Only 5 southern Greenland shelf edge glaciations since the early Pliocene

Tove Nielsen & Antoon Kuipers

Much uncertainty exists about the history of the Greenland Ice Sheet (GIS), particularly as to the frequency of extreme shelf edge glaciations. Because the last glaciation removed most of the record of earlier GIS extent on land and shelf exploration of the older GIS glacial record requires the use of deeper marine archives. Here we present seismic evidence for the frequency of extreme shelf edge glaciations offshore southwest Greenland. Our findings reveal that since the GIS formation only 5 glaciations were characterized by an ice sheet covering the entire shelf of southern Greenland. We estimate an age of around 4.5 million years (my) for the oldest episode and found that such extreme GIS expansions may have occurred here only 3 times within the past c. 1.5 my. We thus conclude that the first large shelf edge glaciation of southern Greenland did occur prior to the Pliocene warmth epoch.

Dокументация ила-носываемого обломочного материала (IRD) демонстрирует существование североамериканских ледников задолго до 10 млн лет назад1-2, хотя ледники на Гренландии могут существовать уже 20 млн лет назад3. Как и ледниковый ледник, отмеченный в палеоокеане, датирован последние два или три голоценовых эпохи4,5,11. Поэтому история разрушения ледника на основе сложения ледникового материала осталась неизвестной. В глубинных водах океана существовали ледники, которые дошли до 1000 метров под водой. В континентальных водах Датского пролива существовали ледники, которые дошли до 1000 метров под водой. В континентальных водах Датского пролива существовали ледники, которые дошли до 1000 метров под водой. В континентальных водах Датского пролива существовали ледники, которые дошли до 1000 метров под водой. В континентальных водах Датского пролива существовали ледники, которые дошли до 1000 метров под водой. В континентальных водах Датского пролива существовали ледники, которые дошли до 1000 метров под водой. В континентальных водах Датского пролива существовали ледники, которые дошли до 1000 метров под водой. В континентальных водах Датского пролива существовали ледники, которые дошли до 1000 метров под водой. В континентальных водах Датского пролива существовали ледники, которые дошли до 1000 метров под водой. В континентальных водах Датского пролива существовали ледники, которые дошли до 1000 метров под водой. В континентальных водах Датского пролива существовали ледники, которые дошли до 1000 метров под водой. В континентальных водах Датского пролива существовали ледники, которые дошли до 1000 метров под водой. В континентальных водах Датского пролива существовали ледники, которые дошли до 1000 метров под водой. В континентальных водах Датского пролива существовали ледники, которые дошли до 1000 метров под водой. В континентальных водах Датского пролива существовали ледники, которые дошли до 1000 метров под водой. В континентальных водах Датского пролива существовали ледники, которые дошли до 1000 метров под водой. В континентальных водах Датского пролива существовали ледники, которые дошли до 1000 метров под водой.
more to the north. Common for all GDF units are the timing of the appearance of the oldest one (GDF 1), which based on the regional seismo-stratigraphic model is assigned to have an early Pliocene age.

Discussion

An early Pliocene age of GDF 1 is supported by records of ice-rafterd materials with Greenlandic provenance documented by ODP drilling Leg 105 and comparable to the timing of glacier formation on Iceland, but notably postdates the first occurrence of drop stones off south-eastern Greenland around 7 my ago. The Neogene drop stone sequence from this area has been interpreted to reflect the results of three major glaciations of southeast Greenland between 2.0 and 5.3 my ago. Based on our seismo-stratigraphy, and supported by the age of the first major coarse-sand peak recorded at ODP Site 918 off Southeast Greenland, we propose an age of near 4.6 my for GDF 1. This age is close to the timing of a negative excursion observed in the time-adjusted global sea level curve suggesting a prominent glaciation event at Northern and Southern high latitudes. These various sources of evidence make us conclude that the first extreme shelf edge glaciation of southern Greenland can be dated between 4.4 and 4.6 my. A full and extreme southern Greenland glaciation at that time does, however, not imply that a permanent ice sheet necessarily has existed here since. Major GIS reductions can be assumed during subsequent Pliocene warming between 3.6 my and 2.6 my and sometime later in the Pleistocene.

As for the youngest GDF 5 unit, we tentatively assign an age corresponding to the Saale glaciation (c. 0.16 my; Marine Isotope Stage 6). This glaciation was characterized by an extreme northern hemisphere ice sheet expansion, and must have been responsible for the production of giant, deep-drafted icebergs originating from southern Greenland ice streams. For information on younger, post-Saale deposits we may refer to the Methods section below. In between these oldest and youngest GDF episodes, glacial advances had resulted in a significant sediment input to the shelf and upper slope, but during this long period only three glaciations produced an extensive ice sheet responsible for the deposition of basinal GDF units. Using our seismo-stratigraphic model we can not assign with high confidence a more specific age to each of these three GDF units. Still, based on recent GIS modelling we suggest that GDF 2 could originate from the earliest Quaternary glaciation era (c. 2.5 my). A shelf edge glaciation during this period could explain the increased accumulation of coarse sand off southeast Greenland dated at ODP site 918 between ca. 2.5 and 2.0 my ago. For reason of climate warmth both the Mid-Pliocene and early Pleistocene may be ruled out for age consideration of one of the remaining GDF units (GDF 3 and 4). The same may apply to the ‘early Brunhes’ era, ca. 0.40–0.75 my, when inter-hemispheric climate asymmetry appears to have been larger, and climate belt and ocean fronts were displaced to the north. During this period ice-free interglacial conditions with more abundant vegetation may have been widespread in

Figure 1 | (a) Bathymetry of the study area together with the outline of the main body of the Davis Strait Drift Complex (DSDC, orange), and location of the seismic section shown in Fig. 2. The basin in question forms the seabed depression between the shelf break and the drift crest. The insert map shows the regional setting of the study area and present-day extent of the Greenland Ice Sheet. (b) Study area with the grid of seismic lines used for this study. Also shown is the location of exploration well Qulleq-1 which provided the base for the seismo-stratigraphic framework as previously published. The green lines mark the location of the seismic examples shown in Figs. 2 and 3. The inset map shows the pattern of the present-day main current systems, both shallow (small arrows) and deep water (thick arrow). WGC = West Greenland Current; DWBC = Deep Western Boundary Current. For further details, see Ref. 11. Bathymetry compiled by GEUS. Maps produced by GEUS.
**Figure 2** | Overview (A) and zoom (B) of seismic section crossing the basin offshore Southwest Greenland, extending from the glaciogenic prograding wedge deposits on the Greenland shelf in the east to the current-dominated Davis Strait Drift Complex (DSDC) deposits in central Davis Strait in the west. The seismic section illustrates the chaotic and semi-transparent appearance of the five major glaciogenic debris flow (GDF) units (blue) identified within the DSDC deposits (orange). The five GDF units are labelled 1 to 5 from bottom to top. The seismic section documents that GDF depositional processes can extend over distances of at least 60 km from the base of the slope. For location – see Fig. 1.

**Figure 3** | Overview (A) and zoom (B) of seismic section crossing the basin offshore Southwest Greenland, extending from the glaciogenic prograding wedge deposits on the Greenland shelf in the east to the current-dominated Davis Strait Drift Complex (DSDC) deposits in central Davis Strait in the west. Location of the seismic section is shown in Fig. 1. For seismic facies interpretation, see Fig. 2. This section illustrates that a similar seismic scenario with five GDF units is still present further to the north. In some cases the GDF units suggest a 2-stage formation as indicated by an intercalated continuous reflection horizon (e.g. Unit 3 in the lower panel B). This we attribute to ice margin fluctuations across the shelf edge associated with a stadial-interstadial climate shift.
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Author contributions

T.N. is responsible for the seismic interpretation and A.K. for chronological aspects and climate-related issues. Both authors contributed equally to the conclusion and writing of the paper.

Additional information

Competing financial interests: The authors declare no competing financial interests.

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