



An Atlas of Submarine Glacial Landforms: Modern, Quaternary and Ancient

In the past two decades there have been several advances that make the production of an atlas of submarine glacial landforms timely. First is the development of high-resolution imaging technologies: multibeam echo-sounding or swath bathymetry that allows the detailed mapping of the seafloor at water depths of tens to thousands of metres across continental margins, and 3-D seismic methods that enable the visualisation of palaeo-continental shelves in Quaternary sediments and ancient palaeo-glacial rocks (e.g. Late Ordovician of Northern Africa). A second technological development is that of ice-breaking or ice-strengthened ships that can penetrate deep into the ice-infested waters of the Arctic and Antarctic to deploy the multibeam systems. A third component is that of relevance – through both the recognition that the polar regions, and especially the Arctic, are particularly sensitive parts of the global environmental system and that these high-latitude margins (both modern and ancient) are likely to contain significant hydrocarbon resources. An enhanced understanding of the sediments and landforms of these fjord-shelf-slope-rise systems is, therefore, of increasing importance to both academics and industry. We are editing an Atlas of Submarine Glacial Landforms that presents a series of individual contributions that describe, discuss and illustrate features on the high-latitude, glacierinfluenced seafloor. Contributions are organised in two ways: first, by position on a continental margin – from fjords, through continental shelves to the continental slope and rise; secondly, by scale - as individual landforms and assemblages of landforms. A final section provides discussion of integrated fjord-shelf-slope-rise systems. Over 100 contributions by scientists from many countries contain descriptions and interpretation of swath-bathymetric data from both Arctic and Antarctic margins and use 3D seismic data to investigate ancient glacial landforms. The Atlas will be published in late 2015 in the Memoir Series of the Geological Society of London.



Overview maps showing the geographic distribution of some contributions to the Atlas of the Submarine Glacial Landforms

Additional contributions are welcome. Deadline is January 30, 2015. Please contact Julian Dowdeswell, jd16@cam.ac.uk

Editors

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Examples of 2-page contributions describing glacial landforms

Corrugation ridges in the Pine Isla
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From: 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. Geological Society, London, Memoirs, xx, 1-2. © The Geological Society of London, 2014. DOI: xx.xxxx/xxx.x.

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Example of a 4-page contribution describing an assemblage of glacial landforms



land Bay glacier trough, West Antarctica N¹* & J. B. ANDERSON² University, Svante Arrhenius väg 8, 106 91 Stockholm, Sweden ²Department of Earth Sciences, Rice University, 6100 Main Street, Houston, Texas 77005, USA *Corresponding author (e-mail: martin.jakobsson@geo.su.se) Glacial landforms with dimensions smaller than the imaging capability of The corrugation ridges in PIB are interpreted to have been generated at the first generation multibeam sonars will become a more frequent topic as the trailing edge of mega-icebergs that broke off at the grounding line of high-resolution seafloor mapping technology advances. In Pine Island Bay the former PIB ice stream and drifted seaward (Jakobsson *et al.* 2011). (PIB) glacial trough, West Antarctica, small regular ridges, only a few Each ridge is formed when an iceberg, or an armada of icebergs in the metres high from trough to crest, were mapped in water depths around 700 case of PIB, rhythmically settles to the sea floor under the influence of m. The small size of these ridges is on the limit for what modern deep- tidal motion and squeezes sediments into ridges that are preserved in the water multibeam sonars are capable of mapping. They are interpreted to wake of the drifting icebergs (Fig. 1d). In PIB, where the corrugation have been formed at the trailing end of mega-icebergs moving up and ridges exist in large parallel furrows, the formation model calls for a rather down in response to tides while ploughing the seafloor (Jakobsson et al. uniformly thick iceberg armada just thick enough to keep the icebergs 2011). The mega-icebergs in PIB were produced by an ice shelf break-up grounded on the gently upward-sloping glacial trough. This mélange of ice would eventually disintegrate into individual icebergs that drifted away on their own; most of them were probably unstable and thus soon to rotate (Fig. 1d). In PIB, iceberg plough ridges were formed at the end of each large megaberg-induced furrow before the icebergs rotated (Fig. 1a). The glacial trough in central PIB contains a suite of landforms indicative While corrugation ridges may form in slightly different glacial of fast-flowing ice streams and episodic ice-sheet retreat following the environments, i.e. behind icebergs or underneath a fractured ice stream, Last Glacial Maximum (Anderson *et al.* 2002; Graham *et al.* 2010; Jakobsson *et al.* 2011). The relatively flat 690 to 710 m deep central from an armada of clustered icebergs rather than from a more intact fast- ANDREASSEN, K., KARIN ANDREASSEN, WINSBORROW, M.C. BJARNADÓTTIR, L.R., RÜTHER, D.C. Accepted. Landform assemblage Within the large furrows, remarkably regular sets of smaller ridges from the collapse of the Bjørnøyrenna Palaeo-ice stream, northern Barents Sea. occur oriented at close-to-right-angles to them (Fig. 1a, b). These ridges *Quaternary Science Reviews.* ANDERSON, J.B. 1999. Antarctic Marine Geology, Cambridge University Press, progressively in a seaward direction; ridge heights range from 1 to 2 m ANDERSON, J.B., SHIPP, S.S., LOWE, A.L., WELLNER, J.S., MOSOLA, A.B. from trough to crest. The extremely regular appearance of these ridges 2002. The Antarctic Ice Sheet during the Last Glacial Maximum and its makes the furrows look corrugated; hence the smaller ridges were named "corrugation ridges" by Jakobsson *et al.* (2011). subsequent retreat history: a review. *Quaternary Science Reviews*, **21**, 49-70. BARNES, P.W., LIEN, R. 1988. Iceberg rework shelf sediments to 500 m off individual iceberg plough marks using side-scan sonar (Lien 1981; Barnes GRAHAM, A.G.C., LARTER, R.D., GOHL, K., DOWDESWELL, J HILLENBRAND, C.-D., SMITH, J.A., EVANS, J., KUHN, G., DEEN, T. 2010. Flow and retreat of the Late Quaternary Pine Island-Thwaites palaeo-ice stream, West Antarctica. Journal of Geophysical Research. 115, F0302 Bjørnøyrenna, Barents Sea (Andreassen et al. 2013), and within mega-GRAHAM, A. G. C., DUTRIEUX, P., VAUGHAN, D. G., NITSCHE, F. O scale glacial lineations in the central (Jakobsson et al. 2011) and western GYLLENCREUTZ, R., GREENWOOD, S. L., LARTER, R. D., AND JENKINS, A., 2013, Seabed corrugations beneath an Antarctic ice shelf revealed by autonomous underwater vehicle survey: Origin and implications for the history of Pine Island Glacier. Journal of Geophysical Research: Earth HOPPE, G., 1959. Glacial morphology and inland ice recession in northern Swede

by Jakobsson et al. (2011) and Graham et al. (2013). Their extreme JAKOBSSON, M., ANDERSON, J.B., NITSCHE, F.O., DOWDESWELL, J.A. regularity excludes formation as recessional moraines formed near a GYLLENCREUTZ, R., KIRCHNER, N., O'REGAN, M.A., ALLEY, R.F. retreating ice margin. This also eliminates the interpretation that the ANANDAKRISHNAN, S., MOHAMMAD, R., ERIKSSON, corrugation ridges are De Geer moraines (Hoppe, 1959; Lindén and FERNANDEZ, R., KIRSHNER, A., MINZONI, R., STOLLDORF, T MAJEWSKI, W. 2011. Geological record of Ice Shelf Breakup and Grounding from the ridges contained poorly sorted glacial diamict and glacimarine LIEN, R. 1981. Seabed features in the Blaaenga area, Weddell Sea, Antarctica, Port LIEN, R. 1981. Seabed features in the Blaaenga area, Weddell Sea, Antarctica, Port sandy clays, suggesting that a current-influenced formation process could and Ocean Engineering under Arctic Conditions, Quebec, Canada, pp. 706iceberg ploughmarks points towards a formation mechanism that occurs at LINDÉN, M., MÖLLER, P., 2005. Marginal formation of De Geer moraines and the trailing end of a ploughing iceberg, because otherwise the iceberg their implications to the dynamics of grounding-line recession. Journal of would itself remove the seafloor imprints from its own impact with the seafloor. *Quaternary Science*, **20**, 113-133. SHIPP, S., ANDERSON, J.B., DOMACK, E.W. 1999. Late Pleistocene-Holocene retreat of the West Antarctic ice-sheet system in the Ross Sea; Part 1 Geophysical results Geological Society of America Bulletin, 111, 1468-1516.

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moraine in Europa Fjord. (e) Glacifluvial delta in Iceberg Fjord and associated braided river. (f) Glacifluvial delta in Bernardo Fjord, showing braided river and adjacent Bernardo

Glacier. (g) Small fluvial delta in Eyre Fjord. Images modified after Dowdeswell & Vásquez (2013)



large furrows with widths from about 150 m to >500 m. (b) Detail of corrugation ridges, white box in (a) shows the location. (c) Location of study area (red box; map from

IBCSO v. 1.0) (d) Schematic model of stages of corrugation ridge formation.

Numerous, regularly-spaced, parallel, linear to curvilinear ridges of deglaciation of the southern Scotian Shelf (Todd et al. 2007). Description bathymetric ranges of up to 25 m. The horizontal distance between ridges, normal to strike, is variable. In some areas, well-defined parallel ridges have a roughly regular spacing of approximately 150 to 200 m. In other areas, sub-parallel ridges are as image (Fig. 1b) are approximately 1.5 m high and 40 m wide. The more north and a steeper slope to the south (Fig. 1d). Cobbles and boulders were smooth seafloor in troughs (Fig. 1b). Interpretation of the southeastern margin of the marine-terminating Laurentide Ice Sheet. former ice-margin positions where sediment is deposited or pushed up Glacial geomorphic features in the northern Barents Sea: direct evidence for during brief stillstands or minor readvances (De Geer 1889; Blake 2000).

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al. 2008).

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DOWDESWELL, J. A. & VÁSQUEZ, M. 2013. Submarine landforms in the fjords of southern Chile: implications for glacimarine processes and sedimentation in a mild glacier influenced environment. *Quaternary Science Reviews*, 64, 1-19 FERNANDEZ, R., GULICK, S., RODRIGO, C., DOMACK, LEVENTER, A. & SAUSTRUP, S. 2013. The seismic record of late glacial variations in the Strait of Magellan: new clues for the interpretation of the glacial history of Magallanes. Bollettino d Geofisica Teorica ed Applicata, Supp. 2 - Geosur, **54**, 257-259 MASIOKAS, M., RIVERA, A., ESPIZUA, L. E. VILLALBA, R DELGADO, S. & ARAVENA, J. C. 2009. Glacier fluctuations in extratropical South America during the past 1000 years. Palaeogeog., Palaeoclim., Palaeoecol., **281**, 242-268. OTTESEN, D. & DOWDESWELL, J. A. 2006. Assemblages of submarine landforms produced by tidewater glaciers in Svalbar Journal of Geophysical Res., 111, doi:10.1029/2005JF000330. OTTESEN, D. & DOWDESWELL, J. A. 2009. An inter-ice stream glaciated margin: submarine landforms and a geomorphic model based on marine-geophysical data from Svalbard. Geologica Society of America Bulletin, **121**, 1647-1665. POWELL, R. D. 1990. Glacimarine processes at grounding-line fai and their growth to ice-contact deltas. In Dowdeswell, J. A. & Scourse, J. D., (eds.), Glacimarine Environments: Processes and

Sediments. Geological Society Special Publications, 53, 53-73. SYVITSKI, J. P. M., BURRELL, D. C. & SKEI, J. M. 1987. Fjords. Processes and Products. Springer, Berlin.

De Geer moraines on German Bank, southern Scotian Shelf of Atlantic Canada B.J. TODD¹* ¹Geological Survey of Canada, Natural Resources Canada, P.O. Box 1006, Dartmouth, Nova Scotia, Canada B2Y 4A2

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sediment are recognized as forming at or close to the position of the The distribution and pattern of De Geer moraines provides insight into grounding lines of water-terminating glaciers (Lindén & Möller 2005). the subtleties of deglaciation of German Bank. After the Last Glacial These ice-flow transverse ridges, sometimes known as De Geer moraines Maximum, the margin of the Laurentide Ice Sheet retreated to the (De Geer 1889), have modest heights and widths and variable lengths. De northwest, punctuated by many small readvances that formed De Geer Geer's original description of Swedish moraines with these characteristics moraines. The pattern of segmented, southeast-convex moraines suggests invoked an annual cycle. Present use of 'De Geer moraine' refers to that the ice sheet margin was gently scalloped in nature. De Geer moraines closely spaced subaqueous moraine ridges which may or may not be are absent on exposed bedrock but are numerous on thin deposits of annual. The distribution and pattern of ubiquitous De Geer moraines on streamlined lineations of till (Fig. 1a); in swales between the lineations the German Bank provides insight into the direction and timing of regional moraines are partly to completely buried by sediment.

Across a bathymetric range of over 100 m, southern German Bank is generally regular horizontal spacing of De Geer moraines suggests that the mantled by swarms of ridges; each ridge displays a quasi-linear or curved rate of ice-front retreat was consistent from one cycle of formation to the line in planform. In topographic depressions, the ridges are subdued in next. Ottesen & Dowdeswell (2006), in a study based on the interpretation relief or are absent (Fig. 1a). The strike of the ridge crests is generally of multibeam sonar imagery and historical aerial photographs of a west-southwest-east-northeast. Individual ridges can be traced tidewater glacier in a Svalbard fjord setting, provide compelling evidence horizontally from short segments of a few hundred metres up to almost 10 that De Geer moraines formed there when the glacier underwent a minor km. Most ridge crests are simple lines in planform, but in some areas the readvance each winter during its general retreat. However, crests are complex with bifurcating crest lines and (or) short, en echelon sedimentological studies from Scandinavia suggest that several annual crest segments. The longer ridge crests are formed of multiple curved cycles may in some cases contribute to the formation of a single De Geer sections 2 to 4 km in length with the crests slightly convex toward the moraine (Lindén & Möller 2005); thus, such moraines do not always southeast. In places on German Bank, individual ridges traverse bathymetric ranges of up to 25 m. represent annual formation. The larger De Geer moraines on German Bank (Fig. 1a) may be the product of several years of ice-front stability or major

closely spaced as 30 to 50 m. The ridges vary in height and width. Ridges BLAKE, K.P. 2000. Common origin for De Geer moraines of variable composition displaying a subtle appearance on the large-scale multibeam-bathymetric in Raudvassdalen, northern Norway. Journal of Quaternary Science, 15, 633– prominent ridges are approximately 5 to 8 m high and 100 to 130 m wide BRADWELL, T., STOKER, M.S., et al. 2008. The northern sector of the last (Fig. 1 c, d). The ridges are generally symmetrical in cross section with British Ice Sheet: Maximum extent and demise. *Earth-Science Reviews*, **88**, some of the larger ridges displaying asymmetry with a gentle slope to the DE GEER, G.F. 1889. Ändmoräner I trakten mellan Spånga och Sundbyberg. Geologiska Föreningens i Stockholm Förhandlingar, **11**, 395–397. observed and recovered from ridges and gravel was recovered from LARSEN, E., LONGVA, O. & FOLLESTAD, B.A. 1991. Formation of De Geer LINDÉN, M. & MÖLLER, P. 2005. Marginal formation of De Geer moraines and their implication on the dynamics of grounding-line recession. Journal of The ridge swarms on German Bank are interpreted to be subaqueous, ice- *Quaternary Science*, **20**, 113–133. OTTESEN, D. & DOWDESWELL, J.A. 2006. Assemblages of submarine flow transverse De Geer moraines formed at or close to the grounding line landforms produced by tidewater glaciers in Svalbard. *Journal of Geophysical*

grounded ice and implications for the pattern of deglaciation and late glacial Using the traditional marine geophysical survey tools of seismic reflection profiling and side-scan sonar, De Geer moraines have been TODD, BJ., VALENTINE, P.C., LONGVA, O. & SHAW, J. 2007. Glacial recognized in the Barents Sea (Solheim et al. 1990) and western Norway landforms on German Bank, Scotian Shelf: evidence for Late Wisconsinan ice-(Larsen *et al.* 1991). In the marine environment, technological constraints sheet dynamics and implications for the formation of De Geer moraines. precluded small-scale (i.e. regional) mapping of glacial landforms like De *Boreas*, **36**, 148–169. Geer moraines until the advent of multibeam sonar in the early 1990s. VAN LANDEGHEM, K.J.J., WHEELER, A.J. & MITCHELL, N.C. 2009. Seafloor Applying this technology, De Geer moraines have also been mapped in the evidence for palaeo-ice streaming and calving of the grounded Irish Sea Ice Irish Sea (Van Landeghem *et al.* 2009) and in the North Sea (Bradwell *et l.* 2000). Stream: Implications for the interpretation of its final deglaciation phase.

The observations on German Bank are consistent with De Geer moraine formation at the grounding line of a tidewater glacier as a result of deposition and (or) pushing during minor readvances and stillstands. The

moraines and implications for deglaciation dynamics. Journal of Quaternary Subaerially exposed De Geer moraines have been interpreted as marking SOLHEIM, A., RUSSWURM, L., ELVERHØI, A. & NYLAND BERG, M. 1990.

sedimentation. In Dowdeswell, J.A. & Scourse, J.D. (eds.): Glacimarine

B.J. TODD



image of De Geer moraines. Acquisition system Simrad MS992. Frequency 120 kHz. (d) Seismic reflection profile of De Geer moraines. VE x 23. Acquisition system

Huntec Deep-Tow Seismic. Frequency 0.5–8 kHz. (e) Location of study area (red box; map from GEBCO_08).