Neoglacial change of ice cover and the related response of the Earth's crust in West Greenland

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The cooling trends of Neoglacial time caused re-formation of minor local glaciers and expansion of the Inland Ice margin. A consequence of this glacial reactivation in West Greenland was the conversion of an early Holocene glacio-isostatic emergence to Neoglacial submergence. Although the major trends of fluctuations of ice margins and relative sea level have been studied over a long time, exact data on the spatial distribution of Neoglacial changes of glacier load and relative sea level are still sparse. Present information points to a major conversion from emergence to submergence between 1000 and 3000 B.P., depending on location and the effect of superimposed secondary oscillations.

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Coverage of Neoglacial events

The last *c.* 4000 years of the Holocene ('Neoglacial time') are characterised by cooling climatic trends which, according to the Camp Century ice core records, were especially pronounced in the cold spells of *c.* 3000 ± 400, 2200 ± 100 and *c.* 1100 B.P., and again in the Little Ice Age of 700–100 B.P. (e.g. Weidick *et al.*, 1990).

Although tantalisingly close to the present time, so that the period to a great extent is covered by archaeological and historical records, knowledge of change in the ice cover and of relative sea level in West Greenland is still limited. This is because the period was essentially one of glacier advances so that datable deposits of former glacier stands are now largely concealed beneath present glacier ice. Furthermore, the period was mainly a time of submergence where relative sea level was at a minimum, implying that datable marine deposits (or deposits related to shore lines of this period) are below present sea level.

Neoglacial events are in many ways still a 'missing link' in Greenland, and better knowledge of this period is needed because of its bearing on the youngest major climatic change (Holocene climatic optimum to present) with its implications for glacier cover and coastal areas. Closer investigation of the climatological, glaciological and geological events of this period has been recommended by IGBP (International Geosphere-Biosphere Programme). GGU has mainly concentrated on the geological approach of dating older glacier events, as well as the dating of historical glacier and sea level changes.

This paper is formulated as a status report in which GGU's contributions are placed in the context of current interdisciplinary work.

The early Holocene

The first half of the Holocene in Greenland is a history of deglaciation, knowledge of which is essentially based on systematic mapping of Quaternary deposits by GGU (e.g. Weidick, 1976; Kelly, 1985; Funder, 1989). The period records a gradual change of the Inland Ice margin from a position close to the outer coast about 10 000 years ago to the present position which was attained at 6000 to 8000 B.P., depending on locality (Fig. 1A). Recession continued beyond the present position of the ice margin, reaching a minimum of 15–20 km farther inland at 4000 B.P. in lowland areas, whereas recession was probably less in intervening highland areas (Weidick, 1992).

Isostatic rebound related to this deglaciation has been illustrated in a number of emergence curves covering the region (cf. Fig. 3) and, although the exact trends of individual emergence curves are still debatable (Kelly, 1979), the general concept is one of a decelerating rate of emergence at the end of the Holocene climatic optimum. Many data on the pattern of emergence come from systematic palynological investigations throughout West Greenland by the Greenland Botanical Survey (e.g. Fredskild, 1983).

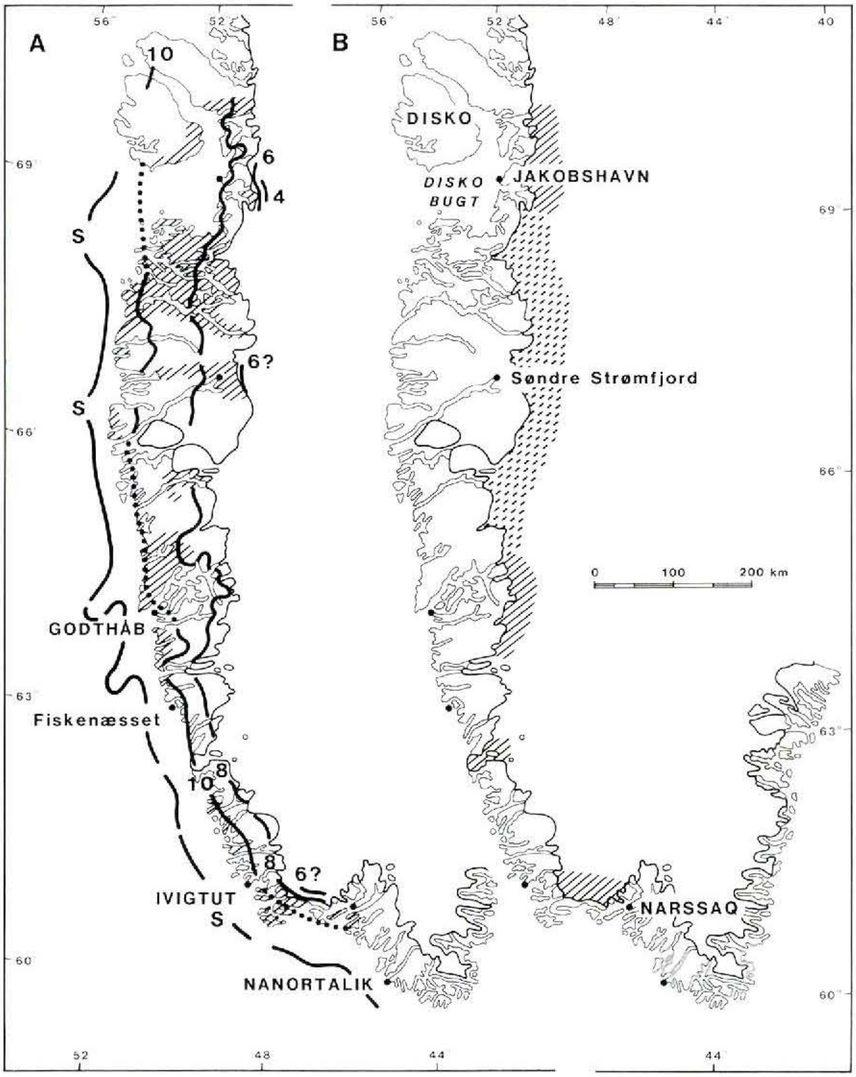

Fig. 1A. Stages in the recession of the Inland Ice margin in West Greenland. Numbers indicate approximate ages in 1000 years ^{14}C B.P. Position of the Sisimiut glaciation (S) is indicated (age estimated at *c.* 14 000 B.P.). Hatched signature: generalised outline of areas lower than *c.* 300 m a.s.l. B. Foci of major Neoglacial (especially Little Ice Age) changes of glaciers (hatched signature). Punctuated hatching: areas of major ice margin change during the past 5000 years according to Letréguilly *et al.* (1991).

Neoglacial changes of the ice cover

In the present 'ice free' coastal area (i.e. the 100–200 km wide strip of land between the west coast of Greenland and the Inland Ice margin), ice is in fact present in the form of numerous local glaciers, ranging from perennial snow patches to large ice caps. The present total area of local glaciers in West Greenland is *c.* 15 000 km^2 according to GGU's glacier atlas (Weidick *et al.*, 1992), but they are widely scattered throughout this coastal area of *c.* 100 000 km^2. Their Neoglacial fluctuations have been relatively restricted, although many cirque glaciers may have reformed in this period after the climatic optimum, and their contribution to glacio-isostatic change must be considered to be small.

The recession of the Inland Ice described above implies a release of up to 2000 m of glacier load as shown in the profile of Fig. 2. This profile also shows that the release was at a maximum close to the present ice margin and that this must have decreased towards the central parts of the ice sheet, where there is little difference between the maximum height of the ice age ice sheet and the present Inland Ice (e.g. Letréguilly *et al.*, 1991).

The subsequent Neoglacial readvances of the Inland Ice will have varied in amplitude and velocity, depending upon local mass balance and dynamic conditions (including dynamic instabilities) and the topographic control within the individual sectors, so that in places it reached its present position or even surpassed it by about 2500 B.P.

In historical time, i.e. during the transition from Little Ice Age conditions to present conditions, the great-

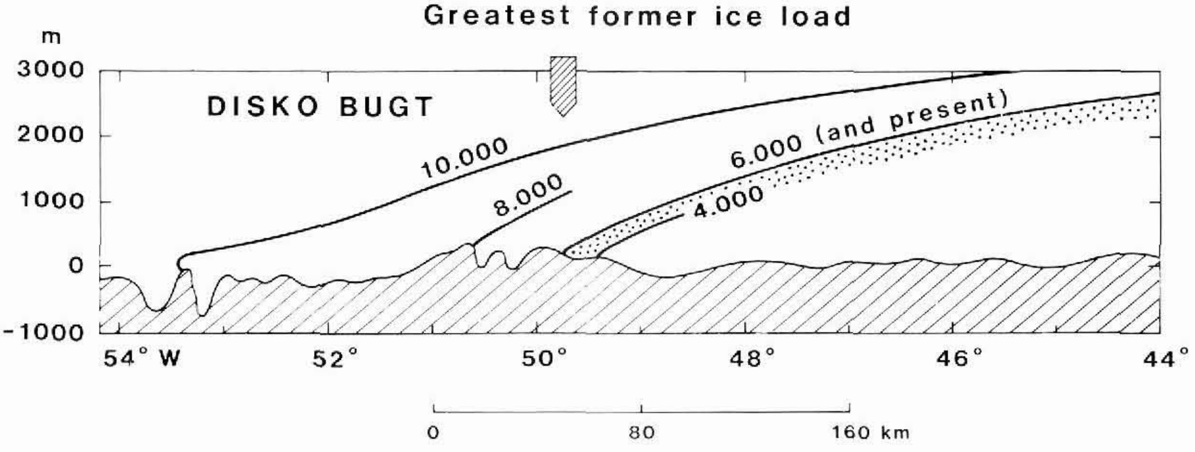

Fig. 2. Profile of some of the ice marginal stages shown in Fig. 1. The cross-section extends from south of Disko through Disko Bugt to Jakobshavn Isbræ.

est horizontal marginal (and thickness) variations of the Inland Ice are found at specific drainage sectors in lowland areas. From the Principle of Uniformitarianism it seems likely that the major changes in ice sheet geometry and glacier load in the Neoglacial took place at such lowland centres (separated from each other by highland areas) along the periphery of the present Inland Ice margin. The approximate positions of these centres are indicated in Fig. 1B where foci of fluctuations during the Little Ice Age are indicated by hatching. A generalised modelling of the extent of the Inland Ice between 5000 B.P. and the present (Letréguilly *et al.*, 1991) points to the entire region between Disko Bugt and Godthåbsfjord being an area of major change of ice margin position (shown by punctuated hatching).

Minimum relative sea level and succeeding submergence

Emergence curves for West Greenland suggest that the present sea level position was reached at most places about 3000 years ago, as illustrated by the Holocene shore line positions in Fig. 3, although there is great uncertainty about the date in any one area because of the scarcity of geological data for the lowest shore lines younger than *c.* 6000 B.P.

The lack of information about the late stages of emergence and the subsequent transition to submergence during the Neoglacial may in part be overcome by including the growing amount of archaeological information which has become available during the past few decades. This information was updated recently at a symposium on Paleo-Eskimo Cultures of Greenland, held in May 1992 at the Institute of Prehistoric and Classical Archaeology in Copenhagen; with several contributions concerning former relative sea level heights (e.g. K. Møller Hansen, E. Brinch Petersen, F. Kramer, H. Kapel).

Sites belonging to the oldest Sarqaq culture (*c.* 4200–2800 B.P.) are located mainly on shore lines between 10 and 4 metres above sea level in the outer or central parts of the coastal areas between Disko Bugt and Søndre Strømfjord. However, sites of the same culture in the inner parts of Disko Bugt (Larsen & Meldgaard, 1957) and central parts of Godthåbsfjord (Gulløv, 1988) are below or very close to present sea level.

The scattered occurrence of the subsequent Dorset culture sites (*c.* 2500 to *c.* 1500 B.P.) may be explained by their frequent situation at sea levels lower than the present. The existence of low relative sea levels can also be concluded from desiccation horizons in bottom cores from the harbours of Sisimiut/Holsteinsborg and Narssaq (Foged *in* Kelly, 1988), of which a horizon at the latter locality has been radiocarbon dated to just prior to 3080 ± 110 B.P. (Ua-2425).

Provisionally it can be concluded that in many areas emergence seems to have ended somewhere between 3000 and 1000 years ago, marked in time by the submergence of shore lines now below sea level. However, contradictory evidence exists where shore lines of this age lie at or above present sea level. Thus, a few hundred metres from the present Inland Ice margin in Disko Bugt a terrace 1–2 m above present sea level has been dated to 2190 ± 75 B.P. (Funder *in* Ingolfsson *et al.*, 1990). The indication of this high Neoglacial sea level of 2.1 ka is in contradiction with Dorset (and Sarqaq) culture sites 20 km farther to the west which

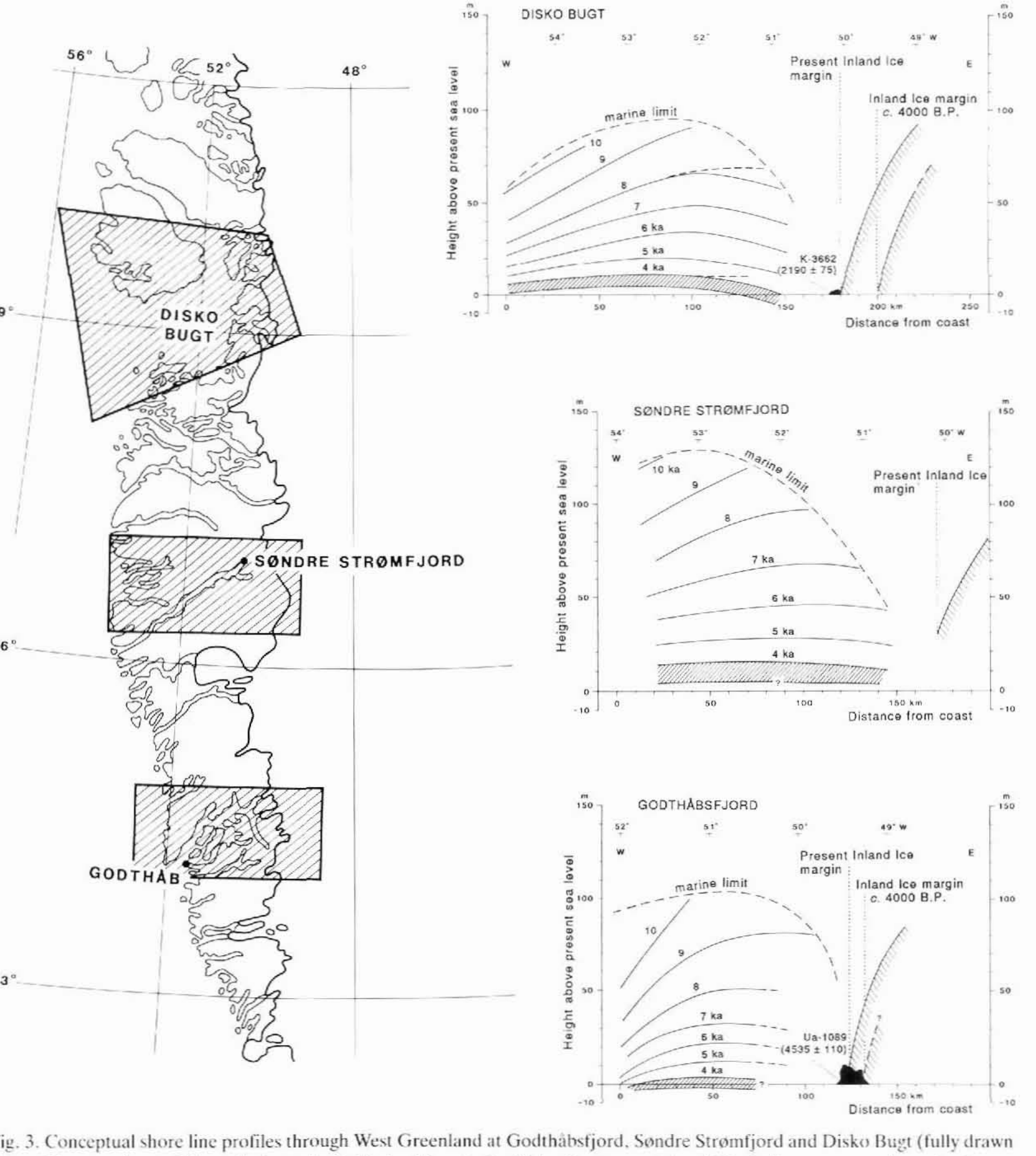

Fig. 3. Conceptual shore line profiles through West Greenland at Godthåbsfjord, Søndre Strømfjord and Disko Bugt (fully drawn lines with approximate ^{14}C age (ka) attached). Dashed lines in the Disko Bugt area at 4 and 8 ka indicate suggested trends of same shore line before Neoglacial build-up and advance of the Inland Ice margin.

Hatched zone between *c.* 3 and 4 ka B.P. indicates relative height of shore lines during the time of the Sarqaq culture according to present geological and archaeological information.

show no signs of higher Neoglacial relative sea levels than the present clue. The contradictory evidence may be related to a down-buckling of the crust of areas close to the present ice margin due to a readvance of the ice sheet as depicted in the model by Walcott (1970).

The last millennium

The submergence of West Greenland during the past millennium is classical in the sense that it had been widely documented by observations from the entire

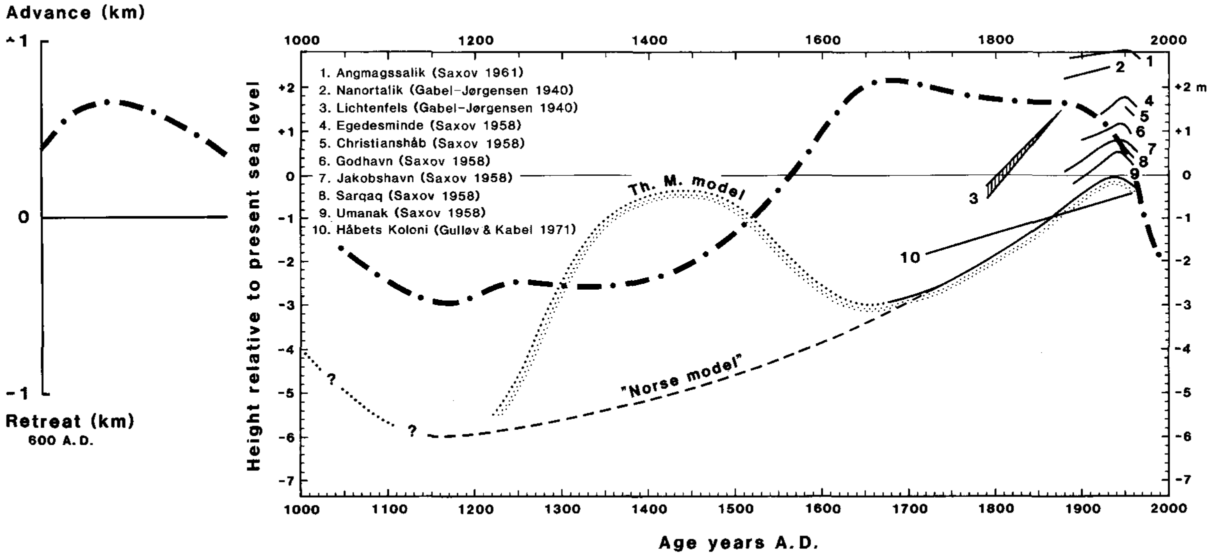

Fig. 4. Inferred fluctuations of relative sea level during the last millennium: 'Th. M. model' refers to the concepts of Therkel Matthiassen (*in* Gabel-Jørgensen & Egedal, 1940). 'Norse model' describes the rise of relative sea level at Sandnes (Kilaersarfik), Ameragdla, Godthåbsfjorden area, assuming a fairly constant rate of increase throughout at the millennium. It reflects, in a generalised way, an increasing glacier load between the early mediaeval age and this century, as shown by a generalised curve for glacier fluctuations in Disko Bugt since *c.* A.D. 600 (Reeh, 1983). Inset: Observations from historical records. Their position does not relate to any specific sea level and only the slope of the rate of sea level change should be considered.

west coast of Greenland by Pingel (1841). Thus the Norse church of Sandnes from *c.* 800 B.P., according to the archaeological investigations of Roussell (1941), has been submerged by about 6 m since its construction. Numerous historic observations indicate the same trend and order of magnitude for the rate of submergence during the last part of the present millennium (Fig. 4), and as early as 1927 Vogt estimated the general subsidence to be 3.5 to 5.5 m since the Norse period.

This trend of submergence may be overlain by secondary fluctuations. Based on the age of Eskimo ruins, it has been concluded that the present flooding is restricted to the ruins younger than A.D. 1700, whereas older sites were undisturbed by the sea (Matthiassen *in* Gabel-Jørgensen & Egedal, 1940). Relative sea level in mediaeval time must therefore have been close to the present, to be followed by an emergence and subsequently (after A.D. 1700) by submergence. A high sea level for the 14th–15th centuries does not, however, agree well with the low relative sea level of the Norse period referred to above. According to Saxov (1958), the general pattern of submergence changed to one of emergence about 1950, i.e. 50–100 years after the onset of the general glacier recession of the Greenland ice cover after the Little Ice Age.

Both Matthiassen's model and a model with nearly constant rate of submergence throughout most of the millennium are considered in Fig. 4. Assuming some of Matthiassen's changes to be due to errors caused by different modes of settling, the truth probably lies somewhere between the two extremes. The Matthiassen model may be more appropriate for the outer coastal regions, whereas the Norse model applies better to the interior parts of the coastal area.

The two models of relative sea level change can be compared to the calculated change of the Inland Ice margin in Disko Bugt (Reeh, 1983; Fig. 4). It can be seen that the Norse model with continued submergence since *c.* A.D. 1200 agrees with a gradual build-up of the ice margin, culminating during the Little Ice Age maximum from A.D. 1600–1850. In the same way, the thinning of the ice margin cover in this century might have led to the reversal to emergence, initiated around A.D. 1950 (Saxov, 1958, 1961).

Eustatic change of ocean level

Eustatic corrections are not discussed in this account of Greenland sea levels. This is due to the uncertainty of Neoglacial changes of the ocean level, which in general are considered to be small (about 1–2 m). The curves of Fig. 4 show that the rates of submergence or emergence of Greenland during the last few centuries are everywhere a matter of centimetres per year, whereas the corresponding reported changes of oceanic level are a matter of millimetres per year. For a first approach to describing relative sea levels in Greenland, the 'noise' caused by eustatic change will scarcely have any effect on the trends due to isostatic change.

Outlook

Present information on the Neoglacial changes of glaciers and relative sea levels in Greenland is vague and in places contradictory. The history of these changes is, however, a significant factor in studies of the impact of climate on the Greenland ice cover as a control for glaciological modelling, and also for geophysical concepts of the visco-elastic properties of the Earth's crust. In the latter context, Greenland is unique in having a constantly pulsating Inland Ice margin in contrast to other deglaciated regions, which offers a true scale 'laboratory' for stress/strain experiments.

Archaeological interest in sea level fluctuations relative to studies of sea-dependent cultures is obvious, and a close relationship between geologists and archaeologists is natural, for example in plotting the spatial form of a 'Sarqaq horizon' of shore lines.

The study of Neoglacial variations of the ice cover forms part of GGU's contribution to an EEC project on 'Climate and Sea Level Change and the Implications for Europe' which is planned to serve as a control for the ice-dynamical modelling of glacier response based on mass balance/climate investigations (cf. Braithwaite *et al.*, 1992).

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