://doi.org/10.1111/j.1365-3091.1993.tb01087.x

Eyles, C.H., Eyles, N., Miall, A.D., 1985. Models of glaciomarine sedimentation and their application to the interpretation of ancient glacial sequences. Palaeogeogr. Palaeoclimatol. Palaeoecol. 51, 15–84. https://doi.org/10.1016/0031-0182(85)90080-X

Eyles, N., 2008. Glacio-epochs and the supercontinent cycle after ~ 3.0 Ga: Tectonic boundary conditions for glaciation. Palaeogeogr. Palaeoclimatol. Palaeoecol. 258, 89–129. https://doi.org/10.1016/j.palaeo.2007.09.021

Eyles, N., 1993. Earth's glacial record and its tectonic setting. Earth Sci. Rev. 35, 1–248. https://doi.org/10.1016/0012-8252(93)90002-O

Farmer, G.T., Cook, J., 2013. Pleistocene Glaciations, in: Climate Change Science: A Modern Synthesis. Springer Netherlands, Dordrecht, pp. 407–427. https://doi.org/10.1007/978-94-007-5757-8_21

Fichler, C., Henriksen, S., Rueslaatten, H., Hovland, M., 2005. North Sea Quaternary morphology from seismic and magnetic data: indications for gas hydrates during glaciation? . Pet. Geosci. 11, 331–337. https://doi.org/10.1144/1354-079304-635

Fildani, A., Hessler, A.M., Mason, C.C., McKay, M.P., Stockli, D.F., 2018. Late Pleistocene glacial transitions in North America altered major river drainages, as revealed by deep-sea sediment. Sci. Rep. 8, 13839. https://doi.org/10.1038/s41598-018-32268-7

Firth, J., Vinje, V., 2018. On top of the spread. Oilf. Technol.

Fjeldskaar, W., 1994. The amplitude and decay of the glacial forebulge in Fennoscandia. Nor. Geol. Tidsskr. 74, 2–8.

Fleisher, P.J., 1986. Dead-ice sinks and moats: environments of stagnant ice deposition. Geology 14, 39–42. https://doi.org/10.1130/0091-7613(1986)14<39:DSAMEO>2.0.CO;2

Forbes, G.A., Janseni, H.S.M., Schreurs, J., 2010. Lexicon of oman subsurface stratigraphy. GeoArabia 15, 210–215.

Fortuin, A.R., 1984. Late ordovician glaciomarine deposits (orea shale) in the sierra de albarracin, Spain. Palaeogeogr. Palaeoclimatol. Palaeoecol. 48, 245–261. https://doi.org/10.1016/0031-0182(84)90047-6

Fyfe, G.J., 1990. The effect of water depth on ice-proximal glaciolacustrine sedimentation: Salpausselkä I, southern Finland. Boreas 19, 147–164. https://doi.org/10.1111/j.1502-3885.1990.tb00576.x

Gales, J., Hillenbrand, C.-D., Larter, R., Laberg, J.S., Melles, M., Benetti, S., Passchier, S., 2019. Processes influencing differences in Arctic and Antarctic trough mouth fan sedimentology. Geol. Soc. London, Spec. Publ. 475. https://doi.org/10.1144/SP475.7

García, J.L., Strelin, J.A., Vega, R.M., Hall, B.L., Stern, C.R., 2015. Ambientes glaciolacustres y construcción estructural de morrenas frontales tardiglaciales en Torres del Paine, Patagonia austral chilena. Andean Geol. 42, 190–212. https://doi.org/10.5027/andgeoV42n2-a03

Ghienne, J.F., 2003. Late Ordovician sedimentary environments, glacial cycles, and post-glacial transgression in the Taoudeni Basin, West Africa. Palaeogeogr. Palaeoclimatol. Palaeoecol. 189, 117–145. https://doi.org/10.1016/S0031-0182(02)00635-1

Ghienne, J.F., Deynoux, M., 1998. Large-scale channel fill structures in Late Ordovician glacial deposits in Mauritania, western Sahara. Sediment. Geol. 119, 141–159. https://doi.org/10.1016/S0037-0738(98)00045-1

Girard, F., Ghienne, J.-F., Rubino, J.-L., 2012. Channelized sandstone bodies (‘cordons’) in the Tassili N’Ajjer (Algeria & Libya): snapshots of a Late Ordovician proglacial outwash plain. Geol. Soc. London, Spec. Publ. 368, 355–379. https://doi.org/10.1144/sp368.3

Glückert, G., 1995. The Baltic Ice Lake in south Finland and its outlets. Quat. Int. 27, 47–51. https://doi.org/10.1016/1040-6182(94)00059-E

Glückert, G., 1986. The First Salpausselkä at Lohja, southern Finland. Bull. Geol. Soc. Finl. 58, 45–55.

Gold, C., 2009. Varves in lacustrine sediments – an overview. Www.Geo.Tu-Freiberg.De 11.

Gomez, B., Smith, L.C., Magilligan, F.J., Mertes, L.A.K., Smith, N.D., 2000. Glacier outburst floods and outwash plain development: Skeiäarársandur, Iceland. Terra Nov. 12, 126–131. https://doi.org/10.1111/j.1365-3121.2000.00277.x

Graham, A.G.C., Larter, R.D., Gohl, K., Hillenbrand, C.-D., Smith, J.A., Kuhn, G., 2009. Bedform signature of a West Antarctic palaeo-ice stream reveals a multi-temporal record of flow and substrate control. Quat. Sci. Rev. 28, 2774–2793. https://doi.org/10.1016/j.quascirev.2009.07.003

Graham, A.G.C., Lonergan, L., Stoker, M.S., 2007. Evidence for Late Pleistocene ice stream activity in the Witch Ground Basin, central North Sea, from 3D seismic reflection data. Quat. Sci. Rev. 26, 627–643. https://doi.org/10.1016/j.quascirev.2006.11.004

Greenwood, S.L., Simkins, L.M., Halberstadt, A.R.W., Prothro, L.O., Anderson, J.B., 2018. Holocene reconfiguration and readvance of the East Antarctic Ice Sheet. Nat. Commun. 9, 3176. https://doi.org/10.1038/s41467-018-05625-3

Griffiths, J.S., Martin, C.J., 2017. Engineering Geology and Geomorphology of Glaciated and Periglaciated Terrains: Engineering Group Working Party Report, Volume 28. ed, Geological Society, London, Engineering Geology Special Publications. The Geological Society of London. https://doi.org/DOI: https://doi.org/10.1144/EGSP28

Gruszka, B., Morawski, W., Zieliński, T., 2012. Sedimentary record of a Pleistocene ice-sheet interlobate zone (NE Poland). Geologos 18, 65–81. https://doi.org/10.2478/v10118-012-0005-1

Gupta, S., Collier, J.S., Garcia-Moreno, D., Oggioni, F., Trentesaux, A., Vanneste, K., De Batist, M., Camelbeeck, T., Potter, G., Van Vliet-Lanoë, B., Arthur, J.C.R., 2017. Two-stage opening of the Dover Strait and the origin of island Britain. Nat. Commun. 8, 15101. https://doi.org/10.1038/ncomms15101

Haavik, K.E., Landrø, M., 2014. Iceberg ploughmarks illuminated by shallow gas in the central North Sea. Quat. Sci. Rev. 103, 34–50. https://doi.org/10.1016/j.quascirev.2014.09.002

Hadley, D., Ain, a, Focke, J., 1991. Old Sandstones, New Horizons. Middle East Well Eval. Rev. 11, 10–26.

Hanson, M.A., Clague, J.J., 2016. Record of glacial Lake Missoula floods in glacial Lake Columbia, Washington. Quat. Sci. Rev. 133, 62–76. https://doi.org/10.1016/j.quascirev.2015.12.009

Heron, D.P. Le, 2018. An exhumed Paleozoic glacial landscape in Chad. Geology 46, 91–94. https://doi.org/10.1130/G39510.1

Heron, D.P. Le, Meinhold, G., Elgadry, M., Abutarruma, Y., Boote, D., 2015. Early Palaeozoic evolution of Libya: perspectives from Jabal Eghei with implications for hydrocarbon exploration in Al Kufrah Basin. Basin Res. 27, 60–83. https://doi.org/10.1111/bre.12057

Hesse, R., Klaucke, I., Khodabakhsh, S., Piper, D.J.W., Ryan, W.B.F., Hesse, R., 2001. Potential deep-water reservoirs 8, 1499–1521.

Heward, A.P., Penney, R.A., 2014. Al Khlata glacial deposits in the Oman Mountains and their implications. Geol. Soc. London, Spec. Publ. 392, 279–301. https://doi.org/10.1144/SP392.15

Hirst, J.P.P., 2012. Ordovician proglacial sediments in Algeria: insights into the controls on hydrocarbon reservoirs in the In Amenas field, Illizi Basin. Geol. Soc. London, Spec. Publ. 368, 319–353. https://doi.org/10.1144/SP368.17

Hirst, J.P.P., Benbakir, A., Payne, D.F., Westlake, I.R., 2002. Tunnel valleys and density flow processes in the Upper Ordovician glacial succession, Illizi Basin, Algeria: Influence on reservoir quality. J. Pet. Geol. 25, 297–324. https://doi.org/10.1111/j.1747-5457.2002.tb00011.x

Hirst, J.P.P., Khatatneh, M., 2019. Depositional model for the distal Ordovician glaciated margin of Jordan; implications for the reservoir potential of the Risha Formation. Geol. Soc. London, Spec. Publ. 475, 109–129. https://doi.org/10.1144/SP475.4

Hodell, D.A., Nicholl, J.A., Bontognali, T.R.R., Danino, S., Dorador, J., Dowdeswell, J.A., Einsle, J., Kuhlmann, H., Martrat, B., Mleneck-Vautravers, M.J., Rodríguez-Tovar, F.J., Röhl, U., 2017. Anatomy of Heinrich Layer 1 and its role in the last deglaciation. Paleoceanography 32, 284–303. https://doi.org/10.1002/2016PA003028

Hodgson, D.A., Graham, A.G.C., Griffiths, H.J., Roberts, S.J., Cofaigh, C.Ó., Bentley, M.J., Evans, D.J.A., 2014. Glacial history of sub-Antarctic South Georgia based on the submarine geomorphology of its fjords. Quat. Sci. Rev. 89, 129–147. https://doi.org/10.1016/j.quascirev.2013.12.005

Holmes, R., Stoker, S.J., 2005. Investigation of the origin of shallow gas in outer Moray Firth open blocks 15/20c and 15/25d.

Houmark-Nielsen, M., 2007. Extent and age of Middle and Late Pleistocene glaciations and periglacial episodes in southern Jylland, Denmark. Bull. Geol. Soc. Denmark 55, 9–35.

Hughes, A.L.C., Clark, C.D., Jordan, C.J., 2014. Flow-pattern evolution of the last British Ice Sheet. Quat. Sci. Rev. 89, 148–168. https://doi.org/10.1016/j.quascirev.2014.02.002

Huuse, M., Le Heron, D.P., Dixon, R., Redfern, J., Moscariello, a., Craig, J., 2012. Glaciogenic reservoirs and hydrocarbon systems: an introduction. Geol. Soc. London, Spec. Publ. 368, 1–28. https://doi.org/10.1144/SP368.19

Huuse, M., Lykke-Andersen, H., 2000. Large-scale glaciotectonic thrust structures in the eastern Danish North Sea. Geol. Soc. London, Spec. Publ. 176, 293–305. https://doi.org/10.1144/GSL.SP.2000.176.01.22

Ingólfsson, Ó., Benediktsson, Í.Ö., Schomacker, A., Kjær, K.H., Brynjólfsson, S., Jónsson, S.A., Korsgaard, N.J., Johnson, M.D., 2016. Glacial geological studies of surge-type glaciers in Iceland - Research status and future challenges. Earth-Science Rev. 152, 37–69. https://doi.org/10.1016/j.earscirev.2015.11.008

Jamieson, S.S.R., Hulton, N.R.J., Hagdorn, M., 2008. Modelling landscape evolution under ice sheets. Geomorphology 97, 91–108. https://doi.org/10.1016/J.GEOMORPH.2007.02.047

Jamieson, S.S.R., Stokes, C.R., Livingstone, S.J., Vieli, A., Cofaigh, C., Hillenbrand, C.D., Spagnolo, M., 2016. Subglacial processes on an Antarctic ice stream bed. 2: Can modelled ice dynamics explain the morphology of mega-scale glacial lineations? J. Glaciol. 62, 285–298. https://doi.org/10.1017/jog.2016.19

Jervey, M.T., 1988. Quantitative geological modeling of siliciclastic rock sequences and their seismic expression. Sea-Level Chang. 42, 47–69. https://doi.org/10.2110/pec.88.01.0047

Jones, B.G., Fergusson, C.L., Zambelli, P.F., 1993. Ordovician contourites in the Lachlan Fold Belt, eastern

Australia. Sediment. Geol. 82, 257–270. https://doi.org/10.1016/0037-0738(93)90125-O

Kehew, A.E., Piotrowski, J.A., Jørgensen, F., 2012. Tunnel valleys: Concepts and controversies - A review. Earth-Science Rev. 113, 33–58. https://doi.org/10.1016/j.earscirev.2012.02.002

Khalifa, M.A., 2015. Glacial and post-glacial deposits of the Unayzah Formation (Carboniferous-Permian), Saudi Arabia: facies analysis and sequence stratigraphy. Carbonates and Evaporites 30, 207–227. https://doi.org/10.1007/s13146-014-0206-5

King, E.L., Rise, L., Bellec, V.K., 2016. Crescentic submarine hills and holes produced by iceberg calving and rotation. Geol. Soc. London, Mem. 46, 267–268. https://doi.org/10.1144/M46.119

Klages, J.P., Kuhn, G., Graham, A.G.C., Hillenbrand, C.-D., Smith, J.A., Nitsche, F.O., Larter, R.D., Gohl, K., 2015. Palaeo-ice stream pathways and retreat style in the easternmost Amundsen Sea Embayment, West Antarctica, revealed by combined multibeam bathymetric and seismic data. Geomorphology 245, 207–222. https://doi.org/10.1016/J.GEOMORPH.2015.05.020

Klages, J.P., Kuhn, G., Hillenbrand, C.-D., Graham, A.G.C., Smith, J.A., Larter, R.D., Gohl, K., 2016. A glacial landform assemblage from an inter-ice stream setting in the eastern Amundsen Sea Embayment, West Antarctica. Geol. Soc. London, Mem. 46, 349–352. https://doi.org/10.1144/M46.147

Kleman, J., Stroeven, A.P., Lundqvist, J., 2008. Patterns of Quaternary ice sheet erosion and deposition in Fennoscandia and a theoretical framework for explanation. Geomorphology 97, 73–90. https://doi.org/10.1016/j.geomorph.2007.02.049

Klett, T.., 2000. Total Petroleum Systems of the Illizi Province , Algeria and Libya — Tanezzuft-Illizi U . S . Department of the Interior. U. S. Geol. Surv. 1.

Knutz, P.C., Newton, A.M.W., Hopper, J.R., Huuse, M., Gregersen, U., Sheldon, E., Dybkjær, K., 2019. Eleven phases of Greenland Ice Sheet shelf-edge advance over the past 2.7 million years. Nat. Geosci. 12, 361–368. https://doi.org/10.1038/s41561-019-0340-8

Koch, Z.J., Isbell, J.L., 2013. Processes and products of grounding-line fans from the Permian Pagoda Formation, Antarctica: Insight into glacigenic conditions in polar Gondwana. Gondwana Res. 24, 161–172. https://doi.org/10.1016/j.gr.2012.10.005

Kocurek, G., Havholm, K.G., 1993. Eolian sequence stratigraphy - A conceptual framework, in: Siliclastic Sequence Stratigraphy: Recent Developments and Applications. AAPG Special Volumes, pp. 393–409.

Kristensen, T.B., Huuse, M., Piotrowski, J. a, Clausen, O.R., 2007. A morphometric analysis of tunnel valleys in the eastern North Sea based on 3D seismic data. J. Quat. Sci. 22, 801–815. https://doi.org/10.1002/jqs

Krüger, J., Schomacker, A., Örn Benediktsson, Í., 2009. 6 Ice-Marginal Environments: Geomorphic and Structural Genesis of Marginal Moraines at Mýrdalsjökull. Dev. Quat. Sci. 13, 79–104. https://doi.org/10.1016/S1571-0866(09)01306-2

Krzyszkowski, D., Zielinski, T., 2002. The Pleistocene end moraine fans: Controls on their sedimentation and location. Sediment. Geol. 149, 73–92. https://doi.org/10.1016/S0037-0738(01)00245-7

Kurjanski, B., Rea, B.R., Spagnolo, M., Winsborrow, M., Cornwell, D.G., Andreassen, K., Howell, J., 2019. Morphological evidence for marine ice stream shutdown, central Barents Sea. Mar. Geol. 414, 64–76. https://doi.org/10.1016/j.margeo.2019.05.001

Kvalstad, T.J., Andresen, L., Forsberg, C.F., Berg, K., Bryn, P., Wangen, M., 2005. The Storegga slide: Evaluation of triggering sources and slide mechanics. Mar. Pet. Geol. 22, 245–256. https://doi.org/10.1016/j.marpetgeo.2004.10.019

Laberg, J.S., Dowdeswell, J.A., 2016. Glacigenic debris-flows on the Bear Island Trough-Mouth Fan, Barents Sea margin. Geol. Soc. London, Mem. 46, 367–368. https://doi.org/10.1144/M46.77

Laier, T., Jørgensen, N.O., Buchardt, B., Cederberg, T., Kuijpers, A., 1992. Accumulation and seepages of biogenic gas in northern Denmark. Cont. Shelf Res. 12, 1173–1186. https://doi.org/10.1016/0278-4343(92)90077-W

Lajeunesse, P., Allard, M., 2002. Sedimentology of an ice-contact glaciomarine fan complex, Nastapoka Hills, eastern Hudson Bay, northern Québec. Sediment. Geol. 152, 201–220. https://doi.org/10.1016/S0037-0738(02)00069-6

Lamb, R.M., Harding, R., Huuse, M., Stewart, M., Brocklehurst, S.H., 2017. The early Quaternary North Sea Basin. J. Geol. Soc. London. jgs2017-057. https://doi.org/10.1144/jgs2017-057

Lambeck, K., 1998. Sea-level change, flacial rebound and mantle viscosity for northen Europe. Geophys 134, 102–144.

Lane, A., Taylor, A., 2002. Geohazards: Are We Looking at Them the Right Way? View From Down Under, in: Offshore Technology Conference. Offshore Technology Conference. https://doi.org/10.4043/14106-MS

Lane, T.P., Roberts, D.H., Rea, B.R., Cofaigh, C., Vieli, A., Rodés, A., 2014. Controls upon the Last Glacial Maximum deglaciation of the northern Uummannaq Ice Stream System, West Greenland. Quat. Sci. Rev. 92, 324–344. https://doi.org/10.1016/j.quascirev.2013.09.013

Lang, J., Dixon, R.J., Le Heron, D.P., Winsemann, J., 2012. Depositional architecture and sequence stratigraphic correlation of Upper Ordovician glaciogenic deposits, Illizi Basin, Algeria. Geol. Soc. London, Spec. Publ. 368, 293–317. https://doi.org/10.1144/SP368.1

Lawson, D.E., 1981. Sedimentological characteristics and classification of depositional processes and deposits in the glacial environment 81–27, 22 p.

Le Heron, D.P., 2007. Late Ordovician glacial record of the Anti-Atlas, Morocco. Sediment. Geol. 201, 93–110. https://doi.org/10.1016/j.sedgeo.2007.05.004

Le Heron, D.P., Armstrong, H.A., Wilson, C., Howard, J.P., Gindre, L., 2010. Glaciation and deglaciation of the Libyan Desert: The Late Ordovician record. Sediment. Geol. 223, 100–125. https://doi.org/10.1016/j.sedgeo.2009.11.002

Le Heron, D.P., Craig, J., 2012. Neoproterozoic deglacial sediments and their hydrocarbon source rock potential. Geol. Soc. Spec. Publ. 368, 381–393. https://doi.org/10.1144/SP368.16

Le Heron, D.P., Craig, J., Etienne, J.L., 2009. Ancient glaciations and hydrocarbon accumulations in North Africa and the Middle East. Earth-Science Rev. 93, 47–76. https://doi.org/10.1016/j.earscirev.2009.02.001

Le Heron, D.P., Craig, J., Sutcliffe, O.E., Whittington, R., 2006. Late Ordovician glaciogenic reservoir heterogeneity: An example from the Murzuq Basin, Libya. Mar. Pet. Geol. 23, 655–677. https://doi.org/10.1016/j.marpetgeo.2006.05.006

Le Heron, D.P., Hogan, K.A., Phillips, E.R., Huuse, M., Busfield, M.E., Graham, A.G.C., 2019. An introduction to glaciated margins: the sedimentary and geophysical archive. Geol. Soc. London, Spec. Publ. 475. https://doi.org/10.1144/SP475.12

Le Heron, D.P., Sutcliffe, O.E., Whittington, R.J., Craig, J., 2005. The origins of glacially related soft-sediment deformation structures in Upper Ordovician glaciogenic rocks: Implication for ice-sheet dynamics. Palaeogeogr. Palaeoclimatol. Palaeoecol. 218, 75–103. https://doi.org/10.1016/j.palaeo.2004.12.007

Le Heron, D.P.P., Tofaif, S., Melvin, J., 2017. The Early Palaeozoic Glacial Deposits of Gondwana: Overview, Chronology, and Controversies, Past Glacial Environments: Second Edition. Elsevier Ltd. https://doi.org/10.1016/B978-0-08-100524-8.00002-6

Lea, J.M., Mair, D.W.F., Nick, F.M., Rea, B.R., van As, D., Morlighem, M., Nienow, P.W., Weidick, A., 2014. Fluctuations of a Greenlandic tidewater glacier driven by changes in atmospheric forcing: observations and modelling of Kangiata Nunaata Sermia, 1859–present. Cryosph. 8, 2031–2045. https://doi.org/10.5194/tc-8-2031-2014

Lebedeva-Ivanova, N., Polteau, S., Bellwald, B., Planke, S., Berndt, C., Stokke, H.H., 2018. Toward one-meter resolution in 3D seismic. Lead. Edge 37, 818–828. https://doi.org/10.1190/tle37110818.1

Lee, J., 2017. Glacial Lithofacies and Stratigraphy, Past Glacial Environments: Second Edition. Elsevier Ltd. https://doi.org/10.1016/B978-0-08-100524-8.00011-7

Levell, B.K., Braakman, J.H., Rutten, K.W., 1988. Oil-bearing sediments of Gondwana glaciation in Oman. Am. Assoc. Pet. Geol. Bull. 72, 775–796.

Leverington, D.W., Mann, J.D., Teller, J.T., 2002. Changes in the bathymetry and volume of glacial Lake Agassiz between 9200 and 7700 ^{14}C yr B.P. Quat. Res. 57, 244–252. https://doi.org/10.1006/qres.2001.2311

Levson, B.V.M., Ferbey, T., Kerr, B., Johnsen, T., Bednarski, J.M., Smith, R., Blackwell, J., Jonnes, S., 2003. Quaternary Geology and Aggregate Mapping in Northeast British Columbia : Applications for Oil and Gas

Exploration and Development 29–40.

Lewis, M. a., Cheney, C.S., O Dochartaigh, B.E., 2006. Guide to Permeability Indices.

Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. Paleoceanography 20, 1–17. https://doi.org/10.1029/2004PA001071

Livingstone, S.J., Clark, C.D., 2016. Morphological properties of tunnel valleys of the southern sector of the Laurentide Ice Sheet and implications for their formation. Earth Surf. Dyn. 4, 567–589. https://doi.org/10.5194/esurf-4-567-2016

Lonergan, L., Maidment, S.C.R., Collier, J.S., 2006. Pleistocene subglacial tunnel valleys in the central North Sea basin: 3-D morphology and evolution. J. Quat. Sci. 21, 891–903. https://doi.org/10.1002/jqs.1015

Lønne, I., 1995. Sedimentary facies and depositional architecture of ice-contact glaciomarine systems. Sediment. Geol. 98, 13–43. https://doi.org/10.1016/0037-0738(95)00025-4

Lønne, I., Nemec, W., 2004. High-arctic fan delta recording deglaciation and environment disequilibrium. Sedimentology 51, 553–589. https://doi.org/10.1111/j.1365-3091.2004.00636.x

Lopez-Gamundi, O.R., Buatois, L. a, 2010. Introduction: Late Paleozoic glacial events and postglacial transgressions in Gondwana. Geol. Soc. Am. Spec. Pap. 468, v–viii. https://doi.org/10.1130/2010.2468(00).

Lovell, H., Boston, C.M., 2017. Glacitectonic composite ridge systems and surge-type glaciers: an updated correlation based on Svalbard, Norway. Arktos 3, 2. https://doi.org/10.1007/s41063-017-0028-5

Lucchi, R.G., Rebesco, M., 2007. Glacial contourites on the Antarctic Peninsula margin: insight for palaeoenvironmental and palaeoclimatic conditions. Geol. Soc. London, Spec. Publ. 276, 111–127. https://doi.org/10.1144/GSL.SP.2007.276.01.06

Lüning, S., Craig, J., Loydell, D.., Štorch, P., Fitches, B., 2000. Lower Silurian `hot shales' in North Africa and Arabia: regional distribution and depositional model. Earth-Science Rev. 49, 121–200. https://doi.org/10.1016/S0012-8252(99)00060-4

Mackiewicz, N.E., Powell, R.D., Carlson, P.R., Molnia, B.F., 1984. Interlaminated ice-proximal glacimarine sediments in Muir Inlet, Alaska. Mar. Geol. 57, 113–147. https://doi.org/10.1016/0025-3227(84)90197-X

Magilligan, F.J., Gomez, B., Mertes, L. a K., Smith, L.C., Smith, N.D., Finnegan, D., Garvin, J.B., 2002. Geomorphic effectiveness, sandur developpement, and the pattern of lanscape response during jökulhlaups: Skeidarársandur, southeastern Iceland. Geomorphology 44, 95–113. https://doi.org/10.1016/S0169-555X(01)00147-7

Maizels, J., 2007. Sediments and landforms of modern proglacial terrestrial environments. Mod. Past Glacial Environ. 279–316. https://doi.org/10.1016/b978-075064226-2/50012-x

Maizels, J., 1997. Jokulhlaup deposits in proglacial areas. Quat. Sci. Rev. 16, 793–819. https://doi.org/10.1016/S0277-3791(97)00023-1

Margold, M., Stokes, C.R., Clark, C.D., 2015. Ice streams in the Laurentide Ice Sheet: Identification, characteristics and comparison to modern ice sheets. Earth-Science Rev. 143, 117–146. https://doi.org/10.1016/j.earscirev.2015.01.011

Maries, G., Ahokangas, E., Mäkinen, J., Pasanen, A., Malehmir, A., 2017. Architecture et caractéristiques hydrogéologiques associées d'eskers interlobés basées sur une combinaison de sismique réflexion à haute résolution et de tomographie par réfraction, Virttaankangas, Sud-Ouest de la Finlande. Hydrogeol. J. 25, 829–845. https://doi.org/10.1007/s10040-016-1513-9

Marks, L., 2012. Timing of the Late Vistulian (Weichselian) glacial phases in Poland. Quat. Sci. Rev. 44, 81–88. https://doi.org/10.1016/J.QUASCIREV.2010.08.008

Marks, L., 2005. Pleistocene glacial limits in the territory of Poland. Prz. Geol. 53, 988–993. https://doi.org/http://dx.doi.org/10.1016/S1571-0866(04)80079-4

Marren, P.M., 2005. Magnitude and frequency in proglacial rivers: a geomorphological and sedimentological perspective. Earth-Science Rev. 70, 203–251. https://doi.org/10.1016/j.earscirev.2004.12.002

Martin, H., 1981. The late Palaeozoic Gondwana glaciation. Geol. Rundschau 70, 480–496. https://doi.org/10.1007/BF01822128

Martin, J.R., Redfern, J., Aitken, J.F., 2008. A regional overview of the late Paleozoic glaciation in Oman. Resolv. Late Paleoz. Ice Age Time Space, Geol. Soc. Am. Spec. Publ. 441 80301, 175–186. https://doi.org/10.1130/2008.2441(12).

Martin, J.R., Redfern, J., Williams, B.P.J., 2012. Evidence for multiple ice centres during the late Palaeozoic ice age in Oman: Outcrop sedimentology and provenance of the late Carboniferous-Early Permian Al Khlata Formation. Geol. Soc. Spec. Publ. 368, 229–256. https://doi.org/10.1144/SP368.18

Meinsen, J., Winsemann, J., Weitkamp, A., Landmeyer, N., Lenz, A., Dölling, M., 2011. Middle Pleistocene (Saalian) lake outburst floods in the Münsterland Embayment (NW Germany): Impacts and magnitudes. Quat. Sci. Rev. 30, 2597–2625. https://doi.org/10.1016/j.quascirev.2011.05.014

Melvin, J., 2019. Zarqa megafacies: widespread subglacial deformation in the Sarah Formation of Saudi Arabia and implications for the sequence stratigraphy of the Hirnantian glaciation. Geol. Soc. London, Spec. Publ. 475, 53–80. https://doi.org/10.1144/SP475.6

Michael, N.A., Shammari, S., LePain, D., Abubshait, A., Guy, M., Van Dijk, C., Zuhlke, R., 2015. The Sarah Formation: A Glaciogenic Reservoir Analogue in Saudi Arabia. AAPG Annu. Conv. Exhib. 51167.

Michael, N.A., ZÜhlke, R., Hayton, S., 2018. The palaeo-valley infilling glaciogenic Sarah Formation, an example from Rahal Dhab palaeo-valley, Saudi Arabia. Sedimentology 65, 851–876.

https://doi.org/10.1111/sed.12408

Millson, J.A., Mercadier, C.G.L., Livera, S.E., Peters, J.M., 1996. The Lower Palaeozoic of Oman and its context in the evolution of a Gondwanan continental margin. J. Geol. Soc. London. 153, 213–230. https://doi.org/10.1144/gsjgs.153.6.1021

Milne, G.A., Gehrels, W.R., Hughes, C.W., Tamisiea, M.E., 2009. Identifying the causes of sea-level change. Nat. Geosci. 2, 471–478. https://doi.org/10.1038/ngeo544

Mitrovica, J.X., Milne, G.A., 2002. On the origin of late Holocene sea-level highstands within equatorial ocean basins. Quat. Sci. Rev. 21, 2179–2190. https://doi.org/10.1016/S0277-3791(02)00080-X

Moreau, J., Huuse, M., 2014. Infill of tunnel valleys associated with landward-flowing ice sheets: The missing Middle Pleistocene record of the NW European rivers? Geochemistry, Geophys. Geosystems 15, 1–9. https://doi.org/10.1002/2013GC005007

Mountney, N.P., Russell, A.J., 2009. Aeolian dune-field development in a water table-controlled system: Skeiðarársandur, Southern Iceland. Sedimentology 56, 2107–2131. https://doi.org/10.1111/j.1365-3091.2009.01072.x

Murton, J.B., Bateman, M.D., Dallimore, S.R., Teller, J.T., Yang, Z., 2010. Identification of Younger Dryas outburst flood path from Lake Agassiz to the Arctic Ocean. Nature 464, 740–743. https://doi.org/10.1038/nature08954

Nanda, N.C., 2016. Seismic Data Interpretation and Evaluation for Hydrocarbon Exploration and Production. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-26491-2

Nemec, W., 2009. Aspects of Sediment Movement on Steep Delta Slopes, Coarse-Grained Deltas. Blackwell Publishing Ltd., Oxford, UK. https://doi.org/10.1002/9781444303858.ch3

Nichols, G.J., Fisher, J.A., 2007. Processes, facies and architecture of fluvial distributary system deposits. Sediment. Geol. 195, 75–90. https://doi.org/10.1016/J.SEDGEO.2006.07.004

Nielsen, T., Rasmussen, T.L., 2018. Reconstruction of ice sheet retreat after the Last Glacial maximum in Storfjorden, southern Svalbard. Mar. Geol. 402, 228–243. https://doi.org/10.1016/J.MARGEO.2017.12.003

Nygård, A., Sejrup, H.P., Haflidason, H., Bryn, P., 2005. The glacial North Sea Fan, southern Norwegian Margin: Architecture and evolution from the upper continental slope to the deep-sea basin. Mar. Pet. Geol. 22, 71–84. https://doi.org/10.1016/j.marpetgeo.2004.12.001

Ó Cofaigh, C., 1996. Tunnel valley genesis. Prog. Phys. Geogr. Earth Environ. 20, 1–19. https://doi.org/10.1177/030913339602000101

Ó Cofaigh, C., Dowdeswell, J.A., Grobe, H., 2001. Holocene glacimarine sedimentation, inner Scoresby Sund, East Greenland: the influence of fast-flowing ice-sheet outlet glaciers. Mar. Geol. 175, 103–129. https://doi.org/10.1016/S0025-3227(01)00117-7

Ó Cofaigh, C., Taylor, J., Dowdeswell, J.A., Pudsey, C.J., 2003. Palaeo-ice streams, trough mouth fans and high-latitude continental slope sedimentation. Boreas 32, 37–55. https://doi.org/Doi 10.1080/03009480310001858

Olsen, L., Sveian, H., Ottesen, D., Rise, L., 2013. Quaternary glacial, interglacial and interstadial deposits of Norway and adjacent onshore and offshore areas. Quat. Geol. Norw. 13, 79–144.

Osterloff, P., Al-Harthy, A., Penney, R., Spaak, P., Williams, G., Al-Zadjali, F., Jones, N., Knox, R., Stephenson, M.H., Oliver, G., Al-Husseini, M.I., 2004a. Depositional sequences of the Gharif and Khuff Formations, subsurface interior Oman, GeoArabia. ed, Carboniferous, Permian and Early Triassic Arabian stratigraphy. GeoArabia.

Osterloff, P., Penney, R., Aitken, J., Clark, N., Al-Husseini, M.I., 2004b. Depositional sequences of the Al Khlata Formation, subsurface interior Oman, GeoArabia. ed, Carboniferous, Permian and Early Triassic Arabian stratigraphy. GeoArabia.

Ottesen, D., Dowdeswell, J. a., Rise, L., Rokoengen, K., Henriksen, S., 2002. Large-scale morphological evidence for past ice-stream flow on the mid-Norwegian continental margin. Geol. Soc. London, Spec. Publ. 203, 245–258. https://doi.org/10.1144/GSL.SP.2002.203.01.13

Ottesen, D., Dowdeswell, J.A., Bellec, V.K., Bjarnadóttir, L.R., 2017. The geomorphic imprint of glacier surges into open-marine waters: Examples from eastern Svalbard. Mar. Geol. 392, 1–29. https://doi.org/10.1016/J.MARGEO.2017.08.007

Ottesen, D., Dowdeswell, J.A., Rise, L., Bugge, T., 2012. Large-scale development of the mid-Norwegian shelf over the last three million years and potential for hydrocarbon reservoirs in glacial sediments. Geol. Soc. London, Spec. Publ. 53–73. https://doi.org/10.1144/SP368.6

Palmu, J.P., 1999. Sedimentary environment of the second salpausselkä ice marginal deposits in the karkkila-loppi area in Southwestern Finland, Tutkimusraportti - Geologian Tutkimuskeskus.

Patton, H., Hambrey, M.J., 2009. Ice-marginal sedimentation associated with the Late Devensian Welsh Ice Cap and the Irish Sea Ice Stream: Tonfanau, West Wales. Proc. Geol. Assoc. 120, 256–274. https://doi.org/10.1016/j.pgeola.2009.10.004

Patton, H., Hubbard, A., Andreassen, K., Auriac, A., Whitehouse, P.L., Stroeven, A.P., Shackleton, C., Winsborrow, M., Heyman, J., Hall, A.M., 2017. Deglaciation of the Eurasian ice sheet complex. Quat. Sci. Rev. 169, 148–172. https://doi.org/10.1016/J.QUASCIREV.2017.05.019

Patton, H., Hubbard, A., Andreassen, K., Winsborrow, M., Stroeven, A.P., 2016. The build-up, configuration, and dynamical sensitivity of the Eurasian ice-sheet complex to Late Weichselian climatic and oceanic forcing. Quat. Sci. Rev. 153, 97–121. https://doi.org/10.1016/j.quascirev.2016.10.009

Pedersen, S., 2014. Architecture of Glaciotectonic Complexes. Geosciences 4, 269–296. https://doi.org/10.3390/geosciences4040269

Pedersen, S.A.S., 2012. Glaciodynamic sequence stratigraphy Glaciodynamic sequence stratigraphy 29–51. https://doi.org/10.1144/SP368.2

Peltier, W.R., 2002. On eustatic sea level history: Last Glacial Maximum to Holocene. Quat. Sci. Rev. 21, 377–396. https://doi.org/10.1016/S0277-3791(01)00084-1

Phillips, E., Cotterill, C., Johnson, K., Crombie, K., James, L., Carr, S., Ruiter, A., 2018. Large-scale glacitectonic deformation in response to active ice sheet retreat across Dogger Bank (southern central North Sea) during the Last Glacial Maximum. Quat. Sci. Rev. 179, 24–47. https://doi.org/10.1016/j.quascirev.2017.11.001

Phillips, E.R., Evans, D.J.A., Auton, C.A., 2002. Polyphase deformation at an oscillating ice margin following the Loch Lomond Readvance, central Scotland, UK. Sediment. Geol. 149, 157–182. https://doi.org/10.1016/S0037-0738(01)00250-0

Piasecka, E.D., Winsborrow, M.C.M., Andreassen, K., Stokes, C.R., 2016. Reconstructing the retreat dynamics of the Bjørnøyrenna Ice Stream based on new 3D seismic data from the central Barents Sea. Quat. Sci. Rev. 151, 212–227. https://doi.org/10.1016/j.quascirev.2016.09.003

Pisarska-Jamrozy, M., 2015. Factors controlling sedimentation in the Toru??-Eberswalde ice-marginal valley during the Pomeranian phase of the Weichselian glaciation: An overview. Geologos 21, 1–29. https://doi.org/10.1515/logos-2015-0001

Pisarska-Jamrozy, M., 2006. Transitional deposits between the end moraine and outwash plain in the Pomeranian glaciomarginal zone of NW Poland: a missing component of ice-contact sedimentary models. Boreas 35, 126–141. https://doi.org/10.1080/03009480500359038

Pisarska-Jamrozy, M., Weckwerth, P., 2013. Soft-sediment deformation structures in a Pleistocene glaciolacustrine delta and their implications for the recognition of subenvironments in delta deposits. Sedimentology 60, 637–665. https://doi.org/10.1111/j.1365-3091.2012.01354.x

Pisarska-Jamrozy, M., Zieliński, T., 2014. Pleistocene sandur rhythms, cycles and megacycles: Interpretation of depositional scenarios and palaeoenvironmental conditions. Boreas 43, 330–348. https://doi.org/10.1111/bor.12041

Postma, G., 1990. An analysis of the variation in delta architecture. Terra Nov. 2, 124–130. https://doi.org/10.1111/j.1365-3121.1990.tb00052.x

Powell, J.H., Moh'd, B.K., Masri, A., 1994. Late ordovician-early silurian glaciofluvial deposits preserved in palaeovalleys in South Jordan. Sediment. Geol. https://doi.org/10.1016/0037-0738(94)90099-X

Powell, R.D., 1990. Glacimarine processes at grounding-line fans and their growth to ice-contact deltas. Geol. Soc. London, Spec. Publ. 53, 53–73. https://doi.org/10.1144/GSL.SP.1990.053.01.03

Powell, R.D., Alley, R.B., 1996. Grounding-Line Systems: Processes, Glaciological Inferences and the Stratigraphic Record. American Geophysical Union, pp. 169–187. https://doi.org/10.1029/AR071p0169

Powell, R.D., Cooper, J.M., 2002. A glacial sequence stratigraphic model for temperate, glaciated continental shelves. Geol. Soc. London, Spec. Publ. 203, 215–244. https://doi.org/10.1144/GSL.SP.2002.203.01.12

Powell, R.D., Domack, E., 1995. Modern glaciomarine environments. Mod. Past Glacial Environ. 1, 445–486.

Powell, R.D., Molnia, B.F., 1989. Glacimarine sedimentary processes, facies and morphology of the south-southeast Alaska shelf and fjords. Mar. Geol. 85, 359–390. https://doi.org/10.1016/0025-3227(89)90160-6

Praeg, D., 2003. Seismic imaging of mid-Pleistocene tunnel-valleys in the North Sea Basin-high resolution from low frequencies. J. Appl. Geophys. 53, 273–298. https://doi.org/10.1016/j.jappgeo.2003.08.001

Rea, B.R., Newton, A.M.W., Lamb, R.M., Harding, R., Bigg, G.R., Rose, P., Spagnolo, M., Huuse, M., Cater, J.M.L., Archer, S., Buckley, F., Halliyeva, M., Huuse, J., Cornwell, D.G., Brocklehurst, S.H., Howell, J.A., 2018. Extensive marine-terminating ice sheets in Europe from 2.5 million years ago. Sci. Adv. 4, eaar8327. https://doi.org/10.1126/sciadv.aar8327

Reading, H.G., 2002. Sedimentary environments : processes, facies, and stratigraphy. Blackwell Science.

Reinardy, B.T.I., Leighton, I., Marx, P.J., 2013. Glacier thermal regime linked to processes of annual moraine formation at Midtdalsbreen, southern Norway. Boreas 42, 896–911. https://doi.org/10.1111/bor.12008

Rinterknecht, V., Braucher, R., Böse, M., Bourlès, D., Mercier, J.L., 2012. Late Quaternary ice sheet extents in northeastern Germany inferred from surface exposure dating. Quat. Sci. Rev. 44, 89–95. https://doi.org/10.1016/j.quascirev.2010.07.026

Rinterknecht, V.R., Clark, P.U., Raisbeck, G.M., Yiou, F., Brook, E.J., Tschudi, S., Lunkka, J.P., 2004. Cosmogenic 10Be dating of the Salpausselkä I Moraine in southwestern Finland. Quat. Sci. Rev. 23, 2283–2289. https://doi.org/10.1016/J.QUASCIREV.2004.06.012

Rose, P., Byerley, G., Vaughan, O., Cater, J., Rea, B.R., Spagnolo, M., Archer, S., 2016. Aviat: a Lower Pleistocene shallow gas hazard developed as a fuel gas supply for the Forties Field. Geol. Soc. London, Pet. Geol. Conf. Ser. 8, 485–505. https://doi.org/10.1144/pgc8.16

Rust, B.R., 1965. The sedimentology and diagenesis of Silurian turbidites in south-east Wigtownshire, Scotland. Scottish J. Geol. 1 Part 3, 231–246. https://doi.org/-

Rust, B.R., Romanelli, Ri., 1975. Late Quaternary ubaqueous Outwash Deposits Near Ottawa, Canada, in: Glaciofluvial and Glaciolacustrine Sedimentation. SEPM (Society for Sedimentary Geology), pp. 177–192.

https://doi.org/10.2110/pec.75.23.0177

Rüther, D.C., Andreassen, K., Spagnolo, M., 2013. Aligned glaciotectonic rafts on the central Barents Sea seafloor revealing extensive glacitectonic erosion during the last deglaciation. Geophys. Res. Lett. 40, 6351–6355. https://doi.org/10.1002/2013GL058413

Rüther, D.C., Mattingsdal, R., Andreassen, K., Forwick, M., Husum, K., 2011. Seismic architecture and sedimentology of a major grounding zone system deposited by the Bjørnøyrenna Ice Stream during Late Weichselian deglaciation. Quat. Sci. Rev. 30, 2776–2792. https://doi.org/10.1016/j.quascirev.2011.06.011

Saarnisto, M., Saarinen, T., 2001. Deglaciation chronology of the Scandinavian Ice Sheet from the Lake Onega Basin to the Salpausselkä End Moraines. Glob. Planet. Change 31, 387–405. https://doi.org/10.1016/S0921-8181(01)00131-X

Sandersen, P.B.E., Jørgensen, F., 2012. Substratum control on tunnel valley formation in Denmark 145–157. https://doi.org/10.1144/SP368.12#The

Sejrup, H.P., Clark, C.D., Hjelstuen, B.O., 2016. Rapid ice sheet retreat triggered by ice stream debuttressing: Evidence from the North Sea. Geology 44, 355–358. https://doi.org/10.1130/G37652.1

Sengbush, R.L., 1983. Seismic Exploration Methods. Springer Netherlands, Dordrecht. https://doi.org/10.1007/978-94-011-6397-2

Shmatkova, A.A., Shmatkov, A.A., Gainanov, V.G., Buenz, S., 2015. Identification of geohazards based on the data of marine high-resolution 3D seismic observations in the Norwegian Sea. Moscow Univ. Geol. Bull. 70, 53–61. https://doi.org/10.3103/S0145875215010068

Simkins, L.M., Greenwood, S.L., Anderson, J.B., 2018. Diagnosing ice sheet grounding line stability from landform morphology. Cryosph. 2707–2726. https://doi.org/10.5194/tc-2018-44

Soubaras, R., Whiting, P., 2011. Variable depth streamer — The new broadband acquisition system, in: SEG Technical Program Expanded Abstracts 2011. Society of Exploration Geophysicists, pp. 4349–4353. https://doi.org/10.1190/1.3628115

Spagnolo, M., Clark, C.D., Ely, J.C., Stokes, C.R., Anderson, J.B., Andreassen, K., Graham, A.G.C., King, E.C., 2014. Size, shape and spatial arrangement of mega-scale glacial lineations from a large and diverse dataset. Earth Surf. Process. Landforms n/a-n/a. https://doi.org/10.1002/esp.3532

Spagnolo, M., Phillips, E., Piotrowski, J.A., Rea, B.R., Clark, C.D., Stokes, C.R., Carr, S.J., Ely, J.C., Ribolini, A., Wysota, W., Szuman, I., 2016. Ice stream motion facilitated by a shallow-deforming and accreting bed. Nat. Commun. 7, 10723. https://doi.org/10.1038/ncomms10723

Spratt, R.M., Lisiecki, L.E., 2016. A Late Pleistocene sea level stack. Clim. Past 12, 1079–1092. https://doi.org/10.5194/cp-12-1079-2016

Steno, N., 1671. Nicolai Stenonis De solido intra solidum naturaliter contento dissertationis prodromus. The Macmillan Company.

Stewart, M.A., Lonergan, L., 2011. Seven glacial cycles in the middle-late Pleistocene of northwest Europe: Geomorphic evidence from buried tunnel valleys. Geology 39, 283–286. https://doi.org/10.1130/G31631.1

Stewart, M.A., Lonergan, L., Hampson, G., 2013. 3D seismic analysis of buried tunnel valleys in the central North Sea: Morphology, cross-cutting generations and glacial history. Quat. Sci. Rev. 72, 1–17. https://doi.org/10.1016/j.quascirev.2013.03.016

Stoker, M.S., Balson, P.S., Long, D., Tappin, D.R., 2011. An overview of the lithostratigraphical framework for the Quaternary deposits on the United Kingdom continental shelf 48.

Stokes, C.R., Clark, C.D., 2002. Ice stream shear margin moraines. Earth Surf. Process. Landforms 27, 547–558. https://doi.org/10.1002/esp.326

Stokes, C.R., Clark, C.D., 2001. Palaeo-ice streams 20, 1437–1457. https://doi.org/10.1016/S0277-3791(01)00003-8

Stokes, C.R., Clark, C.D., 1999. Geomorphological criteria for identifying Pleistocene ice streams. Ann. Glaciol. 28, 67–74. https://doi.org/10.3189/172756499781821625

Stokes, C.R., Clark, C.D., Lian, O.B., Tulaczyk, S., 2007. Ice stream sticky spots: A review of their identification and influence beneath contemporary and palaeo-ice streams. Earth-Science Rev. 81, 217–249. https://doi.org/10.1016/j.earscirev.2007.01.002

Stokes, C.R., Tarasov, L., Blomdin, R., Cronin, T.M., Fisher, T.G., Gyllencreutz, R., Hättestrand, C., Heyman, J., Hindmarsh, R.C.A., Hughes, A.L.C., Jakobsson, M., Kirchner, N., Livingstone, S.J., Margold, M., Murton, J.B., Noormets, R., Peltier, W.R., Peteet, D.M., Piper, D.J.W., Preusser, F., Renssen, H., Roberts, D.H., Roche, D.M., Saint-Ange, F., Stroeven, A.P., Teller, J.T., 2015. On the reconstruction of palaeo-ice sheets: Recent advances and future challenges. Quat. Sci. Rev. 125, 15–49. https://doi.org/10.1016/j.quascirev.2015.07.016

Storrar, R.D., Ewertowski, M., Tomczyk, A.M., Barr, I.D., Livingstone, S.J., Ruffell, A., Stoker, B.J., Evans, D.J.A., 2019. Equifinality and preservation potential of complex eskers. Boreas bor.12414. https://doi.org/10.1111/bor.12414

Storrar, R.D., Stokes, C.R., Evans, D.J.A., 2014. Morphometry and pattern of a large sample (>20,000) of Canadian eskers and implications for subglacial drainage beneath ice sheets. Quat. Sci. Rev. 105, 1–25. https://doi.org/10.1016/J.QUASCIREV.2014.09.013

Strand, K., 2012. Global and continental-scale glaciations on the Precambrian earth. Mar. Pet. Geol. 33, 69–79. https://doi.org/10.1016/j.marpetgeo.2012.01.011

Stroeven, A.P., Hättestrand, C., Kleman, J., Heyman, J., Fabel, D., Fredin, O., Goodfellow, B.W., Harbor, J.M., Jansen, J.D., Olsen, L., Caffee, M.W., Fink, D., Lundqvist, J., Rosqvist, G.C., Strömberg, B., Jansson, K.N., 2016. Deglaciation of Fennoscandia. Quat. Sci. Rev. 147, 91–121. https://doi.org/10.1016/j.quascirev.2015.09.016

Stuart, J.Y., Huuse, M., 2012. 3D seismic geomorphology of a large Plio-Pleistocene delta - “Bright spots” and contourites in the Southern North Sea. Mar. Pet. Geol. 38, 143–157. https://doi.org/10.1016/j.marpetgeo.2012.06.003

Stumm, D., 2012. A review on tunnel valleys in northern Europe. Quat. Int. 279–280, 474. https://doi.org/10.1002/esp.1668.Nagra

Swartz, J.M., Gulick, S.P.S., Goff, J.A., 2015. Gulf of Alaska continental slope morphology: Evidence for recent trough mouth fan formation. Geochemistry, Geophys. Geosystems 16, 165–177. https://doi.org/10.1002/2014GC005594

Taylor, J., Dowdeswell, J. a., Kenyon, N.H., O’Cofaigh, C.S., 2002. Late Quaternary compositional architecture of trough-mouth fans: debris flows and suspended sediments on the Norwegian margin. Glacier-Influenced Sediment. High-Latitude Cont. Margins 55–71. https://doi.org/10.1144/GSL.SP.2002.203.01.04

Thomas, G.S.P., 1984. Sedimentation of a sub-aqueous esker-delta at Strabathie, Aberdeenshire. Scottish J. Geol. 20, 9–20. https://doi.org/10.1144/sjg20010009

Thomas, G.S.P., Chiverrell, R.C., 2006. A model of subaqueous sedimentation at the margin of the Late Midlandian Irish Ice Sheet, Connemara, Ireland, and its implications for regionally high isostatic sea-levels. Quat. Sci. Rev. 25, 2868–2893. https://doi.org/10.1016/j.quascirev.2006.04.002

Thorleifson, L.H., 1996. Review of Lake Agassiz history. Geol. Assoc. Canada 55–84.

Thwaites, F.T., 1926. The Origin and Significance of Pitted Outwash. J. Geol. 34, 308–319. https://doi.org/10.1086/623315

Todd, B.J., 2016. The Laurentian Channel: A major cross-shelf trough in Atlantic Canada. Geol. Soc. Mem. 46, 161–162. https://doi.org/10.1144/M46.124

Todd, B.J., 2014. De Geer moraines on German Bank , southern Scotian Shelf of Atlantic Canada 1–2. https://doi.org/10.1144/M46.112

Uścinowicz, S., 2004. Rapid sea level changes in the Southern Baltic during late glacial and early Holocene. Polish Geol. Inst. Spec. Pap. 11, 9–18.

van der Vegt, P., Janszen, A., Moscariello, A., Janszen, A., Moscariello, A., 2016. Tunnel valleys : current knowledge and future perspectives. Geol. Soc. London, Spec. Publ. 368, 75–97. https://doi.org/10.1144/SP368.13

van der Wateren, F.M., 1994. Proglacial subaquatic outwash fan and delta sediments in push moraines—indicators of subglacial meltwater activity. Sediment. Geol. 91, 145–172. https://doi.org/10.1016/0037-0738(94)90127-9

Van der Wateren, F.M., 1995. Structural Geology and Sedimentology of Push Moraines - Processes of soft sediment deformation in a glacíal environment and the distribution of glaciotectonic styles. Meded. Rijks Geol. Dienst. 54, 1–168.

Van Landeghem, K.J.J., Wheeler, A.J., Mitchell, N.C., 2009. Seafloor evidence for palaeo-ice streaming and calving of the grounded Irish Sea Ice Stream: Implications for the interpretation of its final deglaciation phase. Boreas 38, 111–131. https://doi.org/10.1111/j.1502-3885.2008.00041.x

Van Loon, A.J. (Tom), Pisarska-Jamroży, M., 2017. Changes in the Heavy-Mineral Spectra on Their Way From Various Sources to Joint Sinks. Sediment Proven. 49–62. https://doi.org/10.1016/B978-0-12-803386-9.00004-6

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S., Hardenbol, J., 1988. An Overview of the Fundamentals of Sequence Stratigraphy and Key Definitions, in: Sea-Level Changes. SEPM (Society for Sedimentary Geology), pp. 39–45. https://doi.org/10.2110/pec.88.01.0039

Vaslet, D., 1990. Upper Ordovician glacial depositsin Saudi Arabia. Episodes 13, 147–162.

Vassiljev, J.J., Saarse, L., 2013. Timing of the Baltic ice lake in the eastern Baltic. Bull. Geol. Soc. Finl. 85, 9–18. https://doi.org/10.1016/j.quaint.2008.10.005

Vaughan-Hirsch, D.P., Phillips, E.R., 2017. Mid-Pleistocene thin-skinned glaciotectonic thrusting of the Aberdeen Ground Formation, Central Graben region, central North Sea. J. Quat. Sci. 32, 196–212. https://doi.org/10.1002/jqs.2836

Velichko, A.A., Kononov, Y.M., Faustova, M.A., 1997. The last glaciation of earth: Size and volume of ice-sheets. Quat. Int. 41–42, 43–51. https://doi.org/10.1016/S1040-6182(96)00035-3

Visser, J.N.J., Loock, W.P., Colliston, W.P., 2003. Subaqueous Outwash Fan and Esker Sandstones in the Permo-Carboniferous Dwyka Formation of South Africa. SEPM J. Sediment. Res. Vol. 57, 467–478. https://doi.org/10.1306/212f8b66-2b24-11d7-8648000102c1865d

Vorren, T.O., Laberg, J.S., 1997. Trough mouth fans - Palaeoclimate and ice-sheet monitors. Quat. Sci. Rev. 16, 865–881. https://doi.org/10.1016/S0277-3791(97)00003-6

Walther, J., 1893. Einleitung in die Geologie als historische Wissenschaft. Jena, G. Fischer.

Wang, D., Helmy, M., Rawnsley, K., 2011. Glacial Sedimentological Interpretation from Microresistivity Images , Al Khlata Formation , Oman. AAPG Search Discov. Artic. 50511.

Ward, L.G., Grizzle, R., Johnson, P., 2019. High Resolution Seafloor Bathymetry, Surficial Sediment Maps, and

Interactive Database: Jeffreys Ledge and Vicinity.University of New Hampshire Center for Coastal and Ocean Mapping and Joint Hydrographic Center, Durham. [WWW Document]. URL http://ccom.unh.edu/project/jeffreys-ledge (accessed 10.26.19).

Weckwerth, P., Wysota, W., Piotrowski, J.A., Adamczyk, A., Krawiec, A., Dąbrowski, M., 2019. Late Weichselian glacier outburst floods in North-Eastern Poland: Landform evidence and palaeohydraulic significance. Earth-Science Rev. https://doi.org/10.1016/j.earscirev.2019.05.006

Westoby, M.J., Glasser, N.F., Brasington, J., Hambrey, M.J., Quincey, D.J., Reynolds, J.M., 2014. Modelling outburst floods from moraine-dammed glacial lakes. Earth-Science Rev. 134, 137–159. https://doi.org/10.1016/j.earscirev.2014.03.009

Winsborrow, M., Andreassen, K., Hubbard, A., Plaza-Faverola, A., Gudlaugsson, E., Patton, H., 2016. Regulation of ice stream flow through subglacial formation of gas hydrates. Nat. Geosci. 9, 370–374. https://doi.org/10.1038/ngeo2696

Winsemann, J., Alho, P., Laamanen, L., Goseberg, N., Lang, J., Klostermann, J., 2016. Flow dynamics, sedimentation and erosion of glacial lake outburst floods along the Middle Pleistocene Scandinavian Ice Sheet (northern central Europe). Boreas 45, 260–283. https://doi.org/10.1111/bor.12146

Zecchin, M., Catuneanu, O., Rebesco, M., 2015. High-resolution sequence stratigraphy of clastic shelves IV: High-latitude settings. Mar. Pet. Geol. 68, 427–437. https://doi.org/10.1016/j.marpetgeo.2015.09.004

Zhang, Z., Wardlaw, S., Haneberg, W.C., 2016. Seismic AVO Analysis for Shallow Hazard Assessments in Stratigraphically Complicated Areas in Onshore Alaska Locations, in: SPE Western Regional Meeting. Society of Petroleum Engineers. https://doi.org/10.2118/180455-MS

Zheng, W., Pritchard, M.E., Willis, M.J., Stearns, L.A., 2019. The Possible Transition From Glacial Surge to Ice Stream on Vavilov Ice Cap. Geophys. Res. Lett. 2019GL084948. https://doi.org/10.1029/2019GL084948

Zielinski, T., Van Loon, A.J., 2003. Pleistocene sandur deposits represent braidplains, not alluvial fans. Boreas 32, 590–611. https://doi.org/10.1111/j.1502-3885.2003.tb01238.x

Zieliński, T., van Loon, A.J., 2000. Subaerial terminoglacial fans III: overview of sedimentary characteristics and depositional model. Netherlands J. Geosci. - Geol. en Mijnb. 79, 93–107. https://doi.org/10.1017/S0016774600021600

Zieliński, T., van Loon, A.J.J., 1999. Subaerial terminoglacial fans II: A semi-quantitative sedimentological analysis of the middle and distal environments. Geol. en Mijnb. 78, 73–85. https://doi.org/10.1023/A:1003862730530

Zieliński, T., van Loon, A.J.J., 1998. Subaerial terminoglacial fans I: A semi-quantitative sedimentological analysis of the proximal environment. Geol. en Mijnbouw/Netherlands J. Geosci. 77, 1–15. https://doi.org/https://doi.org/10.1023/A:1003535101480

Figures

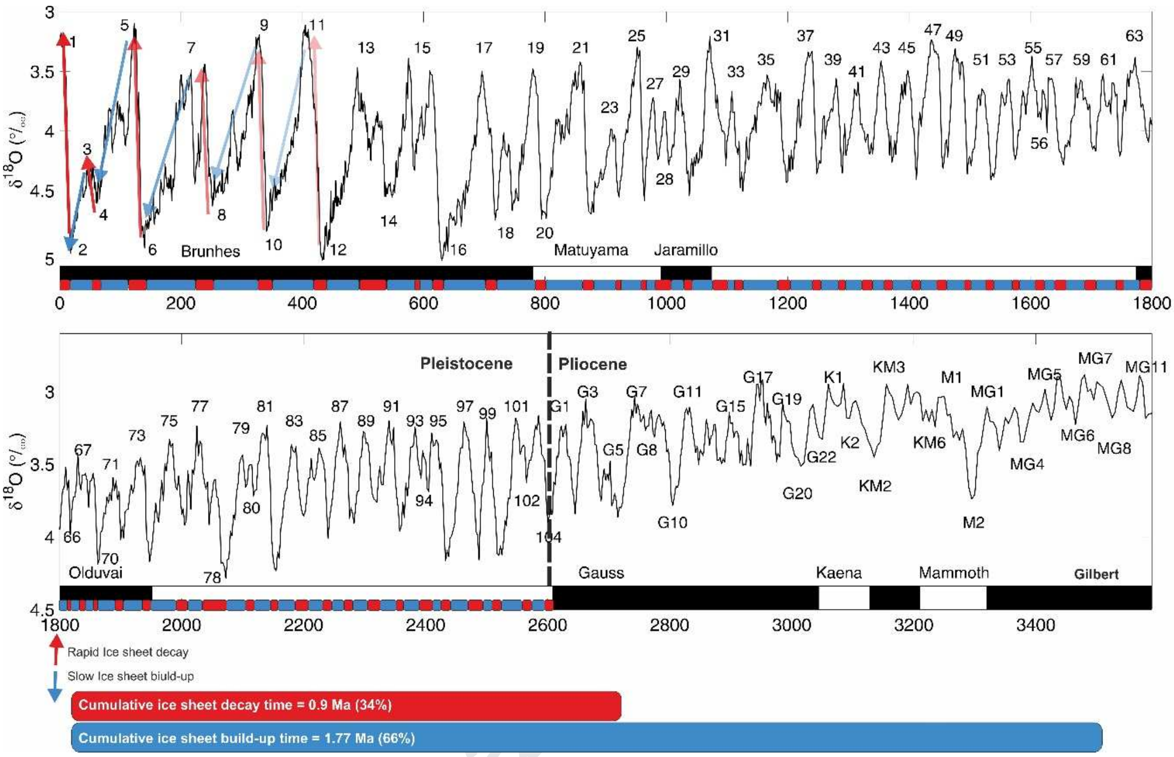
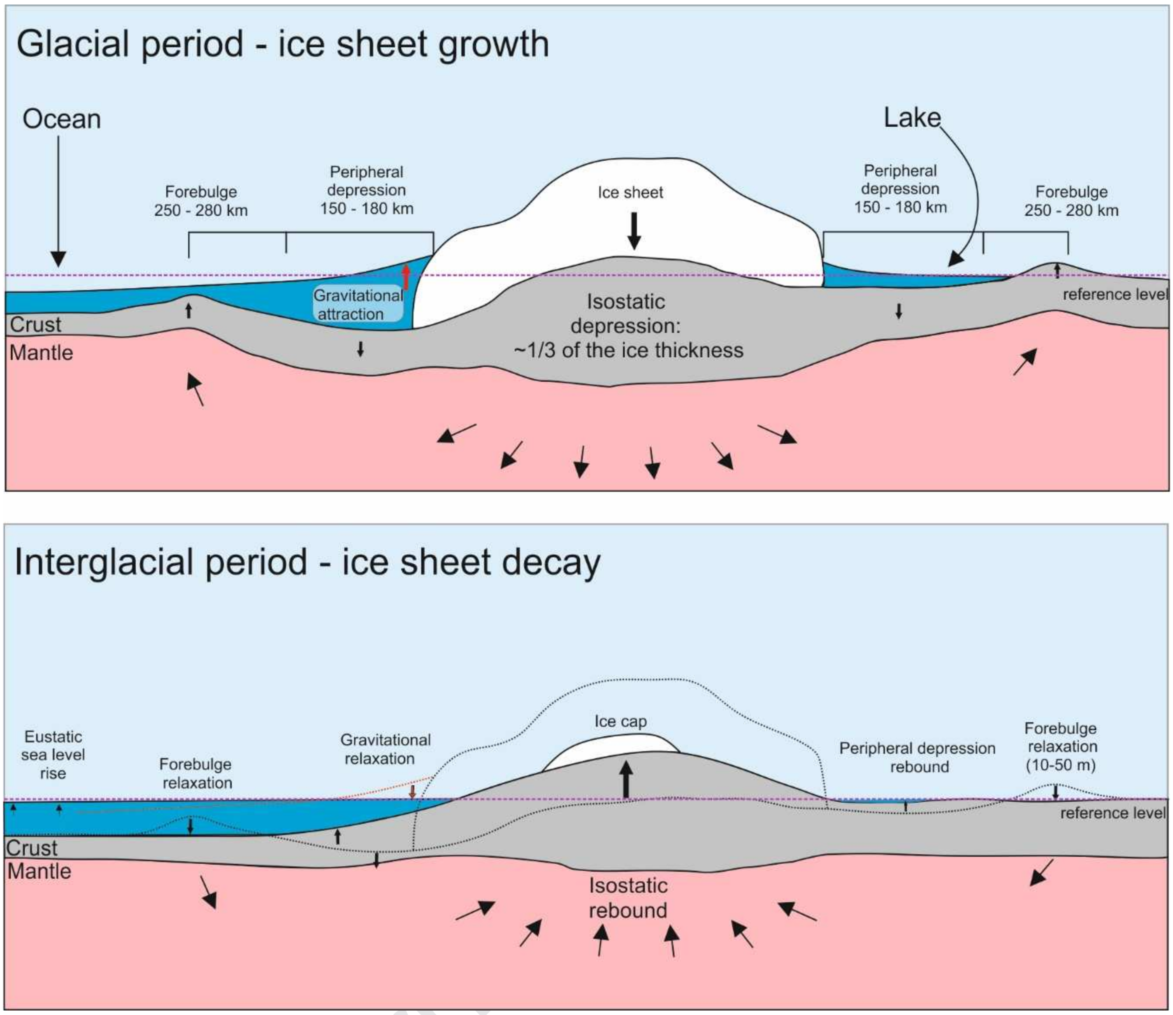


Figure 1: $\delta^{18}O$ ($^0/_{00}$) Marine oxygen isotope (MIS) stages for the past 3.6 Ma, modified from Lisiecki & Raymo (2005). Note the asymmetry in time between global ice build-up and decay (termination). This is most pronounced for the last four cycles, but a similar pattern is visible through the entire Pleistocene. Time is shown in kilo-years and the magnetic reversal timescale is shown as the black (normal polarity) and white (reversed polarity) bars.



1835

1836 Figure 2: Crust and mantle response to growth (top) and decay (bottom) of ice sheets during glacial -
1837 interglacial cycles. Note the changes to the ocean/lake level proximally and distally to the ice sheet.
1838 Approximated distances and elevation changes based on Fjeldskaar (1994)

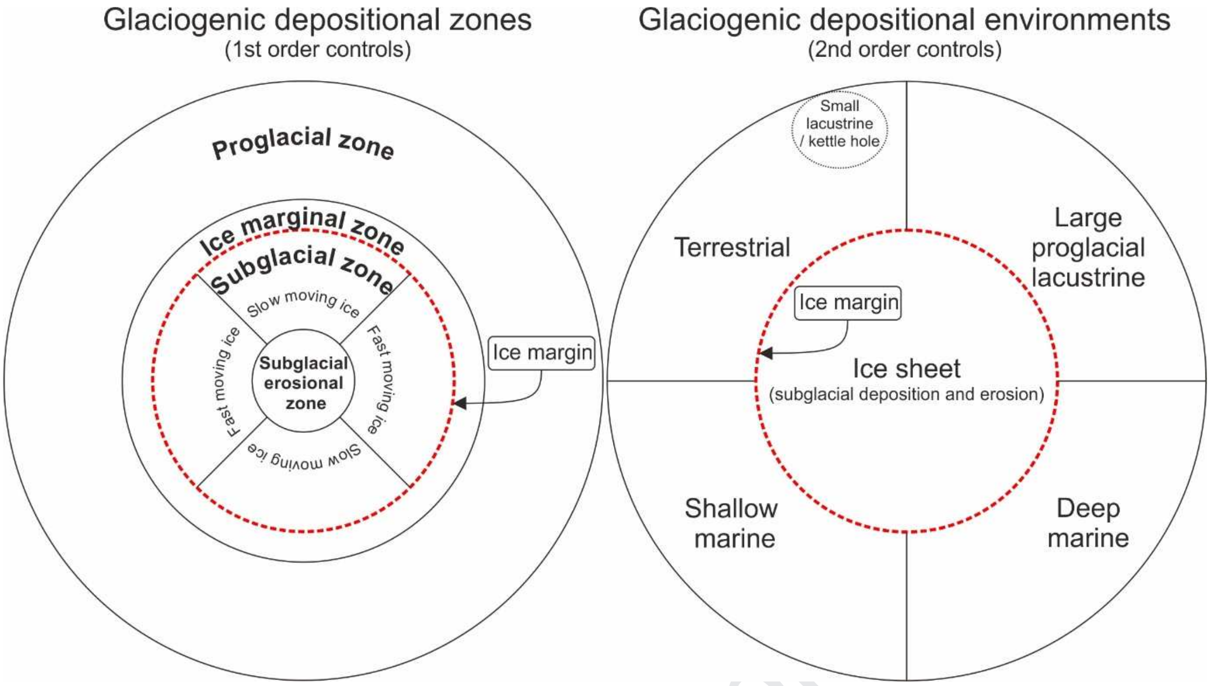


Figure 3: Schematic representation of the model framework. Left: the model is divided into three major depositional zones: proglacial, ice marginal and subglacial. The subglacial zone is further subdivided into an erosional zone, spreading from the ice sheet centre (ice divide) where erosion > deposition, and the subglacial depositional zone, where the opposite is true. Subglacial deposition is differentiated into zones of fast-moving ice (ice streams or lobes) and slow mowing ice (ice divides and inter-stream areas). Right: the model is divided into depositional environments in which the ice sheet terminates, which exerts a second order control on sediment and landform distributions.

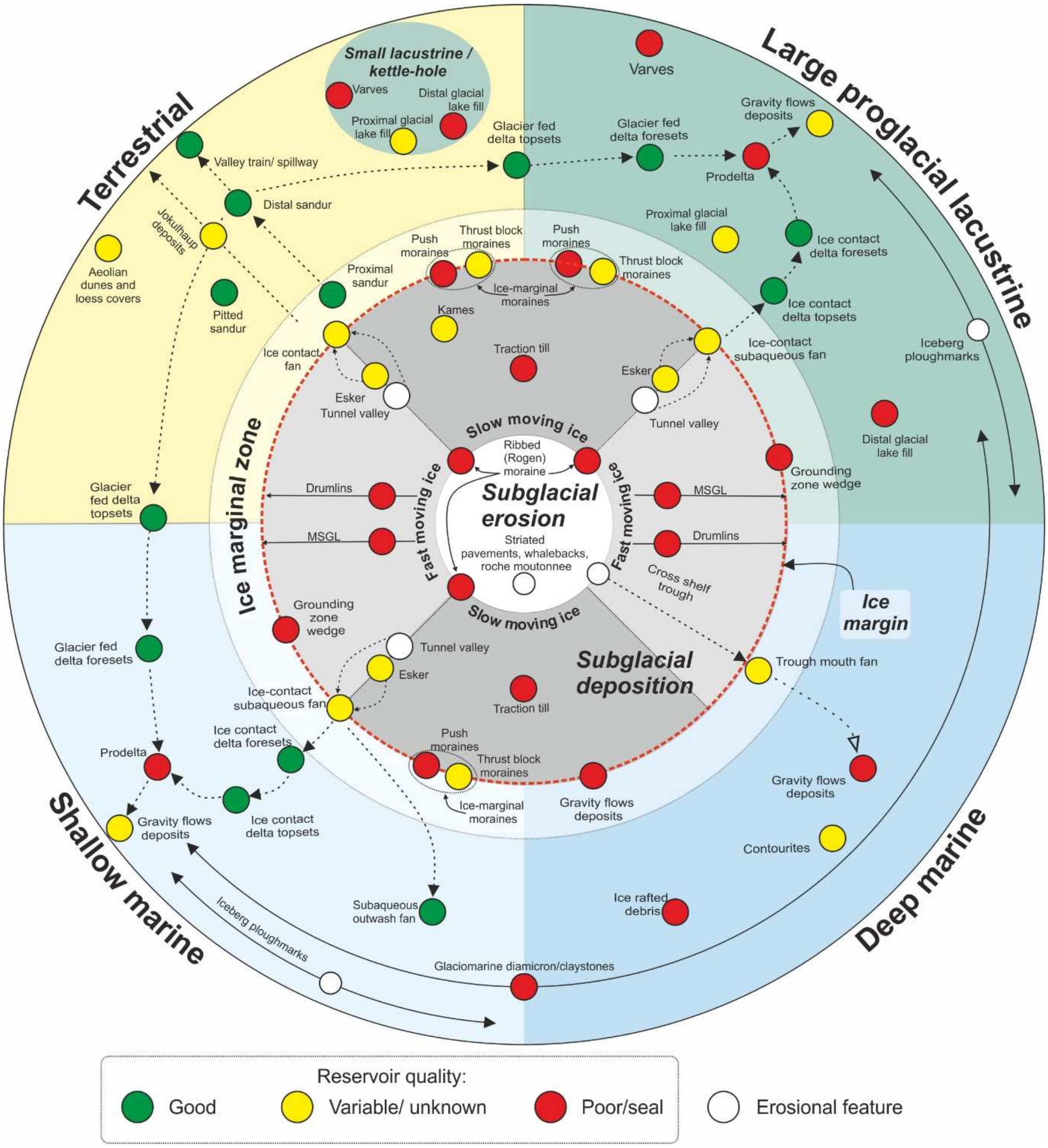
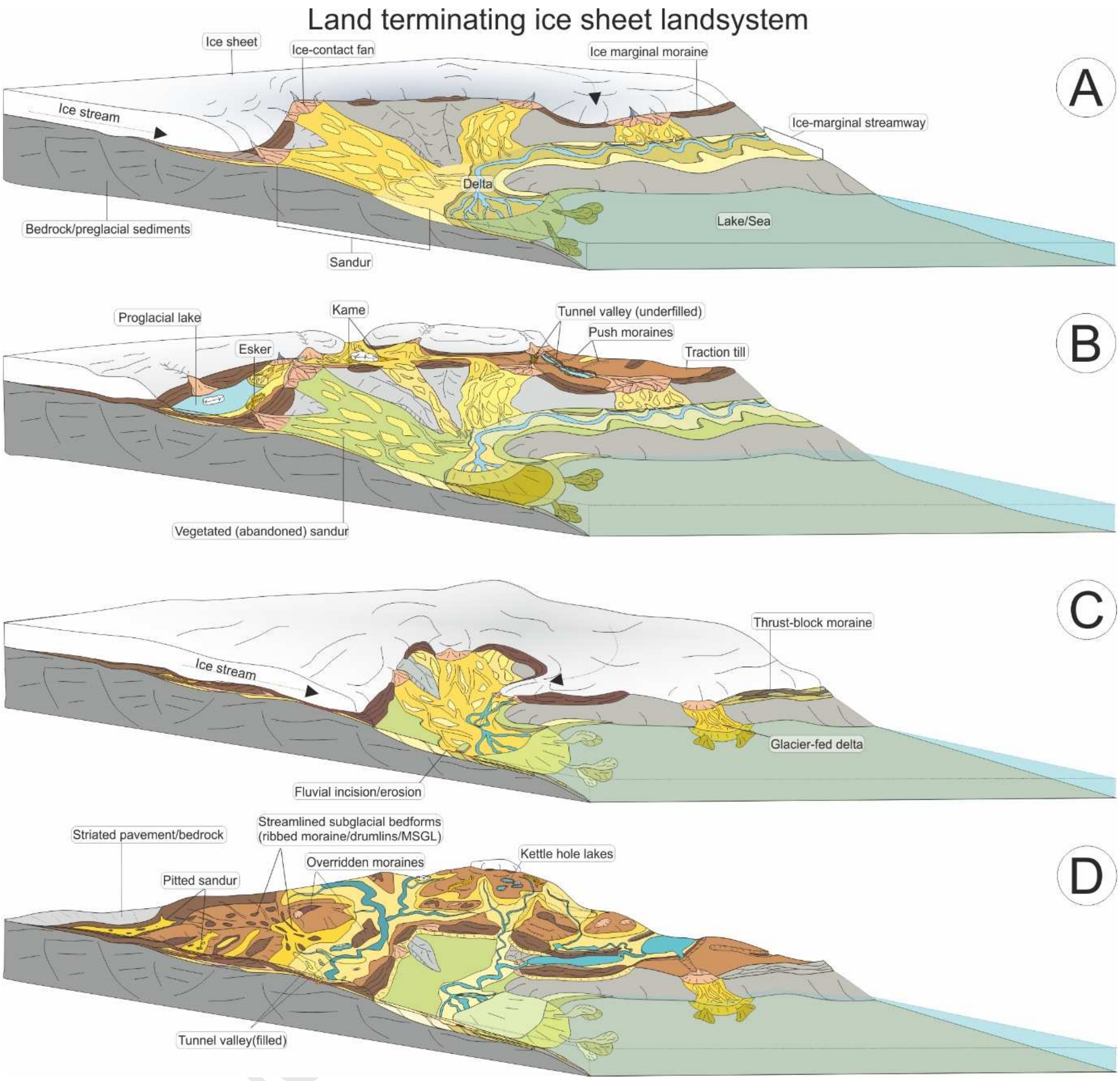


Figure 4: Conceptual diagram generalizing the planform (bird eye view) sediment and landform distribution for ice sheet depositional systems. The diagram is centred on the ice sheet which is located within the inner circle (deliniated by the ice margin, i.e. the red, dashed line) and "covers" the subglacial erosional zone and the subglacial depositional zone and ignores cold based ice. Landforms are positioned radially (proximal-distal) relative to the ice sheet divide, which is located at the very centre of the diagram (subglacial erosional zone). Where possible, sediments and *landforms are positioned in relative position, for example proximal sandur, distal* sandur, glacier-fed delta, indicated by dotted black arrows. Landforms/sediments with attached solid black arrows can be found across the environment. A traffic light system is used to highlight landforms/sediment reservoir potential : Green - good reservoir, yellow - variable/unknown, red - poor reservoir/seal. White dots represent major, recognizable glaciogenic erosional features that are extremely useful, or even diagnostic, for identification of the location within a glaciated palaeo landscape.



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1862 Figure 5: Land terminating ice sheet depositional system across a glacial cycle. A: First ice sheet
1863 advance - stadial 1, B: Ice sheet retreat — interstadial 1, C: Second ice sheet advance – stadial 2, D:
1864 Final ice sheet retreat – transition from glacial to interglacial conditions. A - C can happen
1865 repeatedly, within a single glaciation, before D.

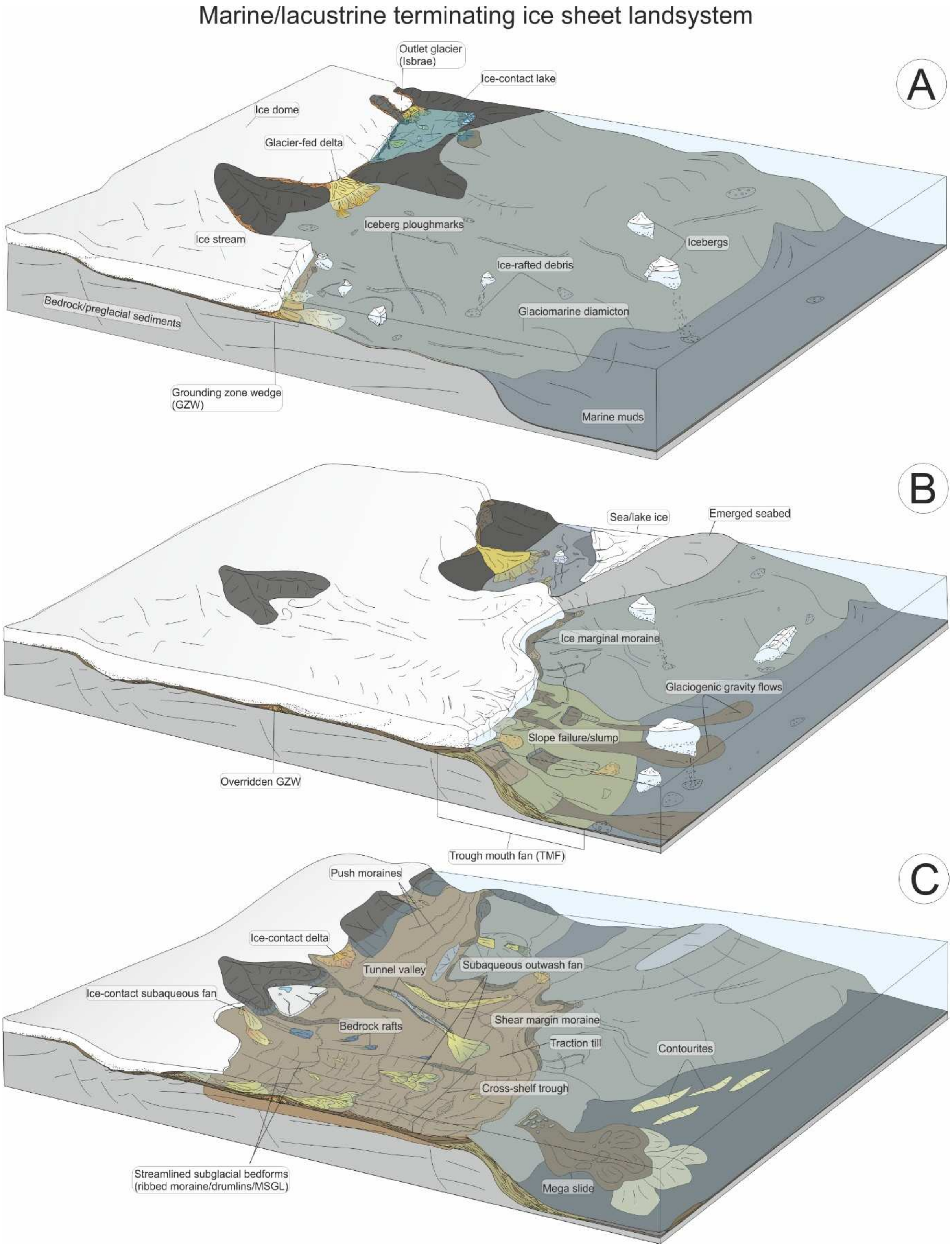

Figure 6: Water terminating ice sheet depositional system across a glacial cycle. A: First ice sheet advance into a basin - Stadial 1, B: Ice advance to the shelf break – maximum ice extent, C: Ice sheet retreat – transition from glacial to interglacial conditions.

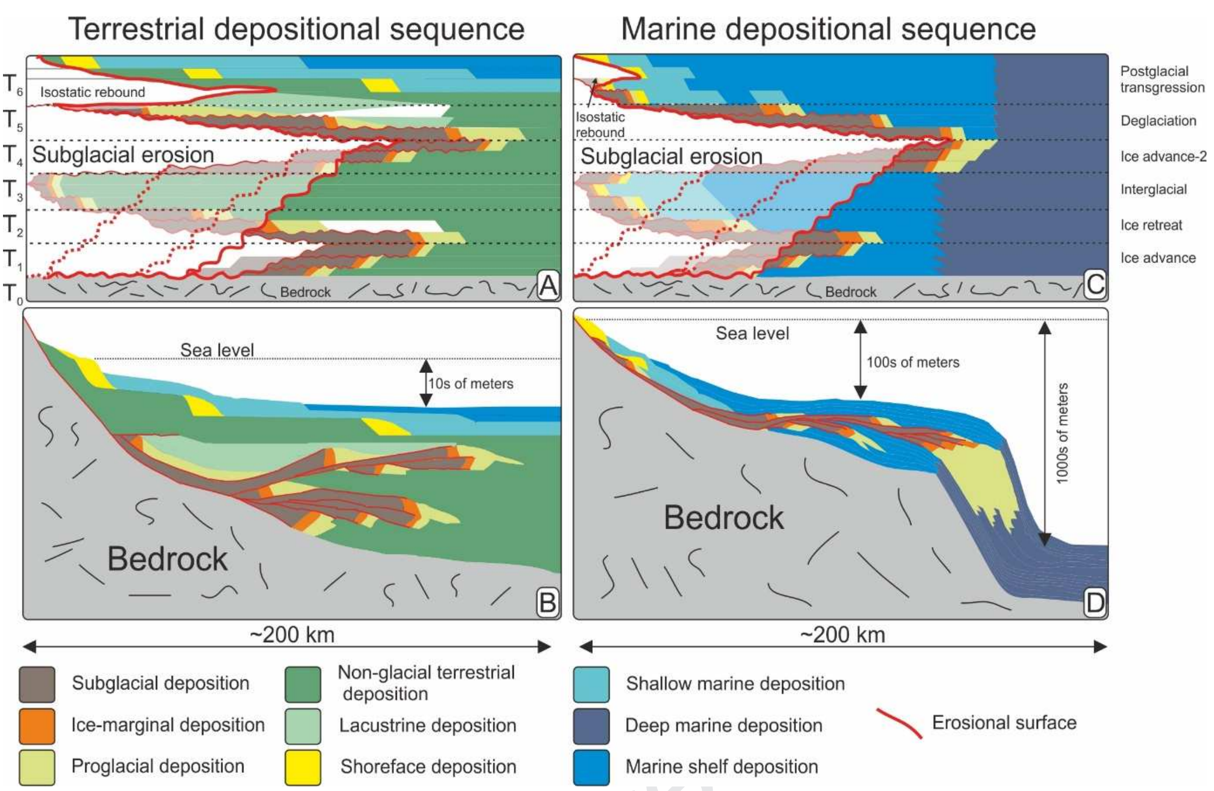

Figure 7: Simplified conceptual sections through terrestrial (A and B) and marine (C and D) depositional sequences, illustrating multiple phases of ice advance and retreat. Subglacial erosion is responsible for removal of previous glacial and interglacial deposits. The missing section is visible on chronostratigraphic cross-sections A and C as the faded area. The extent and depth of subglacial erosion is dependent on numerous factors, including the duration of glaciation, subsidence rate, basal thermal regime and initial thickness of the underlying sediments.

Tables

Table 1: Alias table of some of the glaciogenic features, landforms and sediments

Glacial feature		Also known as	References
Ice marginal streamway		urstromtal, spillway, pradolina, valley train, ice marginal valley	(Brodzikowski and van Loon, 1987; Pisarska-Jamrozy, 2015)
Sandur		glacial outwash, outwash plain, fluvioglacial outwash, sander plateau, braided outwash, proglacial braided river, glacial braidplain, sandur plain, sandar (plural)	(Girard et al., 2012; Gomez et al., 2000; Khalifa, 2015; Marren, 2005; Martin et al., 2008; Zielinski and Van Loon, 2003)
Glacier-fed delta		sandur delta, glacial outwash delta, glacio-lacustrine delta, sandur/delta system, proglacial delta, braid-delta	(Benn and Evans, 2010; Dietrich et al., 2017, 2016)
Ice-contact delta		kame delta, glacial delta, esker delta, ice-marginal delta, glacio-lacustrine delta, glacier delta	(Benn and Evans, 2010; Glückert, 1986; Lønne, 1995; Powell and Molnia, 1989)
Jökulhlaup		glacial lake outburst flood (GLOF), outburst flood, megaflood	(Gomez et al., 2000; Maizels, 1997; Westoby et al., 2014)
Traction till		subglacial diamicton, comminution till, lodgement till, melt-out till, deformation till, boulder clay, tillite (if lithified)	(Batchelor and Dowdeswell, 2015; Benn and Evans, 2010; Deschamps et al., 2013; Eyles, 1993; Lewis et al., 2006)
Ice marginal moraine		terminal moraine, retreat moraine, frontal moraine???, moraine ridges, terminoglacial fans	(Benediktsson et al., 2009; Benn and Evans, 2010; Bennett et al., 2000; Krüger et al., 2009; Krzyszkowski and Zielinski, 2002; Lønne, 1995)
	Push moraines	recessional moraines, de Geer moraines, transverse ridges, annual moraine ridges, push and squeeze moraines, morainal bank (subaqueous)	(Benn and Evans, 2010; Bennett, 2001; Todd, 2014)
	Thrust block moraines	composite ridges, push moraines, end moraine marginal moraine, end moraine, terminal moraine, morainal bank (subaqueous)	(Aber et al., 1989a, 1989b; Benn and Evans, 2010; Lovell and Boston, 2017; Patton et al., 2016; Pedersen, 2014; Phillips et al., 2018, 2002; Van der Wateren, 1995; Vaughan-Hirsch and Phillips, 2017)
Ice-contact fan		proglacial fan, terminoglacial subaerial fan, latero-frontal fan, end moraine fans	(Benn and Evans, 2010; Zieliński and van Loon, 1998)
Esker		subglacial tunnel fill, serpent kame, complex eskers, interlobate esker	(Burke et al., 2015; Maries et al., 2017; Storrar et al., 2019, 2014)
Grounding zone wedge		till delta	(Batchelor and Dowdeswell, 2015; Benn and Evans, 2010; Powell and Alley, 1996; Rüther et al., 2011; Simkins et al., 2018)
Ice-contact subaqueous fan		grounding line fan, ice-contact glaciomarine fan, subaqueous esker delta, ice–proximal fan, esker-fan complex,	(Hirst, 2012; Hirst and Khatatneh, 2019; Koch and Isbell, 2013; Lajeunesse and Allard, 2002; Lønne, 1995; Powell, 1990; Thomas, 1984)
	Subaqueous outwash fan: used when describing a large body of sand and gravel without a defined association with a grounding line and deposited from meltwater entering	turbiditic outwash fan, glacial submarine fan	(Rose et al., 2016; Rust and Romanelli, 1975; Thomas and Chiverrell, 2006; Visser et al., 2003)

a water body		
Iceberg ploughmarks	iceberg keel marks, iceberg grooves, iceberg plough marks	(Berkson and Clay, 1973; J. A. A. Dowdeswell and Bamber, 2007; Graham et al., 2007; Haavik and Landrø, 2014; Klages et al., 2016; Ottesen et al., 2017)
Ice rafted debris	IRD, iceberg rafted debris, ice rafted detritus	(Dowdeswell and Dowdeswell, 1989; Lucchi and Rebesco, 2007; Powell and Cooper, 2002)
Glaciomarine diamicton	glaciomarine muds, glaciomarine sediments, rainout diamicton, glaciomarine claystones	(Benn and Evans, 2010; Bennett et al., 2000; Domack, 1982; Domack and Lawson, 1985; Ó Cofaigh et al., 2001; Powell and Cooper, 2002)
Cross-shelf trough	ice stream trough, palaeo-ice stream, paleo-ice stream pathway	(Batchelor and Dowdeswell, 2015; Canals et al., 2016; Clark and Spagnolo, 2016; Heron, 2018; Klages et al., 2015; Rüther et al., 2013; Swartz et al., 2015; Todd, 2016; Van Landeghem et al., 2009)

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Table 2: A summary of landforms and sediments deposited by land terminating ice sheet. Every sediment/landform is assigned to a depositional zone with an accompanying assessment of reservoir quality.

Element	Description	Depositional zone	Reservoir potential			References
			Presence/distribution	Quality	Overall	
Esker	Elongated, curvilinear or sinuous sediment ridges of glacifluvial origin. They can extend over several hundreds of kilometres in length delineating major subglacial drainage pathways. Esker ridges have been reported to be up to 50 m high and are formed when sediments fill an ice-walled meltwater channel. Eskers sediments can range from cobble and boulder gravels through sands to poorly sorted, massive diamictons. Erosional contacts and re-activation surfaces are likely to be present. When sediment laden meltwaters escape the ice sheet an ice-contact fan may develop as a continuation of an esker. Often, a glaciotectonic signature is present together with late stage normal faulting due to loss of lateral ice support.	Subglacial	Patchy distribution. Elongated, ice margin perpendicular, curvilinear ribbons 100s m to 10s km long and 10s-1000s m wide	Moderately to well sorted boulders to pea gravels with subordinate sand and fine fraction	Moderate/good	*Brennand, 2000; Storrar, Stokes and Evans, 2014; Burke, Brennand and Sjogren, 2015*
Ribbed (Rogen) moraine sediments	Subglacially formed ridges of sediment orientated transverse to the ice flow. They usually cover large, concave or flat surfaces in core areas of former ice sheets in proximity to inferred frozen bed areas. Dimensions range from 300-1200 in length, 150-300 m in width and 1-30 m in height with similar spacing and size distribution for every locality. Ribbed moraines are usually formed of poorly sorted subglacial debris.	Subglacial	Patchy distribution. Irregular. Ice flow perpendicular mounds	Poorly sorted, subglacially derived and transported material-	Poor	*Dunlop and Clark, 2006*
Drumlins/ drumlin fields	Oval or egg-shaped, elongated hill with its longer axis parallel to the ice-flow direction. Drumlins can be up to few km long and up to 50 m high. They could be composed of different type of sediments, usually poorly sorted and homogenized by basal ice coupling over the available substratum. Erosional vs. depositional origin is still debated but most likely represent a case of equifinality.	Subglacial depositional	Patchy distribution in ice stream corridors. 10s-100s m long and wide, and 1s-10s m high	Poor sorting, textural and mineralogical maturity dependent on source sediment, over-compacted,	Poor	*Benn and Evans, 2010; Ely et al., 2016*
Traction till (diamicton)	Homogenized, poorly sorted sediment deposited at the ice-bed interface directly from the ice. Grainsize ranges from fine clays and muds through to cobbles, boulders and bedrock rafts	Subglacial	Discontinuous distribution. Variable thickness, 1s-10s of meters with possible erosional windows. and interbedded, localized sand/gravel lenses	Polymodal grainsize distribution Fine sediments and outsized clasts. Very poor sorting. Over-compacted	Poor	Evans *et al.*, 2006*; Benn and Evans, 2010*
Mega-Scale Glacial Lineations (MSGL)	Elongated, parallel to each other and to the ice flow direction, corrugations in subglacial sediment. 6-70 km long, 200-1300 m wide, typically 1-5 m high, associated mainly with fast flowing ice streams. Their original is still debated, with evidence supporting both erosional and depositional processes.	Subglacial	Patchy distribution in ice stream areas. Elongated, ice flow parallel. 100m to 10 km long, 100s m wide and 1-10	Polymodal grainsize distribution. Fine sediments and outsized clasts. Very poor sorting.	Poor	(Ely et al., 2016; Spagnolo et al., 2014, 2016)

Element	Description		Depositional zone	Reservoir potential			References
				Presence/distribution	Quality	Overall	
				m high.	Over compacted		
Kames	Sediment mounds associated with fluvial reworking of supraglacial, ice-marginal and subglacial sediments. Kames are composed mainly of sands and gravels with subordinate poorly sorted diamictons and fine deposits prone to postglacial reworking. Extremely hard to identify in the subsurface. Predictability of distribution of kame deposits can be challenging. If the ice flow is constrained by topography kame terraces may form along the valley edges where supraglacial meltwater streams are preferentially flowing. After ice melts out kame deposits can be found in contact with subglacial landforms and sediments.		Subglacial - ice marginal	Localized and unpredictable. Irregular mounds, 10s-1000s m, wide and long and 10s m high.	Glaciofluvially sorted sands and gravels (well sorted) glacial diamictons. (poorly sorted) and fines	Variable	(Brodzikowski and van Loon, 1987; Gruszka et al., 2012)
Ice-contact fans	Deposited subaerially by meltwater directly in front of the ice margin. Boulders, gravels and diamictites prevail in the ice-proximal part. Glaciotectonic deformation can be expected due to oscillations of the ice front during deposition. Middle and distal parts of an ice-contact fan appear to be less complex with gravel and sand (middle part) and sand and silt (distal part) deposition prevailing. The term fan- refers to the mode of deposition but not necessarily the shape of the sediment body as ice front shape and position together with the existing topography are the controlling factors. As a result, fans can be irregular in shape or can resemble a frontal moraine when several fans coalesce along the ice front.		Ice marginal/ proglacial zone	Discontinuous distribution proximally, along the ice margin. Deposition from a point source	Boulders, cobbles and gravels poorly /moderately sorted in the proximal part. Cobbles and gravels and sands in the distal part. Glaciotectonic deformation/ bulldozing often present	Variable - poor in proximal part moderate to good in medial to distal	(Zieliński and van Loon, 2000, 1999, 1998)
Ice marginal moraine	**Thrust block moraine**	Glaciotectonic deformed sediments in the subglacial and ice marginal zone as a result of stress exerted by the ice sheet during advance. Thrust block moraines can be laterally extensive along the ice front and over 100 m in relief. Deformation of sediments resembles thin skinned thrusting. The depth of the deformation is limited by failure along a decollement surface most likely corresponding to a zone of contrast of mechanical properties of the substratum (sand /mud, unfrozen sediments/permafrost). Ductile deformation results in the formation of large open folds in the sediments in front of the ice mass. Thrust block moraines can be composed of proglacial outwash sediments, subglacial traction till, or glaciomarine sediments. Primary sedimentary structures are generally	Ice marginal zone	Ice margin parallel mounds, 100s-1000s m wide, 100s m to 10s km long and 10s-100s m high.	Good reservoir quality if well sorted glaciofluvial sands and gravels are thrusted. Variable/poor if other e.g. lacustrine or subglacial sediments are thrusted - substratum dependent. Glaciotectonic deformations decreasing reservoir quality	Variable	(Benn and Evans, 2010; Bennett, 2001; Vaughan-Hirsch and Phillips, 2017)

Element		Description	Depositional zone	Reservoir potential			References
				Presence/distribution	Quality	Overall	
		preserved for most of the sedimentary units.					
	Push moraines	Oscillations of the ice front result in bulldozing of proglacial sediments and formation of push moraines. Small ice-front parallel ridges of unsorted sediment delineate annual re-advances of the ice front. Larger ridges most likely mark positions of longer stillstands. Primary sedimentary structures are unlikely to be preserved. Internal composition of a push moraine is dependent on ice marginal zone sediments and the mode of sediment supply. If meltwater deposition prevails push moraines can be sand and gravel-rich whereas where traction till deposition is dominant or the ice sheet is advancing over sand-poor areas the push moraine will be composed of glacial diamicton.	Ice marginal zone	10s-1000s m long, 10s-100m wide and 10s m high, ice-front parallel, elongated hills, often present in several parallel sets	Very poor sorting, Textural and mineralogical maturity dependent on the substratum. Outsized clasts and large boulders often present (up to several m)	Low	
Sandur	A large sediment body deposited by glacial, braided, meltwater streams in front of an ice terminus known also	Proximal: gravelly deposits of high energy braided channels may prevail in vertical succession.	Proglacial	Broad plains/belts of glaciofluvial sediments, 1-10s km wide, 1-100 km long. Thickness of sediments is highly variable and	Well sorted, rounded and sub-rounded sands and gravels. Multiple erosional internal contacts.	Good	(Magilligan et al., 2002; Maizels, 2007, 1997; Pisarska-Jamrozy and Zieliński, 2014; Zielinski and Van Loon, 2003)
		Distal: both gravel and sand channels deposits can be observed.				Good	

Element	Description	Depositional zone	Reservoir potential			References
			Presence/distribution	Quality	Overall	
	as an outwash plain. Sandar associated with large ice sheets are described as braided river plains rather than alluvial fans with poor proximal-to-distal grainsize variation. Pitted sandur: glaciofluvial rivers can bury dead ice blocks which subsequently melt out causing local depressions. Peat accumulations can often be observed in pitted sandar formed during interglacials.		controlled by the topography.	Primarily as above with finer fractions filling depressions	Good / variable	
	Jökulhlaup deposits: sediments associated with high magnitude outburst floods. Due to the extremely high energy of a jökulhlaup and high sediment concentrations, mega-scale ripples, dunes or boulder bars may be formed. Some may form thick, hyper-concentrated sandur sequences. It may be difficult to distinguish jökulhlaup deposits from normal flood sediments (Maizels, 1997; Gomez et al., 2000; Björnsson, 2003).		Forming part of the sandur sequence with a clearly erosional base.	Composed of coarse gravels, often boulders, and rip-up clasts. Could be poorly sorted if the sediment concentration is high.	Variable	
Ice marginal streamway	Large ice-front-parallel fluvial system develops when meltwaters escaping the ice sheet, after flowing over sandar, do not enter a water body directly. Such situations occur on uplifted areas where little or no sediment accommodation space is available.	Proglacial	100s km long and 10s km wide. Ice margin parallel and formed perpendicular to sandar.	Well sorted fluvial sands and gravels and over bank deposits. Hard to distinguish from a typical fluvial succession	Good	(Pisarska-Jamrozy, 2015; Van Loon and Pisarska-Jamroży, 2017)
Aeolian Dunes	Wind reworking of sandur plains prior to the onset of vegetation may result in winnowing of finer fractions and re-mobilization of fine sands and local deposition of aeolian dunes or cover sands. Finer fractions are transported over longer distances and deposited as loess covers.	Proglacial	Localized distribution mainly on unvegetated sandur plains.	Fine to medium sands- well sorted	Good	(C.K. Ballantyne, 2002; Benn and Evans, 2010; Mountney and Russell, 2009)
Lacustrine glacier-fed delta	Glacier-fed deltas build up when a sandur enters a proglacial water body. Such deltas may be extensive with multiple braided feeder channels. Alternatively, lacustrine deltas may form when smaller lakes are present on a sandur. Such deltas may potentially in-fill all available accommodation space in a lake resulting in continuation of sandur deposition. Annual cyclicity of flow regime and occasional catastrophic flood events may result in preferential preservation of sediments associated with high magnitude events in the proximal parts of the delta and longer depositional distance of sand facies in comparison with the classic delta model. High sedimentation rates may cause rapid progradation of delta front and frequent slope failures (slumping).	Proglacial	Localized distribution. Deposits filling proglacial lakes on the sandur plane. Variable size n hand shape.	Well sorted, texturally mature sands and gravels in the foresets. Topsets could be coarser due to winnowing and sediment bypass, fines deposited distally as prodelta-lake fill	Topsets Good Foresets Good Prodelta Poor	(Benn and Evans, 2010; Dietrich et al., 2016; Fyfe, 1990; Lønne, 1995; Lønne and Nemec, 2004; Nemec, 2009; Osterloff et al., 2004a; Patton and Hambrey, 2009; Phillips et al., 2002; Postma, 1990; Powell, 1990; Powell and Molnia, 1989; Wang et al., 2011)
Lacustrine ice - contact delta	Flat topped ice -contact deltas may develop in places where subaqueous outwash fans fill in accommodation space between a proglacial lake bed and water surface. Deltaic	Ice marginal	Localized deposition controlled by the ice margin	Mostly well-sorted sands and gravels. Bulldozed,	Ice-contact Variable	

Element	Description	Depositional zone	Reservoir potential			References
			Presence/distribution	Quality	Overall	
	topsets are deposited subaerially and act as a sediment by-pass zone with the majority of the deposition occurring on the delta slope (foresets). Ice-contact deltas may not exhibit the classic shape. Ice-contact deltas mimic the shape of the ice margin in their proximal part. Glaciotectonic deformation is most likely to be present in the ice-proximal part. Hyperpycnal, density current deposits can be frequent due to the high sediment load of glacial meltwater. Backstepping of the ice front and secondary delta formation can be observed.		position. Point sourced or amalgamated, ice front parallel deltas may build. 100s m to several km long 100s-1000s m wide. Thickness controlled by the water depth.	subglacially reworeked poorly sorted material and diamicton in the ice-contact part. Coarse gravels, in the topsets. Sands and finer gravels in the foresets. Fine fractions and sands in the prodelta.	Topset Variable Foreset Good Prodelta Variable / poor	
Proximal glacial lake fill	Proglacial lake sedimentation is characterised by deposition from meltwater streams (deltas and fans) or density currents in the proximal zone close to an ice margin or sediment input point. In the distal part of the lake sedimentation occurs mainly by settling from suspension from the meltwater plume in seasonal cycles. As a result, proglacial lakes are usually filled with sands interbedded with silts or silts and clays. Climbing ripple cross lamination of sandy beds is common proximal to the sediment input point. Glacial lakes may develop several levels of shorefaces recording changes in water level during deglaciation.	Proglacial	Present in the proglacial lake distally from the sediment input point.or as a fill of a small, proglacial lake (e.g kettle hole lake). Size and thickness controlled by the size and shape of the lake.	Interbedded fine sands and silts. Subordinate coarse sands in lenses or pockets.	Variable	(Ashley, 2002; Colin K. Ballantyne, 2002; Bogen et al., 2015; Carrivick and Tweed, 2013; García et al., 2015)
Distal glacial lake fill	Distal glacial lake fill is usually characterised by fine grained deposits (silts) deposited from suspension with occasional dropstones/ ice rafted debris. Rhytmites (varvites) represent periodical, often bi-annual, variations in sediment supply and/or oxygen level in the lake.	Proglacial zone	Laterally extensive deposits. The distribution is controlled by the size of the lake.	Fine silts and clays bedded and laminated. Dropstones and varves could be present.	Poor	

Table 3: A summary of landforms and sediments deposited by water terminating ice sheets is provided below. Every sediment/landform is assigned to a depositional zone with an assessment of reservoir quality.

Element	Description	Depositional zone	Reservoir potential			Reference
			Presence/distribution	Quality	Overall	
Esker	For description see Table 2.	Subglacial / ice marginal	For description see Table 2	For description see Table 2	Variable/good	(Brennand, 2000; Burke et al., 2015; Storrar et al., 2014)
Ribbed (Rogen) moraine sediments	For description see Table 2.	Subglacial	For description see Table 2	For description see Table 2	Poor	(Dunlop and Clark, 2006)
Drumlins/ drumlin fields	For description see Table 2.	Subglacial	For description see Table 2	For description see Table 2	Poor	(Benn and Evans, 2010; Bjarnadóttir and Andreassen, 2016; Ely et al., 2016)

Element	Description		Depositional zone	Reservoir potential			Reference
				Presence/distribution	Quality	Overall	
Traction till (diamicton)	For description see Table 2.		Subglacial	For description see Table 2	For description see Table 2	Poor	(Boulton and Deynoux, 1981; Evans et al., 2006)
Mega Scale Glacial Lineations (MSGL)	For description see Table 2.		Subglacial	For description see Table 2	For description see Table 2	Poor	(Bingham et al., 2017; Bjarnadóttir and Andreassen, 2016; Ely et al., 2016; Jamieson et al., 2016; Ottesen et al., 2017; Spagnolo et al., 2016)
Grounding zone wedge	Sedimentary depocenters formed at the grounding line of a marine terminating ice stream with steep distal and shallow dipping proximal slope. Grounding zone wedges are composed mainly of glaciogenic debris derived by melt out from basal ice and lodgement from subglacial traction till. They are found only in the locations of ice streams (cross shelf troughs) and fjords, punctuating stillstand positions of the grounding line, most likely, during ice retreat.		Subglacial	Localized, belts or bands of sediments 100s-1000s m long, 1000s m wide (constrained by the cross-shelf trough width) and 10s m high.	Mostly poorly sorted subglacial till interbedded with debris flow deposits and glaciomarine muds. Localized lenses, beds of better sorted material may be present.	Poor	(Batchelor and Dowdeswell, 2015; Dowdeswell et al., 2016b; Dowdeswell and Fugelli, 2012; Evans et al., 2012; Koch and Isbell, 2013; Powell and Alley, 1996; Powell and Domack, 1995)
Ice marginal moraine	**Thrust block moraine**	Subaqueous thrust block moraines can be composed of subaqueous outwash sediments, traction till, glaciomarine muds or non-glacial marine sediments. For a detailed description see Table 1.	Ice marginal	For a description see Table 2	For a detailed description see Table 2.	Variable - dependent on substratum	(Benn and Evans, 2010; Bennett, 2001; Vaughan-Hirsch and Phillips, 2017)
	Push moraine	Subaqueous push moraines can be composed of subaqueous outwash sediments, traction till, glaciomarine muds or non-glacial marine sediments. For a detailed description see Table 1.	Ice marginal	For a description see Table 2	For a detailed description see Table 2.	Poor	
Grounding line fan	Small sediment depocenters at the grounding line of an ice sheet. Sediments are deposited by a mixture of grounding line processes (traction, debris flows) and fallout from meltwater. As a results glaciofluvial sands and gravels are mixed with cohesive debris flow sediments. Ice front oscillations are responsible for sediment re-deposition and mixing.		Ice marginal	Localized distribution associated with point-sourced meltwater discharge at the grounding line. 10s-100s m long and wide and 10s m thick.	Well sorted, glaciofluvial sands and gravels, interbedded with poorly sorted debris flows deposits and/or glacimarine/subglacial till. Glacitectonic deformation often present.	Variable- dependent on the proportion of glaciofluvially sorted sediment is in the package.	(Evans et al., 2012; Powell, 1990; Powell and Alley, 1996; Rose et al., 2016)

Element	Description	Depositional zone	Reservoir potential				Reference
			Presence/distribution	Quality	Overall		
Subaqueous outwash fan (grounding line fan)	Large sedimentary body comprised of sands and gravels deposited by glacial meltwaters entering a water body at the grounding line of an ice sheet. The water at the time of the deposition is deep enough to prevent the fan from reaching the surface (if the surface is reached an ice-contact delta develops). Sediments may include proximal boulders and gravels sharply transitioning into distal sands and silts. Glaciotectonic deformation and dewatering structures are likely to be present. Characteristic features, distinguishing subaqueous outwash from sandur sediments, are: ripple cross laminations in sand units, large channels with massive fill, co-occurrence of cohesive and non-cohesive subaqueous debris flows deposits.	Ice marginal-proglacial	Large, localized sediment accumulation on the seabed associated with the ice margin position at the time. Deposited during the ice sheet retreat when meltwater discharge is high.100s to 1000s m wide and long, 10s m thick	Well sorted sands are dominant. Silt and marine mud interbeds can be present in the distal part. Boulders and gravels could be present proximal to the grounding line.	Good		(Batchelor and Dowdeswell, 2015; Evans et al., 2012; Koch and Isbell, 2013; Lønne, 1995; Powell, 1990; Rose et al., 2016; Rust and Romanelli, 1975)
Lacustrine glacier-fed delta	For a detailed description see Table 2.	Proglacial	For a description see Table 2	For a detailed description see Table 2	Topsets	Good	(Benn and Evans, 2010; Dietrich et al., 2016; Lønne, 1995; Lønne and Nemec, 2004; Nemec, 2009; Osterloff et al., 2004a; Patton and Hambrey, 2009; Phillips et al., 2002; Postma, 1990; Powell, 1990; Powell and Molnia, 1989; Wang et al., 2011)
					Foresets	Good	
					Prodelta	Low	
Lacustrine ice - contact delta	For a detailed description see Table 2.	Ice marginal	For a description see Table 2	For a detailed description see Table 2	Ice-contact	Variable	
					Topsets	Variable	
					Foresets	Good	
					Prodelta	Low	
Marine glacier-fed delta	If a sandur enters the sea a glacier-fed delta is likely to build up. Such deltas may be extensive with multiple braided feeder channels. Annual cyclicity of flow regime and occasional catastrophic flood events may result in preferential preservation of sediments associated with high magnitude events in the proximal parts of the delta and longer depositional distance of sand facies in comparison with classic delta model. High sedimentation rates may cause rapid progradation of delta front and frequent slope failures (slumping).	Proglacial	Large sediment body deposited as an extension of a sandur entering a marine basin. 1000s m long and wide. Depth controlled by changes in water depth.	Well sorted sands with subordinate gravels in the foresets unconformably overlain by topsets that can be coarser and resemble sandur successions. Silts and muds present in the distal part.	Topsets	Good	
					Foresets	Good	
					Prodelta	Low	
Marine ice-contactdelta	Flat topped, marine ice-contact deltas may develop in places where subaqueous outwash fans fill-in accommodation space between the sea bed and water surface. Deltaic top sets are deposited subaerially and act as a sediment by-pass	Ice marginal	Localized distribution in front of and parallel to the ice margin. Deltas form from	Quality and facies distribution is similar to lacustrine ice-contact	Ice-contact	Variable	

Element	Description	Depositional zone	Reservoir potential: Presence/distribution	Reservoir potential: Quality	Reservoir potential: Overall	Reference
	zone with the majority of the deposition occurring on the delta foresets. Ice-contact deltas may not exhibit the classic D-shape of a delta as it may be controlled by the ice margin geometry in its proximal part. Glacitectonic deformation is most likely to be present in the ice-proximal part of the lobe. Due to the higher density of seawater rainout from suspension can be expected distally from the delta front. Backstepping of the ice front and secondary delta formation can be observed.		one or multiple point sources. Lobate in shape if not topographically constrained. 100s - 1000s m wide, 100s m to 10s km long and 10s m thick.	deltas. Larger proportion of deposition from buoyant sediment plume due to the increased density of sea water. (For details see Table 2)	Topsets Good Foresets Good Prodelta Poor	
Proximal glacial lake fill	For a detailed description see Table 2	Proglacial	For description see Table 2	For description see Table 2.	Variable - substratum dependent	(Ashley, 2002; Colin K. Ballantyne, 2002; Bogen et al., 2015; Carrivick and Tweed, 2013; García et al., 2015)
Distal glacial lake fill	For a detailed description see Table 2	Proglacial	For description see Table 2	For description see Table 2.	Poor	
Trough mouth fan	Fan-like sedimentary depocenters originating at the shelf break and extending for up to several hundreds of kilometres into the abyssal plain. Thickness of sediments can reach 5 km. The sediment forming a TMF is delivered to the shelf break by ice streams from ice sheets and deposited by gravity flows down the continental slope causing progradation. It is inferred that gravity flow sediments are interbedded with glaciogenic muds and interglacial marine muds. The exact sedimentary composition of a TMF is poorly constrained. Poorly sorted and mud rich mass wasting deposits are inferred from remote sensing surveys (sonar). Long runout distances of some lobes may indicate that deposition from density currents takes place in the distal part of the fan.	Proglacial	Deposited on the shelf slope and extending into the abyss. Located at the distal end of cross-shelf troughs. 10s km to 100 km wide and long, 100s to 1000s m thick.	Poorly constrained. Glaciogenic gravity flow deposits are usually poorly sorted and mud/clay rich. Localized meltwater supply and long runout distance of gravity flows may indicate the presence of better sorted packages.	Variable - poorly known and substratum dependent	(Dowdeswell et al., 2008; Ó Cofaigh et al., 2003; Taylor et al., 2002; Vorren and Laberg, 1997)
Gravity flows deposits	Sediment gravity flow sediments are frequently redeposited from sediments of glacial marine or lacustrine origin. Slope instability is a common characteristic of ice marginal landforms due to high sedimentation rates, ice margin oscillations, isostatic rebound-related earthquakes and localised deposition of ice derived sediments. Sediment type in an individual flow depends on the type of material available. High meltwater discharge from the ice sheet during the summer months can lead to deposition of turbidites in the proglacial zone of a marine/lacustrine terminating ice sheet.	Proglacial	Common in all glaciogenic successions. Remobilized from over steepened slopes of previously deposited landforms. Variable in size and thickness	Most of the glaciogenic gravity flow deposits will have decreased sorting with respect to the source lithology. Gravity flows associated with TMFs may be an exception.	Variable- dependent on substratum	(Dowdeswell et al., 2004; Koch and Isbell, 2013; Lønne, 1995; Pisarska-Jamrozy and Weckwerth, 2013; Powell and Molnia, 1989)

Element	Description	Depositional zone	Reservoir potential			Reference
			Presence/distribution	**Quality**	**Overall**	
Contourites	Sediments delivered to the ocean floor are often reworked by slow, semi-permanent bottom currents – contourites, which reflect the thermohaline circulation in global ocean when cold and dense water flows along the base of the continental slope. Two types of contourites are reported: muddy- with up to 15% sand content and sandy- with laminate, rippled or structureless layers of sand up to 25 cm thick. They are extremely hard to identify in the rock record and can be easily mistaken for distal turbidites.	Proglacial	In the abyssal plain at the base of a continental slope. Forming belts or mounds of sediment parallel to the slope base.	Usually fine (silts and v. fine sands) but well sorted sediments. Grainsize controlling reservoir properties. Could have good reservoir properties if coarser sediment were supplied to the abyss - (e.g. by trough mouth fans).	Low / moderate	(Camerlenghi et al., 2001; Jones et al., 1993; Lucchi and Rebesco, 2007; Reading, 2002)
Marine diamicton (glaciomarine muds)	Fine grained, laminated or massive muds deposited by settling from suspension with occasional floating clasts (dropstones). Higher degree of lamination, lower clast content and normal compaction allowing differentiation of glaciomarine muds from subglacial traction till. Glaciomarine muds may be altered by iceberg ploughing in which case lamination will not be preserved.	Proglacial	Regional, large scale distribution within the basin. Dropstone and iceberg rafted debris increases in density proximal to the outlet. Thickness depends on the longevity of glaciation. Often interbedded with typical marine muds.	Poor reservoir quality due to low grainsize. Good seal. Local scouring by iceberg keels (iceberg ploughmarks) can reduce sealing properties.	Low	(Eyles et al., 1985; Lønne, 1995; Powell and Molnia, 1989; Rust, 1965)

Table 4: Sediments and landforms diagnostic of glacial erosion, deposition and presence in the basin enabling unequivocal interpretation of glaciogenic sediments. Mode of identification has been provided for every entry in the table.

Diagnostic element	Description	Depositional zone	Mode of identification	Reference
Striations/ Striated pavement	Grooves in bedrock or underlying sediments. The grooves are formed by debris encased in ice in traction of over the bedrock/sediments. Striations are good indicators of ice movement direction.	**Subglacial erosional zone**	Outcrops	(Clerc et al., 2013; Le Heron, 2007; Levell et al., 1988; Martin et al., 2012; Stroeven et al., 2016)
Traction till (glacial diamictite / diamicton)	For a detailed description see Table 2.	**Subglacial depositional zone**	Core/outcrop/well log data/drilling data	(Boulton and Deynoux, 1981; Evans et al., 2006)
Mega Scale Glacial Lineations	For a detailed description see Table 2.	**Subglacial zone**	3D seismic data	(Bingham et al., 2017; Bjarnadóttir and Andreassen, 2016; Ely et al., 2016; Jamieson et al., 2016; Ottesen et

(MSGL)				al., 2017; Spagnolo et al., 2016, Benjamin Bellwald et al., 2019; Piasecka et al., 2016)
Boulder pavements	A layer of boulders with striated surfaces in traction till. Sediments are deposited subglacially as traction till. Subsequently, after ice retreat, fine grained sediments are winnowed by water and wind leaving a layer of boulders and cobbles.	**Subglacial zone- reworked**	Outcrops, drilling data, well logs/micro imaging logs	(C.K. Ballantyne, 2002; Boulton, 1996)
Sediment/rock rafts	Blocks of rock/sediment excavated, transported and deposited by ice without disaggregation of its primary structure. Rafts are known to reach sizes of up to several km long and wide.	**Subglacial zone**	2D/3D seismic/core (very rare)	(Rüther et al., 2013; Winsborrow et al., 2016)
Shear margin moraine	Ridge of sediments formed subglacially at the boundary between slow-moving is and fast-moving ice (ice stream). 10s m high, 100-1000s m wide and 10s km long. They are composed of available subglacial material (diamicton).	**Subglacial zone**	3D seismic data	(Batchelor and Dowdeswell, 2016; Benjamin Bellwald et al., 2019; Bellwald and Planke, 2019; Stokes and Clark, 2002)
Tunnel valleys	Elongated, deep incisions up to 100 km long, 5 km wide and 400 m deep. Tunnel valleys are oriented perpendicular to former ice margins. Their formation is linked to meltwater erosion in proximity to the ice margin during ice retreat or deglaciation. They are usually filled with deglaciation - to - postglacial sediments.	**Ice marginal zone (subglacial to proglacial)**	Seismic (2D and 3D)	(L. R. Bjarnadóttir et al., 2017; Ghienne and Deynoux, 1998; Kristensen et al., 2007; Praeg, 2003; Stumm, 2012; van der Vegt et al., 2016)
Glaciotectonic deformations	Deformation and remobilization of sediments due to ice front oscillations. Types of deformation include pushing, folding and thrusting of sediments. Shallow decollement and thrusting is known from Pleistocene and older sediments of the North Sea, Denmark and Germany (Cretaceous chalk cliffs of Rhugen).	**Ice marginal zone (ice-contact to proglacial)**	Seismic (2D and 3D)	(Pedersen, 2014; Vaughan-Hirsch and Phillips, 2017)
Iceberg scours/ keel marks	Curvilinear, irregular corrugation in the lake/sea bed. Corrugations are usually V or W shaped in cross-section and can me several km long, and up to 10-20 meters deep. The plough marks are formed by grounded icebergs.	**Proglacial zone - water terminating ice sheet (grounded)**	3D seismic data,	(J. A. Dowdeswell and Bamber, 2007; Graham et al., 2007; Haavik and Landrø, 2014)
Dropstones	Outsized clasts of cobble/ gravel size encased in laminated or massive marine/lacustrine muds. Glacial dropstones are melted out from floating icebergs and dropped onto the seabed/lake bottom. Other mechanisms including plant root rafting and rock projectiles have been suggested as other possible transport mechanisms, but they are likely to be of minor importance in the rock record.	**Proglacial zone - water terminating ice sheet**	Core/micro imaging logs	(Bennett et al., 1996)
Heinrich Layers (Ice rafted debris layers)	Terrigenous material deposited in marine/lacustrine conditions by melt out of sediments from icebergs. Coarse - grained clastic layers encased in marine muds are interpreted as evidence of marine terminating ice sheet dynamics – massive calving and iceberg release.	**Proglacial zone -water terminating ice sheet**	Core/micro imaging logs	(Bond et al., 1992; Hodell et al., 2017)
Varves (varvites)	Alternating layers of light and dark coloured clays or silts deposited in quiescent conditions in a proglacial lake/sea. Dark laminae are seasonal, associated with periods of low oxygen levels when ice covers the lake/sea. Lighter colour laminae are linked to oxygenated meltwater water influx during spring and summer months. Can develop in non-glacial conditions too.	**Proglacial zone**	Core/micro imaging logs	(Evans and Thomson, 2010; Gold, 2009; Powell and Cooper, 2002)

- A novel conceptual model for the distribution of glaciogenic reservoirs
- First-pass interpretation tool for complex glaciogenic sequences
- Ice margin position controlling reservoir quality
- Identification of landforms and sediments crucial to reservoir predictability

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: