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GlaciDat – a GIS database of submarine glacial landforms and sediments in the Arctic

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A digital database for submarine glacial landforms and sediments formed in the Arctic during and since the Last Glacial Maximum was created in order to facilitate and underpin new research on palaeo-ice sheets and tidewater glacier dynamics. The glacimarine database (GlaciDat) documents and standardises evidence of previous glacial activity as visible on the contemporary seafloor of fjords and continental shelves around Svalbard, Greenland, Alaska, northern Russia and north of 66°30′N in Canada and Norway. An extensive literature search was conducted to create GlaciDat, which compiles nearly 60 000 individual submarine landforms, more than 1000 sediment cores and 232 radiocarbon dates. Glacial landforms included are cross-shelf troughs, trough-mouth fans, grounding-zone wedges, lateral moraines, overridden moraines, (mega-scale) glacial lineations, drumlins, crag-and-tails, medial moraines, terminal moraines, debris-flow lobes (including glacier-contact fans), recessional moraines, De Geer moraines, crevasse-fill ridges, eskers, hill-hole pairs, crescentic scours, and submarine channels. They were digitised as point, line and polygon features alongside a list of their individual characteristics. Sediment core locations are attributed with a description of the sampled lithofacies and sedimentation rates where available. Landforms and sediments have been standardised according to predefined nomenclatures to make the glacial evidence as consistent as possible. Marine radiocarbon dates were included when thought to be relevant for constraining the timing of large-scale palaeo-ice dynamics. Outlines of bathymetric data sets, which have previously been used for glacial geomorphological mapping, were also included to give an overview of already investigated research areas. GlaciDat is available for download (https://doi.pangaea.de/10.1594/PANGAEA.937782) and will aid researchers in the reconstruction of past ice dynamics and the interpretation of Arctic glacial landform–sediment assemblages. Moreover, as well as providing a comprehensive bibliography on Arctic glacial geomorphological and sedimentological research, it is intended to serve as a basis for future modelling of Arctic glacier and ice-sheet dynamics.

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Palaeo-ice sheets have been the focus of many research investigations in recent decades (e.g. Elverhøi & Solheim 1983; Svendsen *et al*. 1996; Landvik *et al*. 1998; Anderson *et al*. 2002; Howat & Domack 2003; Ó Cofaigh *et al*. 2003, 2005; Bamber *et al*. 2007; Bradwell *et al*. 2008; Roberts *et al*. 2013; Andreassen *et al*. 2014; Hughes *et al*. 2016) and understanding their configuration and extents has become increasingly important to reliably predict the future of the cryosphere. Numerous attempts have been made, therefore, to reconstruct the dynamics of former and present ice masses, utilising modelling (e.g. Huybrechts 1994; Pollard & DeConto 2009; Simpson *et al*. 2009), geological and geophysical evidence (e.g. Elverhøi *et al*. 1993; Vorren & Laberg 1997; Svendsen *et al*. 1999; Ottesen *et al*. 2005; Ó Cofaigh *et al*. 2013; Streuff *et al*. 2017a, 2018) and the constantly growing information available from satellite imagery (e.g. Joughin *et al*. 2004; Farnsworth *et al*. 2016; Allaart *et al*. 2018; Aradóttir *et al*. 2019). Ice sheets whose outlet glaciers terminate in the ocean, such as the Greenland or the remainder of the Svalbard–Barents Sea ice sheets, have received increasing attention in recent decades, as they are particularly susceptible to changes in ocean currents and increasing air and water temperatures, and have therefore been disintegrating at dramatic rates (Nuth *et al*. 2010; Zwally *et al*. 2011; Rignot *et al*. 2015; Felikson *et al*. 2017; Morris *et al*. 2020). The retreating ice masses, in turn, result in the uncovering of more glacial evidence, and the warmer temperatures as well as reduced sea-ice cover facilitate research even in previously inaccessible fjords. This, as well as advances in the development of geological/geophysical instruments, has led to a wealth of publications on the submarine landform–sediment assemblages observed in front of modern tidewater glaciers and on continental shelves. However, to date, the lack of both a systematic approach and a coherent terminology have made it rather impractical to make use of the existing geomorphological and sedimentological evidence.

In an attempt to assemble the information published to date, and to simultaneously provide a robust basis for future investigations, we have now created GlaciDat, a digital database of submarine glacial landforms and sediment core records from Arctic fjords and continental shelves. The database is available by web download from the PANGAEA repository (https://doi.pangaea.de/10.1594/PANGAEA.937782). While GlaciDat is similar to the Geographical Information Systems (GIS) database for the last British–Irish Ice Sheet (Clark *et al*. 2004, 2018;

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Evans *et al.* 2005), and complementary to the DATED1 database of Hughes *et al.* (2016), it is new and unique in terms of both geographical coverage and the diversity of data included. It inventories previously mapped submarine glacial landforms, sediments, associated radiocarbon dates and outlines of bathymetric data used for glacial reconstructions, while also providing a comprehensive bibliography of the scientific literature relating to the subject of Arctic glacial geology. This paper focuses on the methodology used to create GlaciDat and guidelines on how to use it, while a forthcoming paper will review the evidence included and present a conceptual model of the landforms and sedimentary products commonly observed in Arctic fjords.

Context

The glacigenic sediments and landforms found on the seafloor of contemporary continental shelves provide valuable insight into the dynamics of many palaeo-ice sheets. Moreover, contemporary ice sheets are often drained by fast-flowing tidewater outlet glaciers, which therefore represent an important link between marine and terrestrial environments (e.g. Holland *et al.* 2008; Streuff *et al.* 2017a; Flink & Noormets 2018). The landforms and sediments deposited in Arctic fjords by such glaciers thus also play an important role in reconstructing the response of former ice sheets to large-scale climatic events.

Glacimarine depositional processes and glacial dynamics are generally believed to be dependent on a number of factors including, but not limited to, geographic setting and the resulting local climate, the presence or absence of meltwater and icebergs, and the internal glaciological structure of the ice (e.g. Powell 1984; Dowdeswell *et al.* 1998; Cowan *et al.* 1999; Hambrey *et al.* 1999; Ottesen & Dowdeswell 2009). Furthermore, particularly in Svalbard, many glaciers have been found to undergo cyclic switches between advance and retreat phases, so-called surges, which tend to produce different landform assemblages than those glaciers moving as a result of climatic forcing (Ottesen & Dowdeswell 2006; Streuff *et al.* 2015; Flink *et al.* 2017). In consequence, there is currently a plethora of publications on former ice-sheet margin positions, submarine glacial landforms, glacigenic lithofacies and the glacimarine sedimentary processes observed both in fjords and on the open continental shelf. However, such data records are wide-spread, highly variable in quality and often lack uniformity, which makes them difficult to use. Data limitations, variations in the style of landform and sediment description and interpretation, and selective presentation of the geomorphological record, among other things, have caused the evidence to be inconsistent and difficult to synthesise. Although efforts have been made to conceptualise glacimarine sedimentation and glacier dynamics (e.g. Powell 1981; Ottesen *et al.* 2008; Forwick & Vorren 2011; Streuff 2013; Flink *et al.* 2015), most such publications provide evidence from only limited geographical areas and consider local or regional environmental factors at best. It is therefore difficult to fully comprehend the large-scale dynamics of former and contemporary ice sheets despite their relevance for future sea level (Nick *et al.* 2010; Meredith *et al.* 2019; Fox-Kemper *et al.* 2021).

In an effort to facilitate and motivate future research, and to improve the robustness of forthcoming ice-sheet models in particular, we have created the GlaciDat database with the following objectives: (i) to provide a general overview of geographic areas where research has already been conducted, which will help plan future fieldwork and facilitate easy identification of areas with data gaps; (ii) to compile geomorphological and sedimentological evidence in a consistent manner, thus offering easy access to the submarine glacial record in the Arctic; (iii) to combine radiocarbon dates relevant to the evolution of ice sheets and glaciers during and since the Last Glacial Maximum (LGM); and (iv) to provide a comprehensive bibliography for glacial geomorphological research by including references to relevant publications. The main intention is to encourage ice-sheet modellers to make better use of glacial geomorphological and sedimentological palaeo-data for testing and compiling their models. Systematising this information across different geographic and climatic settings within one framework will not only simplify the comparison of glacial landform–sediment assemblages across different glacimarine settings, but should also ensure that previous work in a specific area is properly credited.

Content

GlaciDat is a compilation of submarine geomorphological evidence pertaining to the LGM and the Holocene. It includes the locations of previously published multibeam-bathymetric data sets and sediment cores (gravity, piston and vibrocores, as well as selected box cores) recovered from fjords and continental shelves, the submarine glacial landforms and lithofacies identified from these data, as well as radiocarbon dates from glacial and glacimarine sediments. Data were included from well over 1100 published scientific articles, books, scholarly reports, Bachelor's, Master's and PhD theses, cruise and fieldwork reports, geological memoirs and institute-specific scientific communications as far as they were accessible (or obtainable directly from the authors) and published up until the end of April 2021. Literature research was exclusively conducted through internet and library searches and by cross-referencing from other papers and research works. Unfortunately, data from publications only existing in hard copy in selected international libraries or from articles published in journals that were difficult to access could not be included.

As a combined terrestrial and marine database containing all glacier-related features and information is unlikely to ever be completed owing to the extensive research that has been done both on- and offshore, GlaciDat concentrates on the inclusion of submarine landforms and sediments occurring in and on Arctic fjords and continental shelves, and particularly those formed during or since the LGM. We define the Arctic as everywhere located north of the Polar Circle, i.e. 66°30′N, but include all of Greenland, due to the fact that its ice sheet remains active also at lower latitudes, and all of the fjords in Alaska, because they are regarded as the temperate end member of glacimarine environments (Dowdeswell *et al.* 1998, 2016). An overview of the areas considered for GlaciDat is given in Fig. 1. The database focuses on glacigenic evidence as visible on the modern seafloor; records from pre-LGM glaciations were therefore generally excluded. Selected landforms, such as iceberg ploughmarks, corrugated ridges, pockmarks, rafts and mega-blocks, and mass-wasting features along fjord walls, as well as gullies and slide scars, were excluded. This is due to the fact that, contrary to Antarctic settings, in the Arctic these features do not provide direct evidence for ice dynamics. Instead, they merely attest to the presence of sufficiently deep-keeled calving icebergs, or a certain degree of sediment redeposition and/or fluid seepage at the seafloor (see e.g. Dowdeswell *et al.* 1993; Forwick & Vorren 2012; Roy *et al.* 2015). Locations of sediment cores were included as far as they provided stratigraphic evidence for glacial or deglacial glacimarine environments and were published as such; sediment cores from publications focusing on other research questions (e.g. palaeoceanographic or sea ice reconstructions) were only included when lithofacies were described and interpreted as wholly or partially glacimarine in origin. Unless they provide relevant evidence for previous ice-sheet behaviour, such as sediment cores taken from trough-mouth fans, cores from deeper water beyond the continental shelf edge were not included, owing to the fact that their lithofacies are often very complex and sedimentary units are unlikely to be purely glacimarine in origin. Sediment ages were usually limited to the oldest reliable deglaciation date from a location. Although dates obtained from cosmogenic dating on terrestrial boulders, as well as radiocarbon dates from former raised shorelines, often play an important role in reconstructing glacial and sea-level change, such features were excluded from the GlaciDat database, but relevant publications were, nevertheless, included in the provided bibliography.

It is important to emphasise that, rather than re-evaluating and re-interpreting the already published landform–sediment assemblages, GlaciDat aims to combine the fragmented information into one easy-to-use inventory of actual geomorphological evidence as visible on the present seafloor. Interpretations of previous ice-sheet extents, flow dynamics and advance/retreat mode were therefore not included in the database, despite the fact that such information can be useful for understanding the complex behaviour of former and present ice masses. An example are changes in ice-flow direction inferred from the observation of variably orientated sets of streamlined subglacial bedforms (see e.g. Andreassen *et al.* 2007; Piasecka *et al.* 2016) or the assumption that an ice sheet retreated in a slow, step-wise manner, based on the presence of grounding-zone wedges and recessional moraines (*see* e.g. Ottesen & Dowdeswell 2006; Batchelor & Dowdeswell 2015).

Methodology

GlaciDat was created as an ESRI ArcMap™ file geodatabase set to the WGS 1984 World Mercator projection. The file geodatabase was subdivided into six feature classes based on feature geometry and type (see also 'Database setup' below). Data entry into the GIS project consisted of three steps: (1) georeferencing, (2) mapping and (3) attributing.

Georeferencing was done by copying figures and maps published in the academic literature, pasting them into ESRI ArcMap™ and relocating them using the georeferencing tool provided by the software. Although in theory this should be a simple process, a surprisingly large number of publications provide no or only insufficiently accurate coordinate data. As a consequence, georeferencing figures by tick marks and grid lines was seldom possible; more often it was necessary to use topographic points along coastlines and/or large-scale bathymetric features from (i) the 'Imagery' base map provided by ESRI online (as of July 2021) or (ii) the international bathymetric chart of the Arctic Ocean (IBCAO, version 3.0; Jakobsson *et al.* 2012) as reference. This method of georeferencing worked reasonably well for the majority of data; however, the range of projections and scales, as well as the inconsistent data quality in the literature, further exacerbated by the fact that map projections in the Polar areas are generally difficult, led to quite variable georeferencing results (see also the section 'Location errors' below). Using the pasted and georeferenced figure as background, glacial features were then digitised manually as points, lines and polygons (Fig. 2), and were assigned attributes through which all of the relevant information, as far as documented in the literature, was summarised.

Database setup

Data layers

The GlaciDat database contains six main layers (= feature classes) defined by feature type and feature geometry. These are: (i) 'Landforms_Points', (ii) 'Landforms_Lines', (iii) 'Landforms_Polygons', (iv) 'SedimentCores' (points),

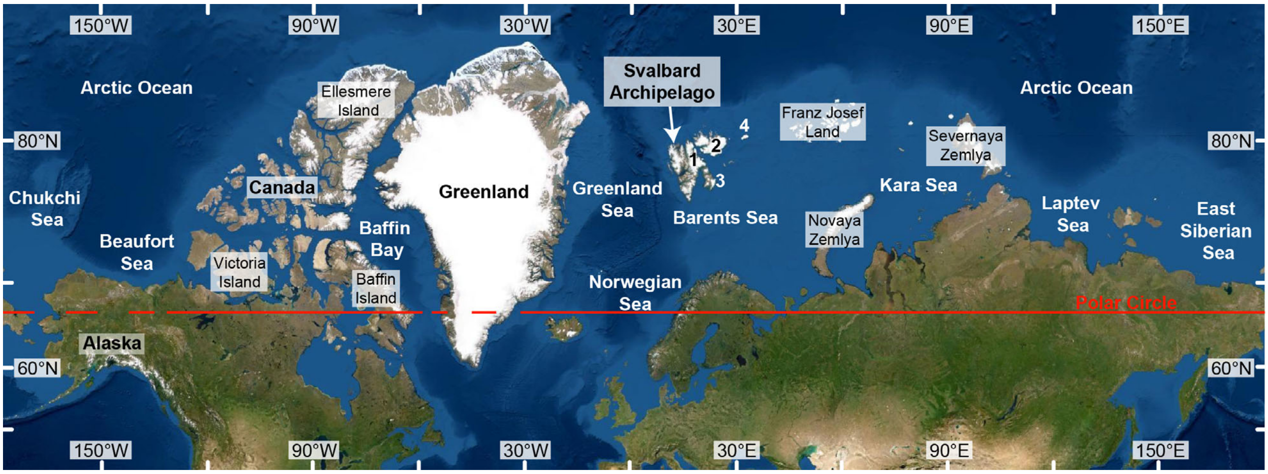


Fig. 1. Overview of the regions used for GlaciDat. Glacial geomorphological and sedimentological evidence were included from everywhere north of the Polar Circle (red line), as well as from all of Greenland and Alaska. Key regions are Alaska, Canada, Greenland, Northern Norway, the Barents and Kara Seas, and Svalbard. 1 = Spitsbergen; 2 = Nordaustlandet; 3 = Edgeøya; 4 = Kvitøya. Background map is the 'Imagery' basemap, courtesy of ESRI Online.

(v) 'Dates' (points) and (vi) 'BathymetryOutlines' (polygons). The geometry was chosen to reflect the typical shape of a landform in the ocean, or was set according to the shape the features were originally mapped as. These feature classes have been converted into six separate layer packages available for download from PANGAEA (https://doi.pangaea.de/10.1594/PANGAEA.937782). An accompanying map package is intended as a user-friendly digital map, which sorts the information into types of landforms and by region using the query builder in ArcGIS®. Regardless of whether one uses the layer packages or the map package, the data within the database can be filtered and customised based on user preference. The three landform feature classes include a total of 17 landform types, which represent the glacial features most commonly observed in the Arctic (Fig. 2A). These are cross-shelf troughs, trough-mouth fans, hill–hole pairs (mapped only as polygon features), grounding-zone wedges, lateral moraines, overridden moraines, glacial lineations, drumlins, medial moraines, terminal moraines, debris-flow lobes, recessional moraines and crevasse-fill ridges and channels (occurring as both polygon and line features), as well as crag-and-tails, crescentic scours and De Geer moraines (line features). A few crag-and-tails, grounding-zone wedges and recessional moraines were also mapped as point features if they were originally mapped as points without clear information on orientation and extent, which should be considered when querying the database for these landforms. Sediment cores were digitised as point features exclusively and were plotted in the location of sediment cores with glacimarine lithofacies (Fig. 2B). We chose to include only piston, vibro- and gravity cores, as they usually provide better information on the long-termsedimentary record than box cores and grab samples. Nevertheless, selected box cores and grab samples were included if they gave relevant information about the post-LGM stratigraphy in a location. The radiocarbon ages in GlaciDat (Fig. 2B) were plotted as data points into the 'Dates' feature class and were derived either from cored glacial sediments or from databases that were previously published (see Hormes *et al.* 2013; Hughes *et al.* 2016). Rather than recalibrating all radiocarbon ages at this stage, we have included the raw, uncorrected dates alongside corrected and calibrated ages (as far as provided) in the attribute table, including information on the calibration technique and the correction parameters. GlaciDat users can therefore recalibrate ages with their desired and customised calibration settings. The polygon features in 'BathymetryOutlines' are outlines of previously published bathymetry data derived from multibeam echosounding (Fig. 2C), which have been used for glacial geomorphological mapping. They thus provide an overview of previous study areas.

Attributes

Each feature included within GlaciDat was attributed with a range of characteristics to make sure that the information is as comprehensive as possible. Standard attributes allocated by ESRI ArcMap™ are ObjectID, Shape, Shape_Length (lines) and Shape_Area (polygons), which provide a unique identifier, as well as information on the geometry and size of the features, respectively. Owing to skewed measurements with the Mercator projection, however, the information given in the _Length and _Area columns does not reflect the actual size of the feature and should be ignored. To find out a feature's actual size as mapped in the GlaciDat database, reprojection of the feature into a different projected coordinate system would be necessary. A range

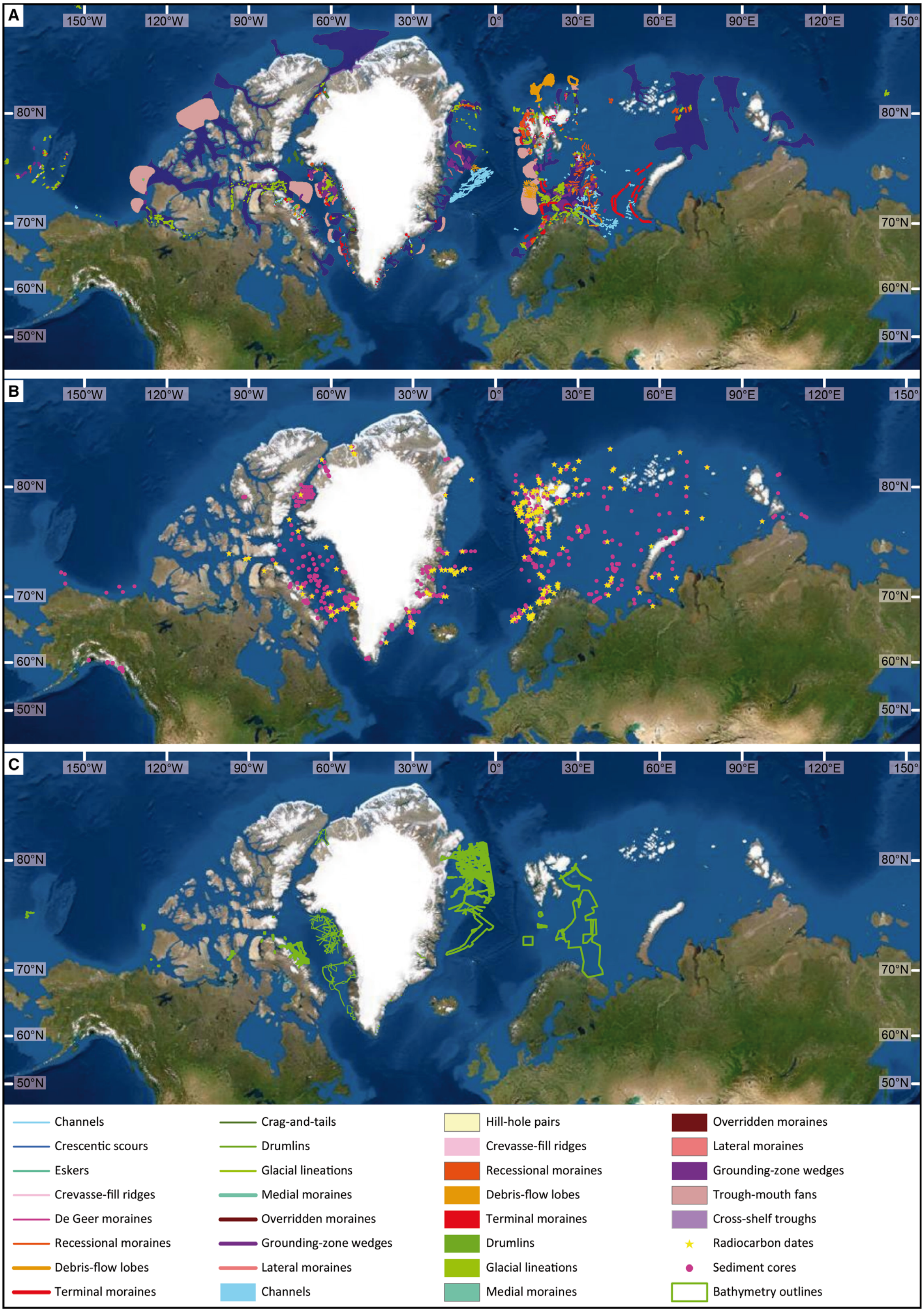


Fig. 2. Overview of the GlaciDat database with the different feature classes. A. Submarine glacial landforms digitised as points, lines and polygons in their respective feature classes. B. Sediment cores documenting glacimarine lithofacies in the Arctic and radiocarbon dates associated with ice sheet dynamics since the LGM. C. Outlines of bathymetry data published and previously used for the interpretation of marine glacial geomorphology.

of additional attributes was defined for each feature class, depending on its type. For the landform feature classes these are: (i) type, which represents our classification of each feature as one of the common landforms outlined above; (ii) description, as given in the original publication; (iii) length; (iv) width; (v) height/depth, as far as specified; (vi) thickness, where sub-bottom data were available; (vii) spacing, only used for recessional moraines; (viii) elongation ratio, only relevant for streamlined features; (ix) interpretation; (x) location; (xi) area; (xii) region; (xiii) references, showing the source publication as well as any others that have mentioned the respective landforms; (xiv) mapping accuracy to indicate the approximate location error (see also 'Database limitations' below); and (xv) notes for general comments. Note that the attribute 'interpretation' was always used to distinguish the authors' original interpretation; if a feature was re-interpreted for simplification purposes, this was mentioned in the 'notes' attribute.

Additional attributes for the 'SedimentCores' features are: (i) core name; (ii) core type; (iii) latitude; (iv) longitude; and (v) water depth given in the publication; (vi) recovery, i.e. length of the core; (vii) description, displaying the authors' sediment description; (viii) lithology, where we applied a standardised facies code according to a defined nomenclature (see 'Standardisation' below); (ix) lithofacies, where we assigned one of a total of eight lithofacies group codes (see 'Standardisation' below); (x) depositional setting and (xi) sedimentation or sediment accumulation rate (both abbreviated SAR) as far as specified; (xii) location; (xiii) area; (xiv) region; (xv) references; (xvi) calculated latitude; (xvii) calculated longitude; and (xiii) notes. Attribute (i) was set to distinguish between different cores and usually includes the names of the cores as described by the authors of the original source publication. However, as cores are often termed 'A' or 'Core 1', core prefixes were defined for those cores to allow for easier distinction between records. Where the information could be deduced from the publications' methodology sections, this was done by adding the first letters of the name of the research vessel and the year the cores were collected (e.g. AH93- or POR0205- for cores taken from RV 'Alpha Helix' in 1993 or RV 'Porsild' between 2002 and 2005, respectively). If acquisition details were unclear, the first letters of the author(s) and the year of the publication, from which the cores were digitised, were used (e.g. Po80- and ES83- for Powell (1980) and Elverhøi & Solheim (1983), respectively). If the core prefix was changed, this was flagged under the notes attribute. Attributes (vii), (viii) and (ix) were set specifically to keep the distinction between our interpretation/classification and the author's original description as transparent as possible. Although the sediment cores as well as the dates were added using the coordinates provided in the literature, owing to georeferencing problems (see 'Database limitations' below) the cores would not always show up in the same place as the core locations provided in overview maps from the original publications. This was problematic when cores described to sample a glacial till from a terminal moraine, for instance, would plot hundreds of metres away from the moraine. This issue was somewhat fixed by moving relevant core locations to their associated landforms; in these cases, the new position coordinates were recalculated in the 'calculated latitude' and 'calculated longitude' columns (attributes xvi and xvii), while the originally supplied coordinates were stored in the 'latitude' and 'longitude' columns of the attribute table (iii and iv). If core coordinates were missing in a source publication, cores were also digitised from the overview maps and approximate coordinates can be inferred from the calculated values in the database.

Attributes for the dates provided state: (i) the core from which the sample was derived; (ii) which age is displayed, with e.g. 8/8 meaning the lowermost reliable age out of eight total dates retrieved; (iii) the assigned lithofacies group; (iv) the sediment depth from which a sample was taken; (v) the dating method, (vi) the sample material; (vii) the calibration method; (viii) the uncalibrated, uncorrected ^{14}C age; (ix) the corrected age (raw age – reservoir effect); (x) the calibrated age range and mean; (xi) the uncalibrated date in ka BP ('date displayed'), intended to be used as a point label for a quick overview; (xii) the Marine Reservoir Effect; (xiii) the ΔR used in the source publication; (xiv) the implications for palaeo-ice dynamics; and again, information on (xv) location, (xvi) area, (xvii) region and (xviii) source publications as well as (xix) notes. Although most dates were obtained on cores included in GlaciDat and would therefore plot in the same location, some dates were plotted using base maps and/or very rough coordinates. As for the sediment cores, the attributes (xx) 'calculated latitude' and (xxi) 'calculated longitude' were added to show the coordinates for each data point. For dates located in Norway, Svalbard and the Barents and Kara seas, an additional attribute (xxii) 'DATED ID' indicates the ID of the date within the DATED database; if this attribute is void, the date was not included in the work by Hughes *et al.* (2016).

Further attributes for 'BathymetryOutlines' include information on: (i) the resolution of the originally published grid; (ii) the type of instrument used during acquisition; (iii) the location; (iv) the area; (v) the region; and (vi) references to the original source publication. Owing to projection issues, some bathymetric data outlines in the central Arctic Ocean could only be partially displayed or had to be separated into an eastern and a western sector (see data from Niessen *et al.* 2013; Jakobsson 2016).

Standardisation

Landforms. – One of the main objectives for creating the GlaciDat database was the intention to make glacial geomorphological and glacimarine records more uniform across the literature, but also across geographic regions. Therefore, although a re-interpretation of the geomorphological evidence documented in the literature was generally avoided, a certain degree of subjective interpretation was inevitable. This is because, as previously mentioned, the lack of a coherent terminology for glacial landforms causes a wide array of interpretative terms in the literature. In order to standardise submarine glacial landforms, GlaciDat therefore uses the list of the 17 most common landforms outlined above as categories (attribute = 'type') for the standardisation of the geomorphological evidence within the database. This means that features with similar morphologies and/or formation processes were included as one type. Examples are 'channels', which include turbidity-current and meltwater channels, as well as tunnel valleys, and glacial lineations and mega-scale glacial lineations, which were subsumed into the 'glacial lineations' type, with the elongation ratio given as a crucial attribute to distinguish between the two (*sensu* Stokes & Clark 2002). Rock drumlins, drumlinoid features and actual drumlins were summarised in the feature class 'drumlins', while crag-and-tails were grouped with streamlined bedrock. Features of the 'debris-flow lobes' type may represent glacier-contact fans or debris-flow lobes deposited on the distal flanks of terminal moraines. Although debris-flow deposits are considered to be the building blocks of trough-mouth fans (e.g. Vorren & Laberg 1997; Dowdeswell *et al.* 2002), the latter were mapped separately. Trough-mouth fans are exclusively related to cross-shelf troughs (Fig. 2A), which were mapped based almost entirely on the work of Batchelor & Dowdeswell (2014). Their location within GlaciDat is expected to be rather broad, however, as original maps were produced at a scale too small for exact georeferencing.

Although several of the different moraines in the database could have been summarised as 'ice-marginal features', different types were distinguished in order to clarify their formation process and their relevance for the reconstruction of past ice dynamics. Moraines are particularly common glacial landforms, and terminal moraines are especially important features for understanding the evolution of glaciers and ice sheets; hence, they should be easily identifiable within the GlaciDat database. Furthermore, although overridden moraines are generally either terminal or recessional moraines from a previous ice advance/retreat, it is not always clear which type they belong to.

The distinction between recessional moraines, De Geer moraines and crevasse-fill ridges is quite difficult based on morphology alone. This is mostly due to the fact that recessional moraines are highly variable in shape and size, and often form complex patterns on the seafloor with variably orientated ridge segments and a large degree of branching and anabranching. This is especially visible on the seafloor in front of Blomstrandbreen in Kongsfjorden, central West Spitsbergen, for example, where the more distal moraines are perfectly transverse to the fjord axis and cross the entire fjord basin, but proximal ridges are short and more chaotically distributed (Fig. 3; Streuff 2013; Streuff *et al.* 2015; Burton *et al.* 2016). Similarly, De Geer moraines can have rather variable orientations and lengths, where spacing tends to be irregular (e.g. Zilliacus 1989; Lundqvist 2000; Streuff *et al.* 2017b). Furthermore, not all crevasse-fill ridges show a pronounced rhombohedral pattern (Streuff *et al.* 2015; Flink *et al.* 2016), commonly regarded as their unique identifier, so that a distinction between those moraines formed through push at the glacier front and those formed from squeezing of subglacial sediments into basal crevasses is nearly impossible in some locations. As the formation mechanism of De Geer moraines has been debated in the literature (Lundqvist 1981, 2000) with some suggesting ice-marginal processes (Boulton 1986; Blake 2000) and others favouring subglacial formation (Hoppe 1957; Zilliacus 1989; Beaudry & Prichonnet 1991), we suggest classifying those moraines with ambivalent origin as De Geer moraines. Accordingly, some ridges within GlaciDat were re-interpreted as De Geer moraines (flagged in the 'notes' attribute).

Sediments. – Inconsistent descriptions and interpretations are not only a problem for glacial landforms, but also apply to glacial sediments, which, despite the availability of a clear nomenclature (Eyles *et al.* 1983; Krüger & Kjær 1999; Benn & Evans 2010; Lee 2017), are often described subjectively. To organise all sedimentological data in a systematic manner within GlaciDat, we have re-classified sediments described in the literature according to a nomenclature suggested by Eyles *et al.* (1983), which was modified to include more detail (Table 1). These lithofacies were then related to a total of eight main lithofacies groups (LG1–LG7, LGX) with 12 subgroups, which were defined on the basis of commonly interpreted lithofacies in the glacimarine realm; an overview is given in Fig. 4. Both the re-classification and the lithofacies group (LG) allocation reflect our own interpretation.

Database limitations

Owing to the fact that data for the GlaciDat database were gathered from numerous standalone publications rather than from research investigations undertaken as part of a systematic survey, there are some caveats to keep in mind when using GlaciDat. The two overarching caveats are data consistency and reliability, because, as previously mentioned, the quality of the data presented in the literature was extremely variable. As a result, the data included in the database are subject to certain limitations, which are described in more detail in the following paragraphs. We would like to emphasise at this point that the GlaciDat database is intended to provide a

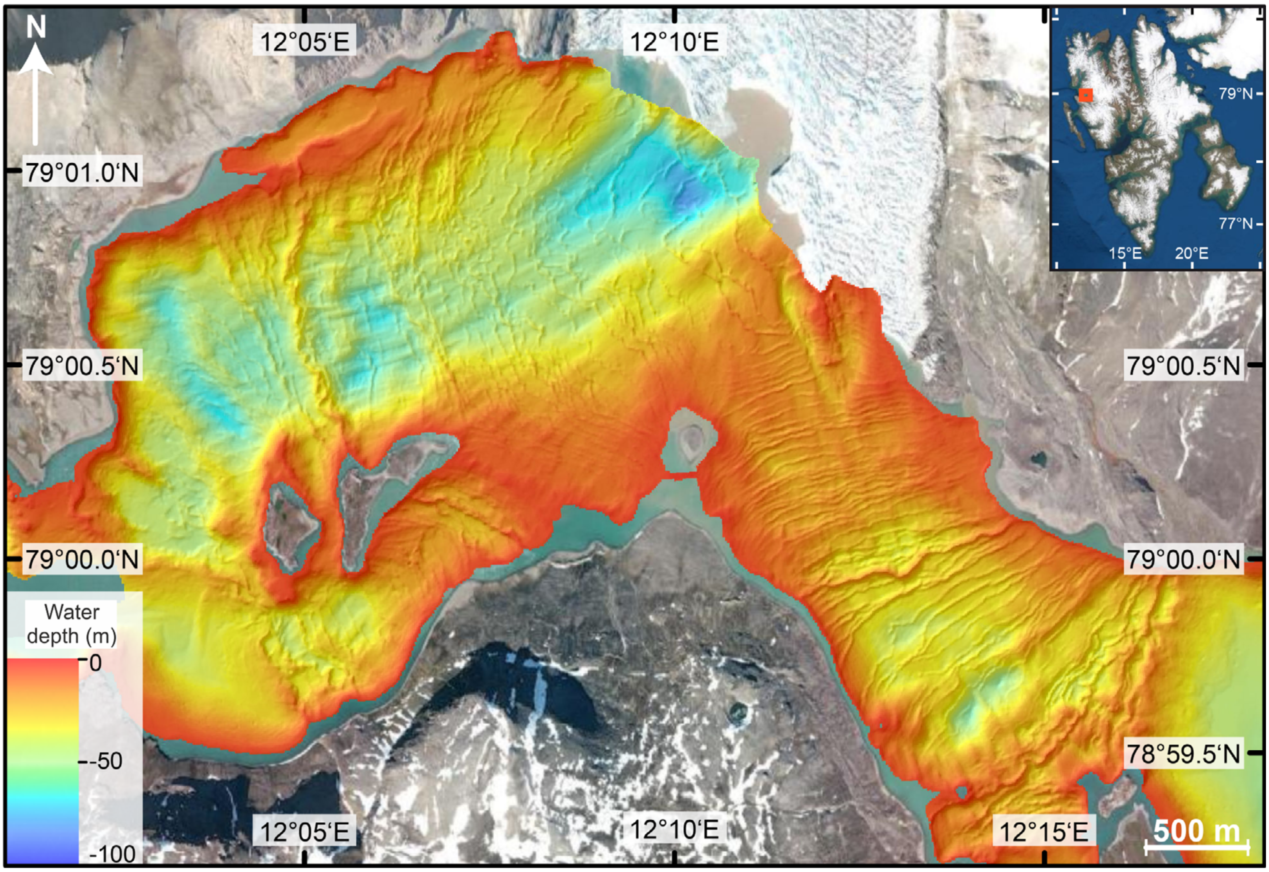


Fig. 3. Submarine retreat moraines in front of Blomstrandbreen, Kongsfjorden, NW Spitsbergen. Note the continuous, parallel and relatively straight nature of the ridges in the east and the much more chaotic and discontinuous distribution in the west. The little inset at the top right shows Spitsbergen with the location of Blomstrandbreen and its retreat moraines indicated by the small red rectangle. Bathymetry data used in this figure were previously published in Streuff (2013) and Streuff *et al.* (2015).

broad overview of glacial landforms and sediments already documented in the literature and the user is therefore advised to always refer to the cited literary sources from which the features were derived.

Location errors

Depending on the quality of the maps used in the literature, the georeferencing of certain features was not always straightforward. In a number of cases selected marks would align perfectly in one area, but would be off by sometimes up to several kilometres in another area. This could lead to considerable mapping inaccuracies. Unfortunately, coordinate points given in the literature also frequently omit the seconds or the decimal digits. With 60 arc seconds being equivalent to up to ~900 m above 60° latitude, this may obviously lead to rather substantial errors in location. In an attempt to qualify the degree of inaccuracy for the location of individual features, the attribute 'Mapping Accuracy' was assigned to each feature class. For this attribute four different values were defined: (i) accurate; (ii) approximate; (iii) rough; and (iv) schematic (Fig. 5). 'Accurate' was used for information gathered from actual georeferenced data, such as shapefiles and feature classes provided by authors or available from the internet, or for published figures and maps which could be exactly aligned with prominent landmarks and coastlines (Fig. 5A). In these cases, especially with the data already including geospatial information, it is relatively certain that the data plot in the correct location and any errors will be in the range of a few metres to some tens of metres in rare cases. The attribute 'approximate' was used for maps and figures that could be georeferenced reasonably well in at least two points, but could not be exactly aligned with the coastline or other prominent landmarks (Fig. 5C). Where the mapping accuracy is set to this value, a location error of generally <200 m and in very few cases up to 500 m to 1 km should be expected. Location errors of around 50–150 m were attributed 'accurate to approximate' (Fig. 5B). The mapping accuracy was set to 'rough' where published figures only included sketched or drawn landmarks that could not be assimilated with

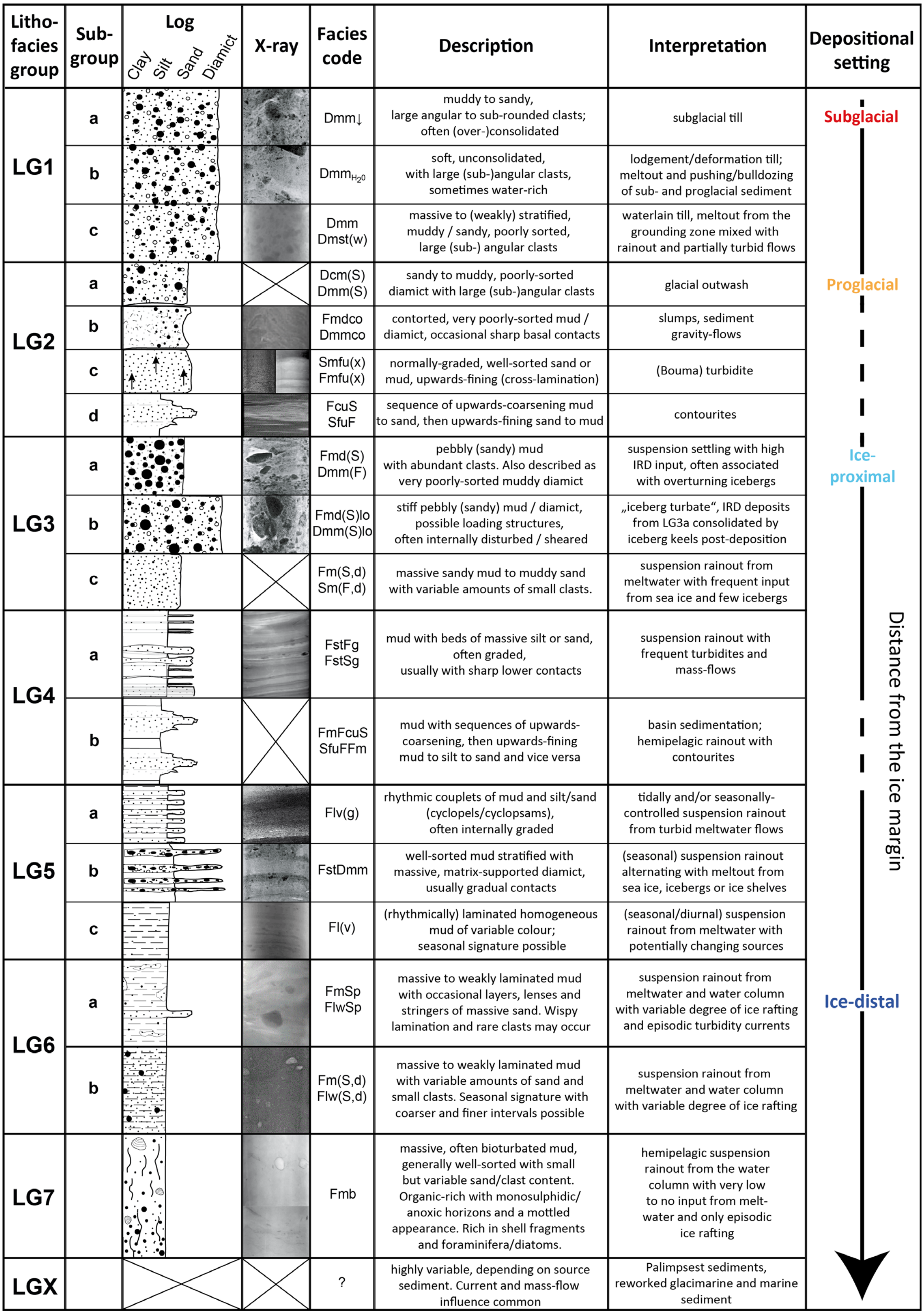
Table 1. Lithofacies codes used in the GlaciDat database, modified from Eyles *et al.* (1983). Changes to the original lithofacies codes are emphasised in italics.

Lithofacies code	Description	Lithofacies code	Description
D	Diamicts	F	Fines (silts and clays)
Dmm	Matrix-supported, massive	Fm	Massive mud
Dmst	Matrix-supported, stratified	*Fst*	*Stratified mud*
Dcm	Clast-supported, massive	*Fstw*	*Weakly stratified mud*
		Fl	Laminated (<1 cm) mud
Dmstw	*Weakly stratified matrix-supported diamict*	*Flw*	*Weakly laminated mud*
DmmstFm	*Matrix-supported, massive diamict stratified with massive mud*	Flv	Laminated mud with rhythmites or varves
		FS/F(S)	*Sandy mud/mud with sand*
DmmstFl	*Matrix-supported, massive diamict stratified with laminated mud*	*FG/F(G)*	*Gravelly mud/mud with gravel*
		Fd	*Pebbly mud*
S	Sands	*FmstSm*	*Massive mud interlayered with massive sand*
Sm	Massive sand	*FmSp*	*Massive mud with lenticular sand inclusions*
Sfu	Fining-upwards sand	*FststSm*	*Stratified mud interlayered with massive sand*
Scu	Coarsening-upwards sand	*FststSngr*	*Stratified mud interlayered with normally-graded sand*
Sr	Sand with ripples		
Sp	Sand occurring as lenses or stringers	*FststSfu*	*Stratified mud with fining-upwards sand*
Additional		Additional	
(G)	Gravelly	d, (d)	With (some) clasts/dropstones
(S)	Sandy	*b, (b)*	*With (some) bioturbation*
(F)	Muddy	*lo*	*With loading structures*
ng/rg	normally/reverse-graded	*co*	*convoluted, contorted*
p	lenticular bedding/*occasional lenses*	x	cross-lamination

the true topography, or where, owing to large scaling differences, georeferencing led to a very imprecise alignment of topographic features (Fig. 5D). In some cases, glacial features mapped by different authors needed to be assimilated, as due to the poor quality of reference points, they plotted in different locations. In these cases, this was flagged in the 'notes' attributes and the mapping accuracy was set to 'rough', for which an error of up to around 3 km can be expected. For those features with a location error margin of more than 3 km, the attribute 'schematic' was set. This was used for data provided without coordinates and/or prominent landmarks, and where information on the location of the features needed to be derived from descriptions in the text. With the aim of keeping the database as comprehensive as possible, rather than excluding those features, we chose to map a few schematic features in a location deemed most likely to fit the description. Unfortunately, in rare cases, location information for specific features was completely absent from a publication, or maps had been reproduced at such a coarse scale that even a schematic mapping could not be done. If this was the case the data were excluded from GlaciDat as to avoid unnecessary errors; nevertheless, the respective publication was listed in the bibliography provided for download alongside the database. It is also worth pointing out that sometimes there is a discrepancy in the mapping accuracy assigned to the landforms of the same assemblage, particularly where crevasse-fill ridges are involved. This is due to the fact that crevasse-fill ridges are usually such small features that image-resolution limitations prevented the exact digitisation of previous mappings.

Interpretation errors

Although in recent years the description of glacial landforms has become more systematic and an attempt has been made to use a standardised terminology when describing and interpreting glacial landforms, this is not always the case. Especially in early publications, authors often used their own descriptive terms and names for the interpreted features, which leads to uncertainty when comparing glacial features across the literature. An example is the term 'glacial lineations', which often refers only to elongate groove-ridge features moulded into soft sediments beneath the glacier, but is sometimes used as a blanket term for streamlined features, including drumlins, crag-and-tails, mega-scale glacial lineations and flutes. Furthermore, owing to the variable characteristics of such features in the field, it is sometimes difficult to assign a proper term to the observed landforms. As a consequence, an array of descriptive terms such as 'drumlinoid features' or 'streamlined bedrock' are found in the literature, which made it difficult to assign data to the specific layers within GlaciDat. To keep the database as manageable as possible, we used our own judgment on how to include a landform in GlaciDat,



Litho-facies group	Sub-group	Log Clay Silt Sand Diamict	X-ray	Facies code	Description	Interpretation	Depositional setting
LG1	a			Dmm↓	muddy to sandy, large angular to sub-rounded clasts; often (over-)consolidated	subglacial till	Subglacial
	b			Dmm$_{H_20}$	soft, unconsolidated, with large (sub-)angular clasts, sometimes water-rich	lodgement/deformation till; meltout and pushing/bulldozing of sub- and proglacial sediment	
	c			Dmm Dmst(w)	massive to (weakly) stratified, muddy / sandy, poorly sorted, large (sub-) angular clasts	waterlain till, meltout from the grounding zone mixed with rainout and partially turbid flows	
LG2	a			Dcm(S) Dmm(S)	sandy to muddy, poorly-sorted diamict with large (sub-)angular clasts	glacial outwash	Proglacial
	b			Fmdco Dmmco	contorted, very poorly-sorted mud / diamict, occasional sharp basal contacts	slumps, sediment gravity-flows	
	c			Smfu(x) Fmfu(x)	normally-graded, well-sorted sand or mud, upwards-fining (cross-lamination)	(Bouma) turbidite	
	d			FcuS SfuF	sequence of upwards-coarsening mud to sand, then upwards-fining sand to mud	contourites	
LG3	a			Fmd(S) Dmm(F)	pebbly (sandy) mud with abundant clasts. Also described as very poorly-sorted muddy diamict	suspension settling with high IRD input, often associated with overturning icebergs	Ice-proximal
	b			Fmd(S)lo Dmm(S)lo	stiff pebbly (sandy) mud / diamict, possible loading structures, often internally disturbed / sheared	„iceberg turbate“, IRD deposits from LG3a consolidated by iceberg keels post-deposition	
	c			Fm(S,d) Sm(F,d)	massive sandy mud to muddy sand with variable amounts of small clasts.	suspension rainout from meltwater with frequent input from sea ice and few icebergs	
LG4	a			FstFg FstSg	mud with beds of massive silt or sand, often graded, usually with sharp lower contacts	suspension rainout with frequent turbidites and mass-flows	Distance from the ice margin
	b			FmFcuS SfuFFm	mud with sequences of upwards-coarsening, then upwards-fining mud to silt to sand and vice versa	basin sedimentation; hemipelagic rainout with contourites	
LG5	a			Flv(g)	rhythmic couplets of mud and silt/sand (cyclopels/cyclopsams), often internally graded	tidally and/or seasonally-controlled suspension rainout from turbid meltwater flows	
	b			FstDmm	well-sorted mud stratified with massive, matrix-supported diamict, usually gradual contacts	(seasonal) suspension rainout alternating with meltout from sea ice, icebergs or ice shelves	
	c			Fl(v)	(rhythmically) laminated homogeneous mud of variable colour; seasonal signature possible	(seasonal/diurnal) suspension rainout from meltwater with potentially changing sources	
LG6	a			FmSp FlwSp	massive to weakly laminated mud with occasional layers, lenses and stringers of massive sand. Wispy lamination and rare clasts may occur	suspension rainout from meltwater and water column with variable degree of ice rafting and episodic turbidity currents	Ice-distal
	b			Fm(S,d) Flw(S,d)	massive to weakly laminated mud with variable amounts of sand and small clasts. Seasonal signature with coarser and finer intervals possible	suspension rainout from meltwater and water column with variable degree of ice rafting	
LG7				Fmb	massive, often bioturbated mud, generally well-sorted with small but variable sand/clast content. Organic-rich with monosulphidic/anoxic horizons and a mottled appearance. Rich in shell fragments and foraminifera/diatoms.	hemipelagic suspension rainout from the water column with very low to no input from melt-water and only episodic ice rafting	
LGX				?	highly variable, depending on source sediment. Current and mass-flow influence common	Palimpsest sediments, reworked glacimarine and marine sediment	

Fig. 4. Common lithofacies groups identified in Arctic fjords with exemplary sediment logs and X-ray imagery, and associated lithofacies codes. Lithofacies groups (LG) are numbered according to their relative distance to the ice margin, with the exception of LG2b-d and LG4b, which, although common in proglacial and very proximal settings, may also occur in ice-distal or entirely marine environments, because their formation is not exclusively related to glacial activity.

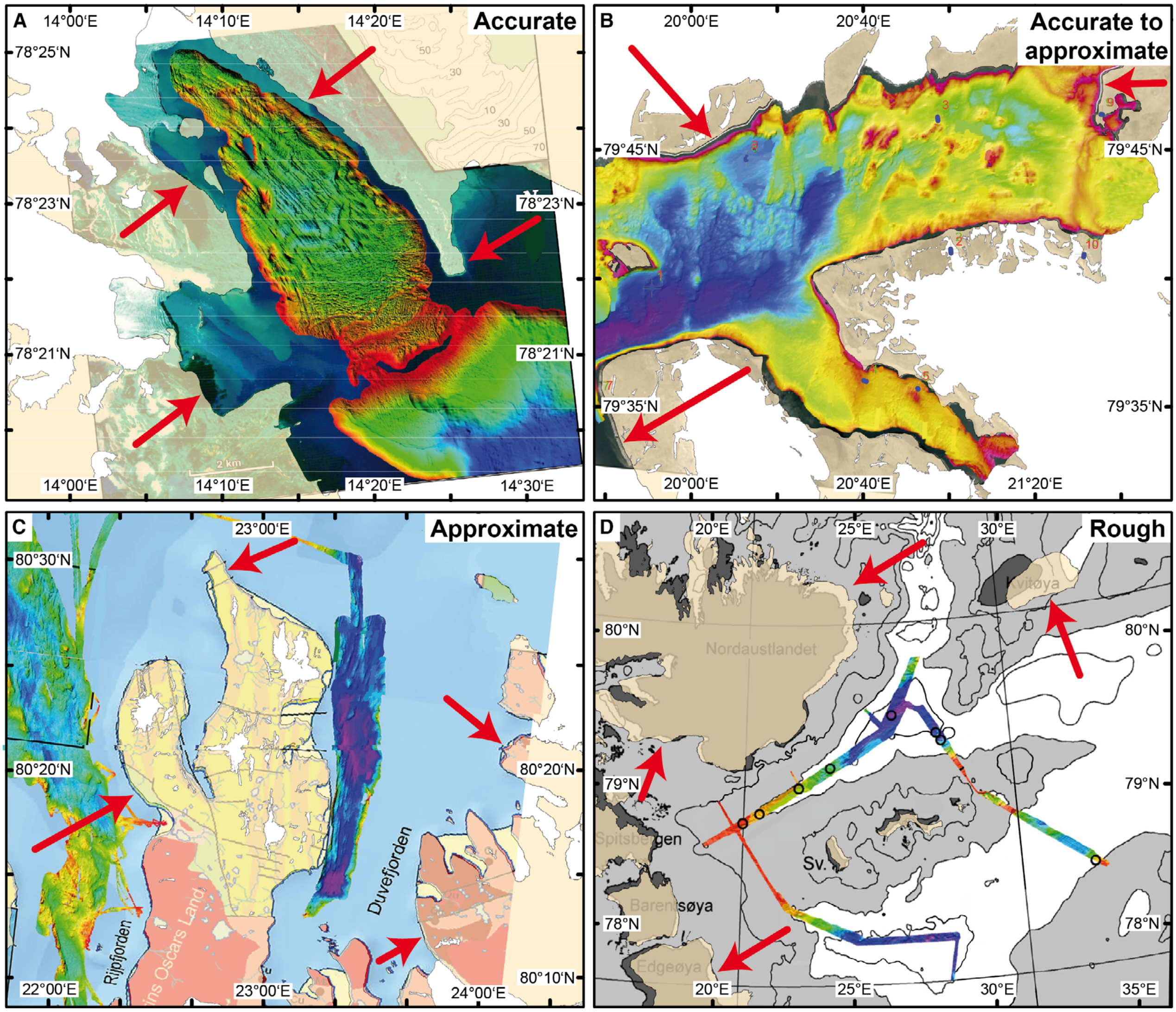


Fig. 5. Examples of the mapping accuracy resulting from variable map quality in publications and from projection issues at high latitudes. The panels show examples of the attributes used to define the location error within GlaciDat. A. Accurate – true locations can be off by a few metres to a few tens of metres at most (modified from Ottesen & Dowdeswell 2006). B. Accurate to approximate – the location error is in the range of ~50–150 m (modified from Flink *et al.* 2017). C. Approximate – the location error is generally less than 200 m (modified from Fransner *et al.* 2017). D. Rough – true locations may be off by a distance of up to 3 km (modified from Hogan *et al.* 2010).

which may have led to interpretation errors. Moreover, as a consequence of poor or limited data, features may have already been misinterpreted in the original publications. Since our intention was a compilation of features described in the literature, presented data or landforms were not double checked, unless interpretations could not be reconciled with the evidence provided; in these cases, we tried to contact the authors and excluded the evidence if it was not verifiable. Nevertheless, such misinterpretations may have been transferred to the database.

As mentioned above, some interpretations on our part were deemed necessary to maintain consistency across the GlaciDat database. Particularly where we assigned nomenclature codes and lithofacies group-codes to glacimarine lithofacies, there is always the possibility of misunderstanding the presented evidence, particularly when descriptions were lacking detail and supplementary data were incomplete (e.g. missing X-radiographs, core logs). Moreover, when mapping previously unmapped features based on only the published bathymetry, variable image quality could lead to the misinterpretation of features. Although these re-interpretations and potentially resulting errors were usually flagged in the features' attributes, the reader is encouraged to double check the source publications in cases of uncertainty.

Mapping inconsistencies

Particularly in areas where several studies have been carried out, there is often an inconsistency in the way a landform has been mapped. Depending on the resolution of the bathymetric data, landforms can appear more or less defined and the mapping of landforms remains a rather subjective undertaking in general. A common example is a glacier's terminal moraine, which has sometimes been mapped as a larger area and sometimes as a single line. Recessional moraines and glacial lineations are another example, where several smaller features identified by one author may have been mapped as only a single line by another author. Because confusion would ensue if each individual landform was included in a database as comprehensive as the one presented here, in areas of overlap the features or mapping extent of only one publication (usually the earliest) were included; this is flagged in the 'notes' column and alternative mappings can be derived from the list provided in the attribute 'references'.

Human error

The GlaciDat database is a product of human work and is therefore prone to human error. Regardless of how conscientiously the literature research was conducted, we are likely to have missed several publications that should have been included. Furthermore, some human errors were detected in the already published literature, such as transposed digits, mix-ups of latitude and longitude, mislabelled figures, etc. Although we tried to correct these where possible, some errors will inevitably have been transferred to the GlaciDat database.

Conclusions

We present a new and unique digital database of submarine glacial landforms and sediments in the Arctic, i.e. from fjords and the surrounding continental shelves in all of Svalbard, Greenland, Alaska, the Barents, Kara and Laptev Seas, as well as north of 66°30′N latitude in Norway, and Canada. The purpose of this glacimarine database, GlaciDat, is to compile previously published information in a comprehensive, easy-to-use inventory, that is intended to standardise previous records and aid and stimulate future research. It includes evidence documented from the contemporary seafloor, but is not an attempt to reconstruct ice-sheet margins or previous ice dynamics. Because the glacial landforms and sediments in the Arctic have never been compiled in such a systematic manner, there are some limitations to consider when using GlaciDat: (i) owing to issues with projection and geographic referencing, the landforms may not always plot in exactly the right location; (ii) discrepancies exist where several publications have mapped the same morphological features or described the same sediments – we have usually chosen the earliest mapping or interpretation and have referred to the alternative publications; (iii) systematically going through the literature and trying to gather data in a consistent manner was a very large project and it is therefore likely that some of the evidence was misrepresented or overlooked; and (iv) apart from selected features, such as iceberg ploughmarks, corrugated ridges, pockmarks and submarine gullies as well as slide scars and mega-blocks, which were deliberately excluded from the GlaciDat database, any evidence missing is due to the fact that: (i) it was neither published in map format nor could it be derived from the published source data; (ii) the landforms and/or sediment cores were already mapped from an alternative publication; (iii) it was overlooked; or (iv) we could not get access to the source publication. In case of the latter two, these references would also be missing from the bibliography provided alongside the database. A last reason (v) for data missing from GlaciDat is that the information given in a source publication was insufficient for geographic referencing, which most often involved insufficient tick marks in location maps, as the projection difficulties in polar areas necessitate the use of coordinate information along all of the edges of a map.

GlaciDat is intended as a helpful tool for future research. Its components, i.e. all data layers and sublayers as well as a full bibliography, are freely available for download at the PANGAEA data repository (https://doi.pangaea.de/10.1594/PANGAEA.937782). It is our intention to update GlaciDat periodically to extend the available feature layers, include new publications and correct previous errors. Readers and researchers are therefore strongly encouraged to contact the lead author with suggestions for necessary data revision or newly published evidence. Input on other useful features to include is also much appreciated and collaboration desired. Our long-term goal is to create an interactive glacial database that, over time and through intensive collaboration with researchers and/or other database authors, will include all data relevant to glacial research, including also terrestrial landforms and sediments, deep-sea cores, geological maps, information on past ice-flow directions, etc., and which can be used in an interactive manner.

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Author contributions. – Setup of the database, literature research and according compilation of data within the database were done by KTS, who also wrote the first draft of this manuscript. Several discussions with CÓC at the initial stage of this study led to the idea of an encompassing database as well as the general methodology approach. He also revised and improved the text on several occasions. PW provided IT support, checked the finished database for bugs and errors and gave advice on the database structure.

Data availability statement. – The data that provide the basis for this study will be openly available in the PANGAEA data repository at https://doi.pangaea.de/10.1594/PANGAEA.937782. The data are accessible via https://cloud.marum.de/s/WzADAiDeZsAcidt.

References

Allaart, L., Friis, N., Ingólfsson, Ó., Håkansson, L., Noormets, R., Farnsworth, W. R., Mertes, J. & Schomacker, A. 2018: Drumlins in the Nordenskiöldbreen forefield, Svalbard. *GFF 140*, 170–188.

Anderson, J. B., Shipp, S. S., Lowe, A. L., Smith Wellner, J. & Mosola, A. B. 2002: The Antarctic Ice Sheet during the Last Glacial Maximum and its subsequent retreat history: a review. *Quaternary Science Reviews 21*, 49–70.

Andreassen, K., Ødegaard, C. M. & Rafaelsen, B. 2007: Imprints of former ice streams, imaged and interpreted using industry three-dimensional seismic data from the south-western Barents Sea. *Seismic Geomorphology: Applications to Hydrocarbon Exploration and Production 277*, 151–169.

Andreassen, K., Winsborrow, M., Bjarnadóttir, L. & Rüther, D. 2014: Ice stream retreat dynamics inferred from an assemblage of landforms in the northern Barents Sea. *Quaternary Science Reviews 92*, 246–257.

Aradóttir, N., Ingólfsson, Ó., Noormets, R., Benediktsson, Í. Ö., Ben-Yehoshua, D., Håkansson, L. & Schomacker, A. 2019: Glacial geomorphology of Trygghamna, western Svalbard - Integrating terrestrial and submarine archives for a better understanding of past glacial dynamics. *Geomorphology 344*, 75–89.

Bamber, J., Alley, R. & Joughin, I. 2007: Rapid response of modern day ice sheets to external forcing. *Earth and Planetary Science Letters 257*, 1–13.

Batchelor, C. L. & Dowdeswell, J. A. 2014: The physiography of High Arctic cross-shelf troughs. *Quaternary Science Reviews 92*, 68–96.

Batchelor, C. L. & Dowdeswell, J. A. 2015: Ice-sheet grounding-zone wedges (GZWs) on high-latitude continental margins. *Marine Geology 363*, 65–92.

Beaudry, L. M. & Prichonnet, G. 1991: Late Glacial De Geer moraines with glaciofluvial sediment in the Chapais area, Québec (Canada). *Boreas 20*, 377–394.

Benn, D. & Evans, D. 2010: *Glaciers and Glaciation*. 816 pp. Routledge, London.

Blake, K. 2000: Common origin for De Geer moraines of variable composition in Raudvassdalen, northern Norway. *Journal of Quaternary Science 15*, 633–644.

Boulton, G. S. 1986: Push-moraines and glacier-contact fans in marine and terrestrial environments. *Sedimentology 33*, 677–698.

Bradwell, T., Stoker, M. S., Golledge, N. R., Wilson, C. K., Merritt, J. W., Long, D., Everest, J. D., Hestvik, O. B., Stevenson, A. G., Hubbard, A. L., Finlayson, A. G. & Mathers, H. E. 2008: The northern sector of the last British Ice Sheet: maximum extent and demise. *Earth-Science Reviews 88*, 207–226.

Burton, D. J., Dowdeswell, J. A., Hogan, K. A. & Noormets, R. 2016: Marginal fluctuations of a Svalbard surge-type tidewater glacier, Blomstrandbreen, since the Little Ice Age: a record of three surges. *Arctic, Antarctic, and Alpine Research 48*, 411–426.

Clark, C. D., Ely, J. C., Greenwood, S. L., Hughes, A. L. C., Meehan, R., Barr, I. D., Bateman, M. D., Bradwell, T., Doole, J., Evans, D. J. A., Jordan, C. J., Monteys, X., Pellicer, X. M. & Sheehy, M. 2018: BRITICE Glacial Map, version 2: a map and GIS database of glacial landforms of the last British-Irish Ice Sheet. *Boreas 47*, 11–27.

Clark, C. D., Evans, D. J. A., Khatwa, A., Bradwell, T., Jordan, C. J., Marsh, S. H., Mitchell, W. A. & Bateman, M. D. 2004: Map and GIS database of glacial landforms and features related to the last British Ice Sheet. *Boreas 33*, 359–375.

Cowan, E. A., Seramur, K. C., Cai, J. & Powell, R. D. 1999: Cyclic sedimentation produced by fluctuations in meltwater discharge, tides and marine productivity in an Alaskan fjord. *Sedimentology 46*, 1109–1126.

Dowdeswell, J. A., Canals, M., Jakobsson, M., Todd, B. J., Dowdeswell, E. K. & Hogan, K. A. 2016: The variety and distribution of submarine glacial landforms and implications for ice-sheet reconstruction. *In* Dowdeswell, J. A., Canals, M., Jakobsson, M., Todd, B. J., Dowdeswell, E. K. & Hogan, K. A. (eds.): *Atlas of submarine glacial landforms - Modern, Quaternary and Ancient*, 519–543. The Geological Society, London.

Dowdeswell, J. A., Elverhøi, A. & Spielhagen, R. 1998: Glacimarine sedimentary processes and facies on the Polar North Atlantic margins. *Quaternary Science Reviews 17*, 243–272.

Dowdeswell, J. A., Ó Cofaigh, C.,Taylor, J., Kenyon, N. H., Mienert, J. & Wilken, M. 2002: On the architecture of high-latitude continental margins: the influence of ice-sheet and sea-ice processes in the Polar North Atlantic. *Geological Society, London, Special Publications 203*, 33–54.

Dowdeswell, J. A., Villinger, H., Whittington, R. J. & Marienfeld, P. 1993: Iceberg scouring in Scoresby Sund and on the East Greenland continental shelf. *Marine Geology 111*, 37–53.

Elverhøi, A. & Solheim, A. 1983: The Barents Sea ice sheet - a sedimentological discussion. *Polar Research 1*, 23–42.

Elverhøi, A., Fjeldskaar, W., Solheim, A., Nyland-Berg, M. & Russwurm, L. 1993: The Barents Sea Ice Sheet - A model of its growth and decay during the last ice maximum. *Quaternary Science Reviews 12*, 863–873.

Evans, D. J. A., Clark, C. D. & Mitchell, W. A. 2005: The last British Ice Sheet: A review of the evidence utilised in the compilation of the Glacial Map of Britain. *Earth-Science Reviews 70*, 253–312.

Eyles, N., Eyles, C. H. & Miall, A. D. 1983: Lithofacies types and vertical profile models; an alternative approach to the description and environmental interpretation of glacial diamict and diamictite sequences. *Sedimentology 30*, 393–410.

Farnsworth, W. R., Ingólfsson, Ó., Retelle, M. & Schomacker, A. 2016: Over 400 previously undocumented Svalbard surge-type glaciers identified. *Geomorphology 264*, 52–60.

Felikson, D., Bartholomaus, T. C., Catania, G. A., Korsgaard, N. J., Kjær, K. H., Morlighem, M., Noël, B., van den Broeke, M., Stearns, L. A., Shroyer, E. L., Sutherland, D. A. & Nash, J. D. 2017: Inland thinning on the Greenland ice sheet controlled by outlet glacier geometry. *Nature Geoscience 10*, 366–369.

Flink, A. E. & Noormets, R. 2018: Submarine glacial landforms and sedimentary environments in Vaigattbogen, northeastern Spitsbergen. *Marine Geology 402*, 244–263.

Flink, A. E., Noormets, R., Fransner, O., Hogan, K. A., ÓRegan, M. & Jakobsson, M. 2017: Past ice flow in Wahlenbergfjorden and its implications for late Quaternary ice sheet dynamics in northeastern Svalbard. *Quaternary Science Reviews 163*, 162–179.

Flink, A. E., Noormets, R. & Kirchner, N. 2016: Annual moraine ridges in Tempelfjorden, Spitsbergen. *In* Dowdeswell, J. A., Canals, M., Jakobsson, M., Todd, B. J., Dowdeswell, E. K. & Hogan, K. A. (eds.): *Atlas of Submarine Glacial Landforms - Modern, Quaternary and Ancient*, 75–76. The Geological Society, London.

Flink, A. E., Noormets, R., Kirchner, N., Benn, D. I., Luckman, A. & Lovell, H. 2015: The evolution of a submarine landform record following recent and multiple surges of Tunabreen glacier, Svalbard. *Quaternary Science Reviews 108*, 37–50.

Forwick, M. & Vorren, T. 2011: Stratigraphy and deglaciation of the Isfjorden area, Spitsbergen. *Norwegian Journal of Geology 90*, 163–179.

Forwick, M. & Vorren, T. O. 2012: Submarine Mass Wasting in Isfjorden, Spitsbergen. *In* Yamada, Y., Kawamura, K., Ikehara, K., Ogawa, Y., Urgeles, R., Mosher, D., Chaytor, J. & Strasser, M. (eds.): *Submarine Mass Movements and their Consequences*, 711–722. Springer, Dordrecht.

Fox-Kemper, B., Hewitt, H. T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S. S., Edwards, T. L., Golledge, N. R., Hemer, M., Kopp, R. E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I. S., Ruiz, L., Sallée, J.-B., Slangen, A. B. A. & Yu, Y. 2021: Ocean, Cryosphere and

Sea Level Change. *In* Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, K., Yelekçi, O., Yu, R. & Zhou, B. (eds.): *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 9-1-9-257. Cambridge University Press, Cambridge.

Fransner, O., Noormets, R., Flink, A. E., Hogan, K. A., O'Regan, M. & Jakobsson, M. 2017: Glacial landforms and their implications for glacier dynamics in Rijpfjorden and Duvefjorden, northern Nordaustlandet, Svalbard. *Journal of Quaternary Science 32*, 437–455.

Hambrey, M. J., Bennett, M. R., Dowdeswell, J. A., Glasser, N. F. & Huddart, D. 1999: Debris entrainment and transfer in polythermal valley glaciers. *Journal of Glaciology 45*, 69–86.

Hogan, K. A., Dowdeswell, J. A., Noormets, R., Evans, J., Ó Cofaigh, C. 2010: Evidence for full-glacial flow and retreat of the Late Weichselian Ice Sheet from the waters around Kong Karls Land, eastern Svalbard. *Quaternary Science Reviews 29*, 3563–3582.

Holland, D., Thomas, R., Young, B., Ribergaard, M. & Lyberth, B. 2008: Acceleration of Jakobshavn Isbræ triggered by warm subsurface ocean waters. *Nature Geoscience 1*, 659–664.

Hoppe, G. 1957: Problems of glacial morphology and the Ice Age. *Geografiska Annaler 39*, 1–18.

Hormes, A., Gjermundsen, E. F. & Rasmussen, T. L. 2013: From mountain top to the deep sea – Deglaciation in 4D of the northwestern Barents Sea ice sheet. *Quaternary Science Reviews 75*, 78–99.

Howat, I. M. & Domack, E. W. 2003: Reconstructions of western Ross Sea palaeo-ice-stream grounding zones from high-resolution acoustic stratigraphy. *Boreas 32*, 56–75.

Hughes, A. L. C., Gyllencreutz, R., Lohne, Ø. S., Mangerud, J. & Svendsen, J. I. 2016: The last Eurasian ice sheets – a chronological database and time-slice reconstruction, DATED-1. *Boreas 45*, 1–45.

Huybrechts, P. 1994: The present evolution of the Greenland ice sheet: an assessment by modelling. *Global and Planetary Change 9*, 39–51.

Jakobsson, M. and 30 others 2012: The international bathymetric chart of the Arctic Ocean (IBCAO) version 3.0. *Geophysical Research Letters 39*, L12609, https://doi.org/10.1029/2012GL052219.

Jakobsson, M. 2016: Submarine glacial landform distribution in the central Arctic Ocean shelf–slope–basin system. *In* Dowdeswell, J. A., Canals, M., Jakobsson, M., Todd, B. J., Dowdeswell, E. K. & Hogan, K. A. (eds.): *Atlas of Submarine Glacial Landforms - Modern, Quaternary and Ancient*, 469–476. The Geological Society, London.

Joughin, I., Abdalati, W. & Fahnestock, M. 2004: Large fluctuations in speed on Greenland's Jakobshavn Isbræ glacier. *Nature 432*, 608–610.

Krüger, J. & Kjær, K. H. 1999: A data chart for field description and genetic interpretation of glacial diamicts and associated sediments with examples from Greenland, Iceland, and Denmark. *Boreas 28*, 386–402.

Landvik, J., Bondevik, S., Elverhøi, A., Fjeldskaar, W., Mangerud, J., Salvigsen, O., Siegert, M. J., Svendsen, J. I. & Vorren, T. O. 1998: The last glacial maximum of Svalbard and the Barents Sea area: ice sheet extent and configuration. *Quaternary Science Reviews 17*, 43–75.

Lee, J. 2017: Glacial lithofacies and stratigraphy. *In* Menzies, J. & van deer Meer, J. J. M. (eds.): *Past Glacial Environments*, 377–429. Elsevier, Oxford.

Lundqvist, J. 1981: Moraine morphology. Terminological remarks and regional aspects. *Geografiska Annaler. Series A. Physical Geography 63*, 127–138.

Lundqvist, J. 2000: Palaeoseismicity and De Geer Moraines. *Quaternary International 68*, 175–186.

Meredith, M., Sommerkorn, M., Cassotta, S., Derksen, C., Ekaykin, A., Hollowed, A., Kofinas, G., Mackintosh, A., Melbourne-Thomas, J., Muelbert, M. M. C., Ottersen, G., Pritchard, H. & Schuur, E. A. G. 2019: Polar Regions. *In* Pörtner, H. O., Roberts, D. C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B. & Weyer, N. (eds.): *Special Report on the Ocean and Cryosphere in a Changing Climate*, 203–320. Intergovernmental Panel on Climate Change, Monaco.

Morris, A., Moholdt, G. & Gray, L. 2020: Spread of Svalbard glacier mass loss to Barents Sea margins revealed by CryoSat-2. *Journal of Geophysical Research: Earth Surface 125*, e2019JF005357, https://doi.org/10.1029/2019jf005357.

Nick, F. M., van der Veen, C. J., Vieli, A. & Benn, D. I. 2010: A physically based calving model applied to marine outlet glaciers and implications for the glacier dynamics. *Journal of Glaciology 56*, 781–794.

Niessen, F., Hong, J. K., Hegewald, A., Matthiessen, J., Stein, R., Kim, H., Kim, S., Jensen, L., Jokat, W., Nam, S.-I. & Kang, S.-H. 2013: Repeated Pleistocene glaciation of the East Siberian continental margin. *Nature Geoscience 6*, 842–846.

Nuth, C., Moholdt, G., Kohler, J., Hagen, J. O. & Kääb, A. 2010: Svalbard glacier elevation changes and contribution to sea level rise. *Journal of Geophysical Research 115*, F01008, https://doi.org/10.1029/2008JF001223.

Ó Cofaigh, C., Dowdeswell, J., Jennings, A., Hogan, K., Kilfeather, A., Hiemstra, J., Noormets, R., Evans, J., McCarthy, D., Andrews, J., Lloyd, J. & Moros, M. 2013: An extensive and dynamic ice sheet on the West Greenland shelf during the last glacial cycle. *Geology 41*, 219–222.

Ó Cofaigh, C., Larter, R. D., Dowdeswell, J. A., Hillenbrand, C.-D., Pudsey, C. J., Evans, J. & Morris, P. 2005: Flow of the West Antarctic Ice Sheet on the continental margin of the Bellingshausen Sea at the Last Glacial Maximum. *Journal of Geophysical Research: Solid Earth 110*, B11103, https://doi.org/10.1029/2005JB003619.

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.

Ottesen, D. & Dowdeswell, J. 2006: Assemblages of submarine landforms produced by tidewater glaciers in Svalbard. *Journal of Geophysical Research 111*, F01016, https://doi.org/10.1029/2005jf000330.

Ottesen, D. & Dowdeswell, J. 2009: An inter-ice stream glaciated margin: submarine landforms and a geomorphic model based on marine-geophysical data from Svalbard. *Geological Society of America Bulletin 121*, 1647–1665.

Ottesen, D., Dowdeswell, J., Benn, D., Kristensen, L., Christiansen, H., Christensen, O. & Vorren, T. O. 2008: Submarine landforms characteristic of glacier surges in two Spitsbergen fjords. *Quaternary Science Reviews 27*, 1583–1599.

Ottesen, D., Dowdeswell, J. & Rise, L. 2005: Submarine landforms and the reconstruction of fast-flowing ice streams within a large Quaternary ice sheet: the 2500-km-long Norwegian-Svalbard margin (57°–80°N). *Geological Society of America Bulletin 117*, 1033–1050.

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. *Quaternary Science Reviews 151*, 212–227.

Pollard, D. & DeConto, R. M. 2009: Modelling West Antarctic ice sheet growth and collapse through the past five million years. *Nature 458*, 329–332.

Powell, R. D. 1980: *Holocene glacimarine sediment deposition by tidewater glaciers in Glacier Bay, Alaska*. Doctoral dissertation, Ohio State University, 480 pp.

Powell, R. 1981: A model for sedimentation by tidewater glaciers. *Annals of Glaciology 2*, 129–134.

Powell, R. 1984: Glacimarine processes and inductive lithofacies modelling of ice shelf and tidewater glacier sediments based on Quaternary examples. *Marine Geology 57*, 1–52.

Rignot, E., Fenty, I., Xu, Y., Cai, C. & Kemp, C. 2015: Undercutting of marine-terminating glaciers in West Greenland. *Geophysical Research Letters 42*, 5909–5917.

Roberts, D., Rea, B., Lane, T., Schnabel, C. & Rodés, A. 2013: New constraints on Greenland ice sheet dynamics during the last glacial cycle: Evidence from the Uummannaq ice stream system. *Journal of Geophysical Research: Earth Surface 118*, 519–541.

Roy, S., Hovland, M., Noormets, R. & Olaussen, S. 2015: Seepage in Isfjorden and its tributary fjords, West Spitsbergen. *Marine Geology 363*, 146–159.

Simpson, M. J. R., Milne, G. A., Huybrechts, P. & Long, A. J. 2009: Calibrating a glaciological model of the Greenland ice sheet from the Last Glacial Maximum to present-day using field observations of relative sea level and ice extent. *Quaternary Science Reviews 28*, 1631–1657.

Stokes, C. & Clark, C. 2002: Are long subglacial bedforms indicative of fast ice flow? *Boreas 31*, 239–249.

Streuff, K. 2013: *Landform assemblages in inner Kongsfjorden, Svalbard: Evidence of recent glacial (surge) activity.* Master's thesis, University of Tromsø, 154 pp.

Streuff, K., Forwick, M., Szczuciński, W., Andreassen, K., Ó Cofaigh, C. 2015: Landform assemblages in inner Kongsfjorden, Svalbard: evidence of recent glacial (surge) activity. *Arktos 1*, 14, https://doi.org/10.1007/s41063-015-0003-y.

Streuff, K., Ó Cofaigh, C., Hogan, K. A., Jennings, A. E., Lloyd, J., Noormets, R., Nielsen, T., Kuijpers, A., Dowdeswell, J. A. & Weinrebe, W. 2017a: Seafloor geomorphology and glacimarine sedimentation associated with fast-flowing ice sheet outlet glaciers in Disko Bay, West Greenland. *Quaternary Science Reviews 169*, 206–230.

Streuff, K., Ó Cofaigh, C., Noormets, R. & Lloyd, J. M. 2017b: Submarine landforms and glacimarine sedimentary processes in Lomfjorden, East Spitsbergen. *Marine Geology 390*, 51–71.

Streuff, K., Ó Cofaigh, C., Noormets, R. & Lloyd, J. 2018: Submarine landform assemblages and sedimentary processes in front of Spitsbergen tidewater glaciers. *Marine Geology 402*, 209–227.

Svendsen, J. I., Astakhov, V. I., Bolshiyanov, D. Y., Demidov, I., Dowdeswell, J. A., Gataullin, V., Hjort, C., Hubberten, H. W., Larsen, E., Mangerud, J., Melles, M., Möller, P., Saarnisto, M. & Siegert, M. J. 1999: Maximum extent of the Eurasian ice sheets in the Barents and Kara Sea region during the Weichselian. *Boreas 28*, 234–242.

Svendsen, J. I., Elverhøi, A. & Mangerud, J. 1996: The retreat of the Barents Sea Ice Sheet on the western Svalbard margin. *Boreas 25*, 244–256.

Vorren, T. O. & Laberg, J. S. 1997: Trough mouth fans - palaeoclimate and ice-sheet monitors. *Quaternary Science Reviews 16*, 865–881.

Zilliacus, H. 1989: Genesis of De Geer moraines in Finland. *Sedimentary Geology 62*, 309–317.

Zwally, H. J., Li, J., Brenner, A. C., Beckley, M., Cornejo, H. G., DiMarzio, J., Giovinetto, M. B., Neumann, T. A., Robbins, J., Saba, J. L., Yi, D. & Wang, W. 2011: Greenland ice sheet mass balance: distribution of increased mass loss with climate warming; 2003–07 versus 1992–2002. *Journal of Glaciology 57*, 88–102.