

Late Holocene glaciers and avalanche activity in the Ålfotbreen area, western Norway: evidence from a lacustrine sedimentary record

ATLE NESJE, SVEIN OLAF DAHL & REIDAR LØVLIE

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Deposits from the proglacial lake Grøndalsvatn in the vicinity of Ålfotbreen, the westernmost glacier in southern Norway, show evidence of avalanches that descended into the lake between at least 2910 ± 60 and 2590 ± 60 ^{14}C yr BP (1170–770 cal. BC). A possible short glacial period from 2590 ± 60 to 2140 ± 60 ^{14}C yr BP (330–60 cal. BC) is thought to be represented by a thin, grey silt interlayer. After this date, the inflow of glacial meltwater to the lake ceased, indicating that few or no glaciers existed on the Ålfotbreen plateau at that time. A drop in organic-matter content and an associated increase in clastic-material supply at the core depth of 100 cm may indicate some renewed glacial activity in the lake's catchment from about 1650 ± 60 ^{14}C yr BP (cal. AD 370–450). The textural and carbon-content change at about 60 cm depth indicates an increased Neoglacial activity in the catchment from 910 ± 70 ^{14}C yr BP (cal. AD 1030–1220). The winter snow-mass balance is the most important factor controlling the net mass balance of Ålfotbreen.

Atle Nesje, Department of Geography, University of Bergen, N-5035 Bergen-Sandviken, Norway; Svein Olaf Dahl, Department of Geology, University of Bergen, N-5007 Bergen, Norway; Reidar Løvlie, Institute of Solid Earth Physics, University of Bergen, N-5007 Bergen, Norway.

Introduction

Lakes are widely recognized as being rather unique sedimentary basins, in which the climate history and geomorphic processes of the catchment are recorded almost continuously (Karlén 1976, 1981; Leonard 1985; Nesje & Dahl 1991a, b; Nesje et al. 1991; Karlén & Matthews 1992; Matthews & Karlén 1992; Leeman & Niessen 1994). The continuity of glacio-lacustrine sedimentary sequences is a major advantage in stratigraphic analysis, compared to other methodological approaches involving lichenometric data (e.g. Matthews & Shakesby 1984; Erikstad & Sollid 1986; Matthews 1987; Bickerton & Matthews 1993), relative age assessment based on the Schmidt hammer rebound values (Matthews & Shakesby 1984; McCarrroll 1989a, b) and radiocarbon-dated palaeosols (Matthews 1980, 1991, 1993). In order to study the regional variations in glacier response to different climatic parameters, it is important to establish the record of the dynamics of the individual glaciers in different climatic regimes.

The amount of sediment, including silt and clay, derived from a glacier generally depends on the glacier's behaviour in response to the local climatic conditions. The proglacial lacustrine deposits, in terms of their accumulated thickness and textural/mineral composition, are thus likely to provide important information on the glacier's behaviour and ice-front fluctuations (e.g. Karlén 1976, 1981, 1988; Karlén & Matthews 1992; Dahl & Nesje 1994; Leeman & Niessen 1994). However, the lacustrine sedimentary record is further complicated by

mass flow avalanches and turbidity currents of non-glacial origin (Shaw 1977; Gilbert & Shaw 1981; Ashley et al. 1985; Eyles 1987; Fitzsimons 1992), which act as a 'noise' component and render the record more difficult to decipher. The sedimentary record thus needs to be very carefully evaluated, by taking into account both climatic factors and local geomorphic conditions (for details, see Karlén & Matthews 1992; Nesje et al. 1994).

The records of avalanche events, which are mainly debris flows, may also reflect period of increased rainfall, possibly also the effect of anthropogenic activity in some cases (Rapp 1960; Nyberg 1985; Brazier & Ballantyne 1989). Investigation in the Sunnmøre area in southwestern Norway (Blikra 1994) indicates an increase in debris-flow avalanche processes around 3000 yr BP and also after 1500 yr BP. Studies in northern Norway (Jonasson 1991), northern Swedish Lapland (Nyberg 1985) and the Scottish Highlands (Brazier & Ballantyne 1989) show a high incidence of debris flows during the last 500 years, probably due to an increase in rainfall or anthropogenic effects.

The present article reports on a study of late Holocene glacier behaviour and avalanche activity in the maritime Ålfotbreen area in western Norway (Figs. 1 and 2), based on an investigation of lacustrine deposits in the proglacial lake Grøndalsvatn south of the glacier. The study points to the importance and palaeoclimatic significance of mass-flow avalanche deposits in lacustrine sedimentary records.

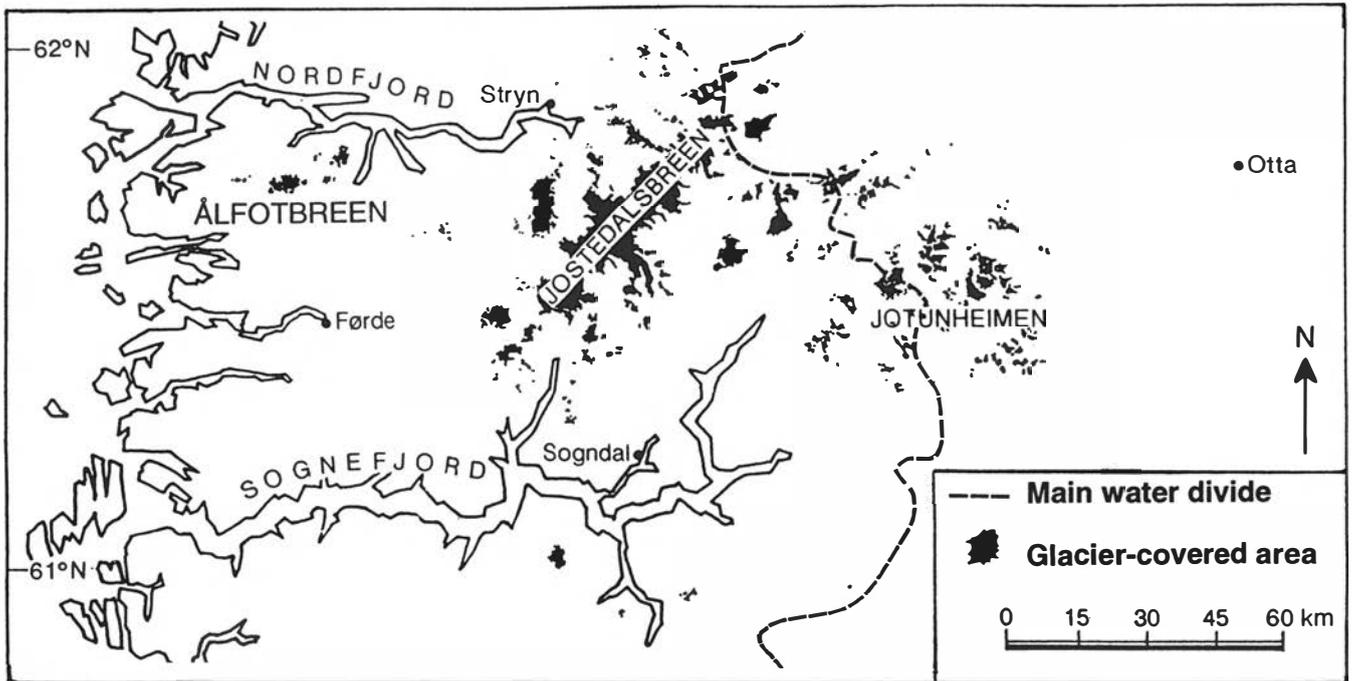


Fig. 1. Locality map, showing Ålfotbreen (south of Nordfjord) in the context of other modern glaciers in western Norway (modified from Østrem et al. 1988).

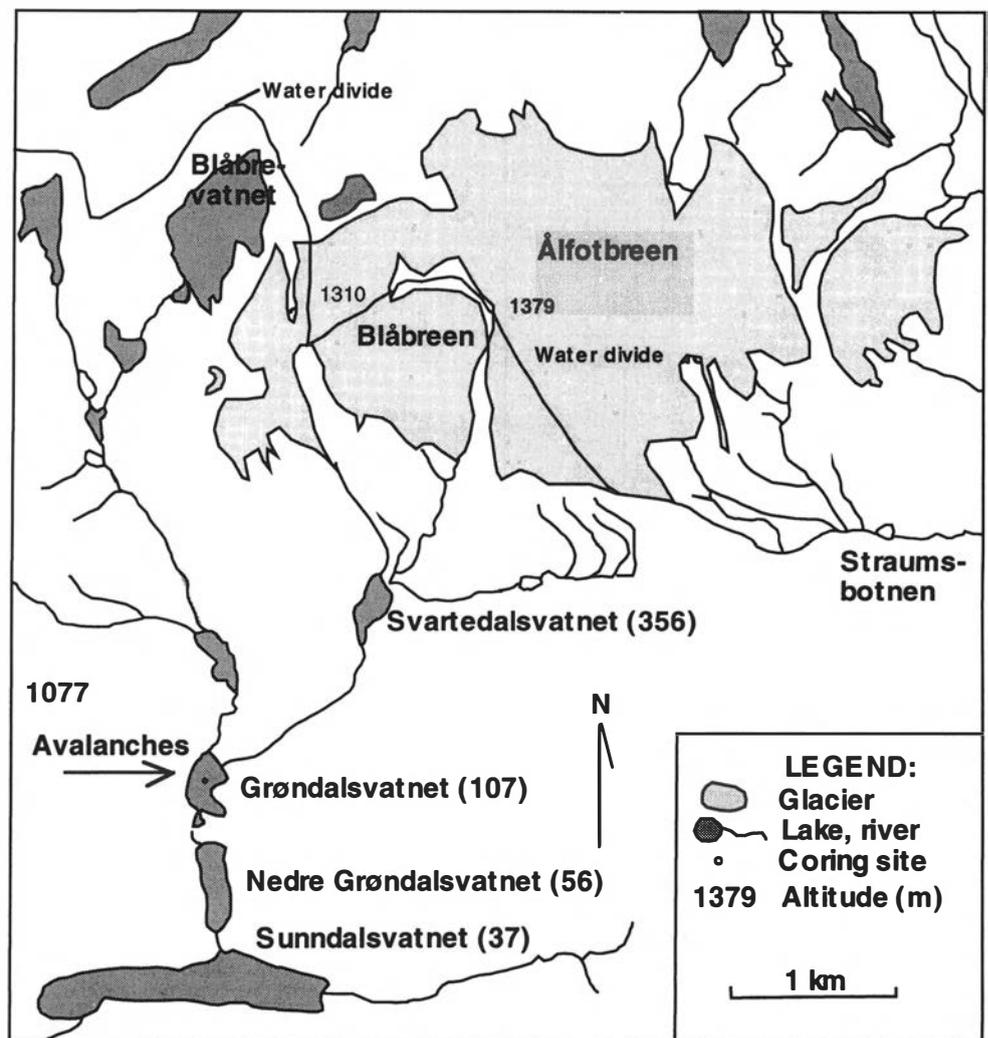


Fig. 2. Ålfotbreen area with the coring site in Grøndalsvatnet.

Methodology

The coring of the Grøndalsvatn deposits was done from lake ice in the spring of 1993, using a modified piston corer with 110 mm diameter core barrel, designed for retrieving 6 m long cores in offshore areas with water depths of up to 100 m (Nesje 1992). Magnetic susceptibility was measured at 2 cm intervals on unextruded core sections with a Bartington M52C sensor loop (125 mm diameter). The total and organic carbon content of the sediment was determined using a LECO furnace.

Six conventional radiocarbon dates were obtained from the Grøndalsvatn sedimentary core. The sediment samples for radiocarbon dating were stored in a cold-storage chamber before submission for dating. In the Beta Analytic Dating Laboratory (Florida, USA) the samples were initially saturated with hot deionized water and inspected for possible rootlet material with a texture different from that of the matrix. No such material was observed. The samples were further subjected to a hot-acid washing to ensure the absence of carbonate. The wood sample (Beta-71472) was also subjected to an alkaline washing to remove secondary organic acids (i.e., acid-alkali-acid pretreatment). After the rinsing to neutrality and drying, the samples were again inspected for

anomalous organic components. The pretreatment was followed by the combustion of the sample carbon to carbon dioxide, which was further synthesized to benzene and measured for ¹⁴C content. A numerical calibration of the radiocarbon age determinations has been applied to convert the radiocarbon years BP to calendar years AD/BC. The calibrated radiocarbon ages (Table 1) are given with one and two standard deviations (68% and 95% probability level, respectively) and with the corresponding intercept values from the calibration curve (Fig. 3).

Study area

Ålfotbreen covers an area of 17 km² (Østrem et al. 1988). The glacier, resting on Devonian sandstones and conglomerates (Sigmond et al. 1984), ranges in altitude from 1380 to 890 m (490-m altitudinal span). Continuous mass-balance measurements of Ålfotbreen have been carried out by the Glaciology Section, Norwegian Water Resources and Energy Administration (NVE) since 1962 (Fig. 4A). A positive cumulative-mass net balance of 14.99 m water equivalent has been found to have occurred since 1973 (Fig 4B). A correlation between the

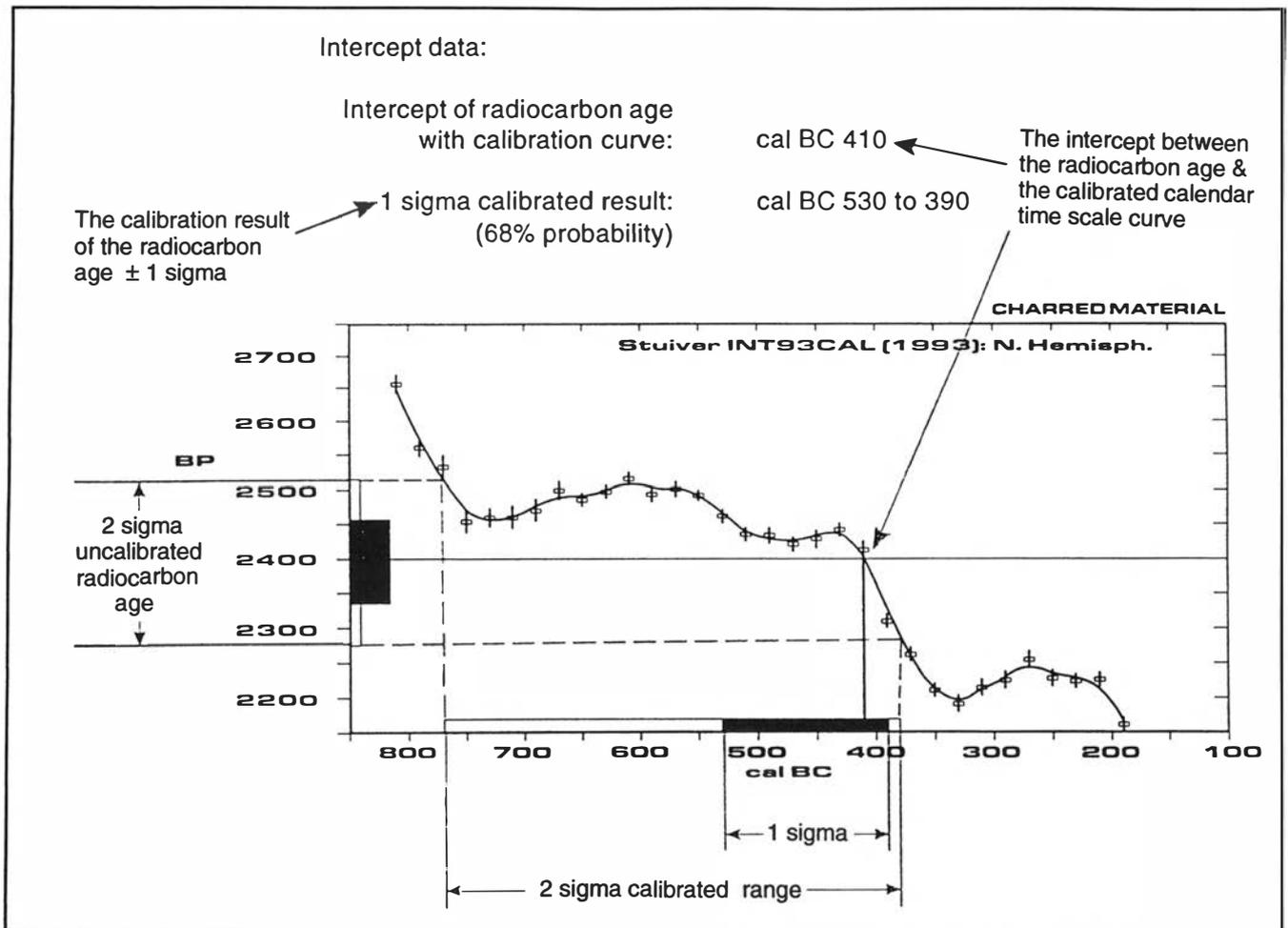


Fig. 3. Explanation of the Beta Analytic calibration of radiocarbon age to calendar years.

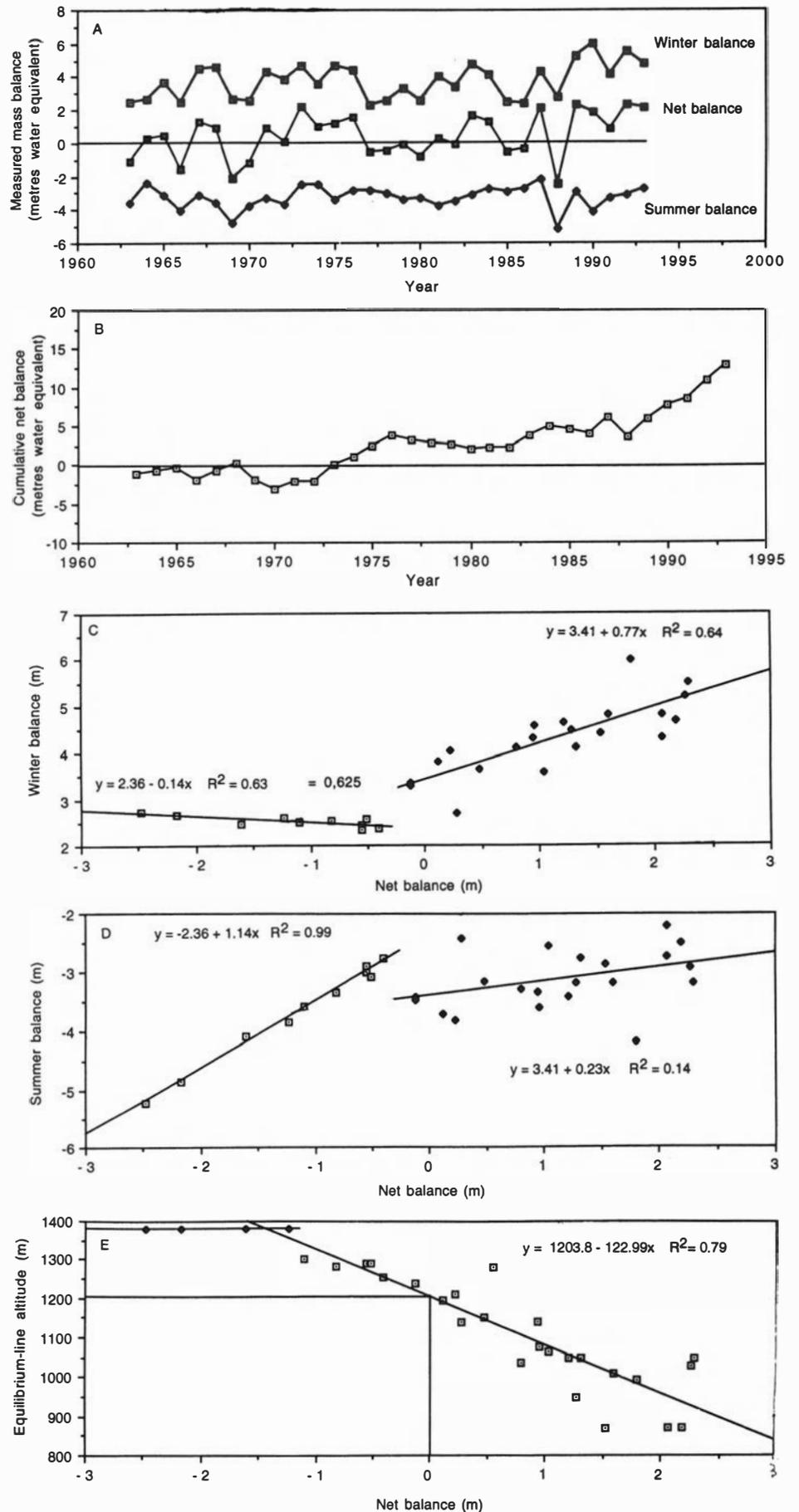


Fig. 4. (A) Annual mass balance data from Ålfotbreen, 1963–93, by the Glaciological Section of the Norwegian Water and Electricity Board (NVE). (B) Cumulative net mass balance of Ålfotbreen 1963–93. (C) Correlation between the winter mass balance and the net mass balance of Ålfotbreen, with a two-tier regression model based on the data. (D) Correlation between the summer mass balance and the net mass balance of Ålfotbreen, with a two-tier regression model based on the data. (E) Regression model of the relationship between the annual net mass balance and the equilibrium-line altitude (ELA) of Ålfotbreen.

Table 1. Radiocarbon dates from Lake Grøndalsvatn. For calibration procedure, see Fig. 3.

Depth (cm)	Laboratory No.	¹⁴ C dates yr BP	Calibrated age		Intercept with calibration curve
			1 Sigma	2 Sigma	
65	Beta-71467	910 ± 70	AD 1030–1220	AD 1000–1270	AD 1160
110	Beta-71468	1650 ± 60	AD 370–450	AD 250–550	AD 410
138	Beta-71469	2140 ± 60	330–60 BC	370–10 BC	170 BC
142	Beta-71470	2910 ± 60	1170–1000 BC	1270–920 BC	1070 BC
234	Beta-71471	2860 ± 70	1120–920 BC	1250–840 BC	1010 BC
330	Beta-71472	2590 ± 60	810–770 BC	830–750 BC	790 BC

annual net mass balance and the winter/summer mass balance indicates that the winter balance in the present case is the principal factor controlling the net mass balance of the glacier (Figs. 4C, D). For example, Fig. 4C shows that when the net balance is negative, the winter balance is almost consistently low. Figure 4D shows an extremely high correlation between the net balance and the summer balance when the net balance is negative. When the net balance is positive, the correlation between the net balance and the summer balance is, in turn, very low. A regression line for the annual net balance and the equilibrium-line altitude (ELA) data shows that the steady-state ELA at Ålfotbreen is about 1200 m (Fig. 4E); the ELA at 1380 m was excluded from this calculation.

The glacier meltwater streams draining Blåbreen

(3.9 km³) and the southwestern part of Ålfotbreen (Fig. 2) pass through another lake, Svartedalsvatnet (356-m altitude), on their way to the lake Grøndalsvatnet at the altitude of 107 m.

Results: stratigraphic interpretation and sedimentation rates

The core sample of lacustrine deposits (370-cm long core with a diameter of 11.0 cm), retrieved from Grøndalsvatn lake at a water depth of 36.90 m, was divided into six stratigraphic units (see A–F in Fig. 5). The sediment's magnetic susceptibility generally increases with decreasing organic-matter content. The low organic-carbon con-

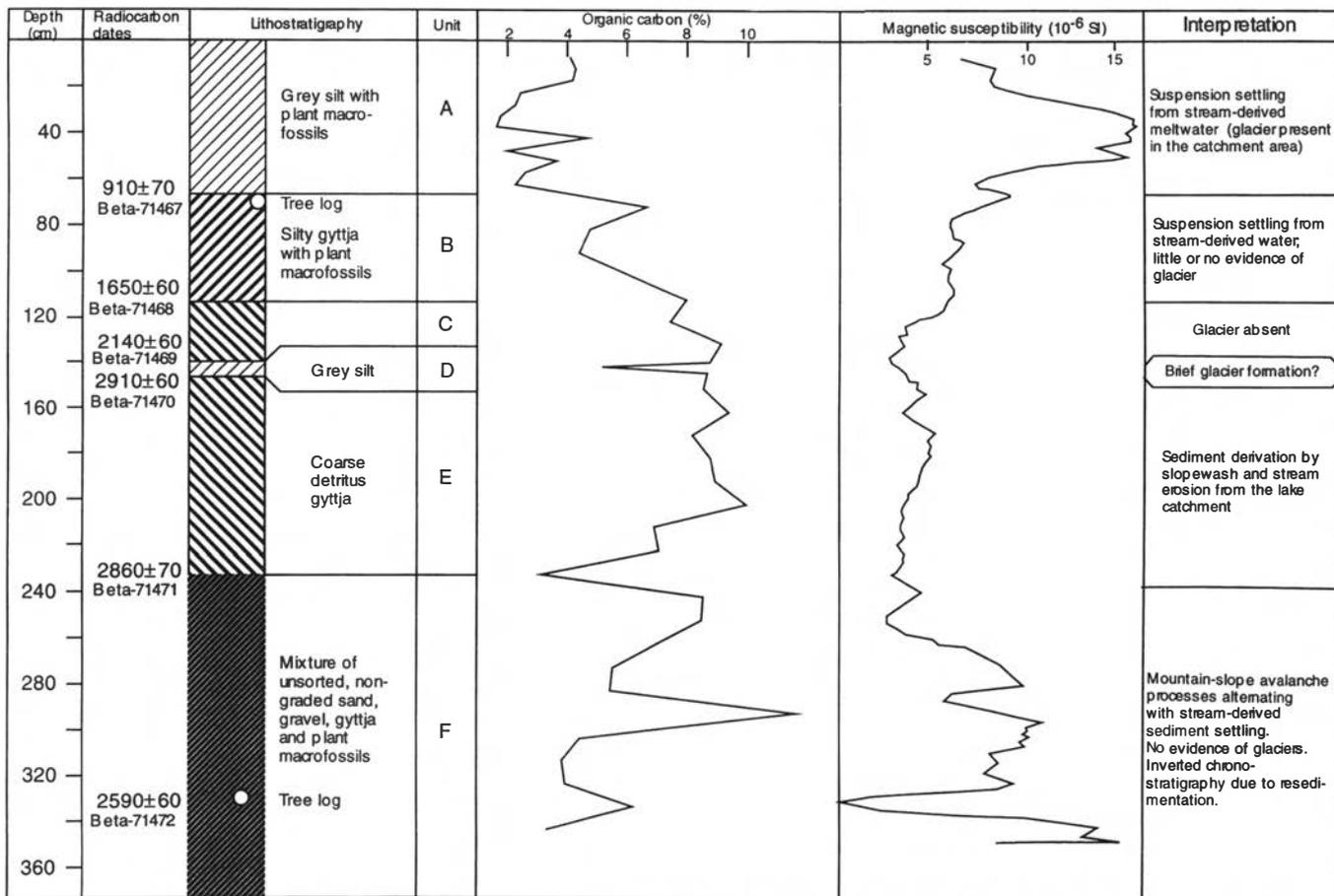


Fig. 5. Stratigraphic section, radiocarbon dates, organic-carbon content and magnetic susceptibility of the Grøndalsvatn core sample.

tent (2–5%) and relatively high magnetic susceptibility of the grey silt on the top unit A (Fig. 5) indicate sedimentation contemporaneous with the presence of glaciers on the Ålfotbreen plateau. The transition from unit A to the underlying unit B has been dated to 910 ± 70 ^{14}C yr BP and calibrated to AD 1030–1220 (see sample Beta-71467 in Fig. 5 and Table 1).

The higher organic-carbon content (up to 8%) and lower magnetic susceptibility of the silty gyttja of unit B (Fig. 5) indicate sedimentation during a period when glaciers in the drainage area were small or possibly absent. Likewise, the organic-carbon content (up to 9%) and low magnetic susceptibility of the coarse detritus gyttja of unit C (Fig. 5) indicate that the glaciers were most likely absent at that time. The transition from unit B to unit C (Fig. 5) has been dated to 1650 ± 60 ^{14}C yr BP and calibrated to AD 370–450 (see sample Beta-71468 in Table 1).

The thin and silty unit D at the core depth of 140 cm (Fig. 5) most probably represents glacier activity in the catchment. However, it cannot be excluded that this sedimentary unit was deposited during a period of heavy rainfall. The top of this unit has been dated to 2140 ± 60 ^{14}C yr BP and calibrated to 330–60 BC (see sample Beta-71469 in Table 1).

Unit E consists of a coarse detritus gyttja, whereas unit F comprises a mixture of unsorted, non-graded sand, gravel, gyttja and plant macrofossils. The textural variation is also reflected in the organic-carbon and magnetic susceptibility data (Fig. 5). The three radiocarbon dates obtained from this stratigraphic unit, at the core depths of 142, 234 and 330 cm, appear to be chronologically inverted (Figs 5 and 6), indicating the unit F comprises resedimented material and is most probably composed of avalanche deposits. The slightly younger date at the depth of 142 cm (see same Beta-71470 in Table 1), though statistically indistinguishable from that at 234 cm (sample Beta-71471), suggests that

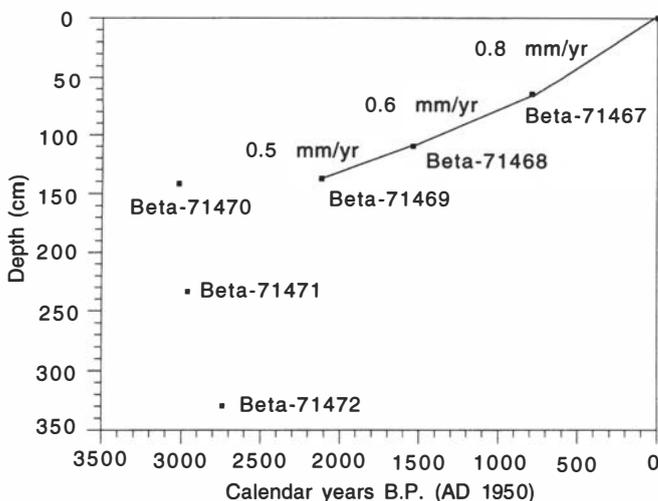


Fig. 6. Radiocarbon dates calibrated to calendar years BP (BP = AD 1950, intercept age, see Fig. 3) plotted against the depth of the Grøndalsvatn core. Note the inverted chronostratigraphy in the lower part of the section.

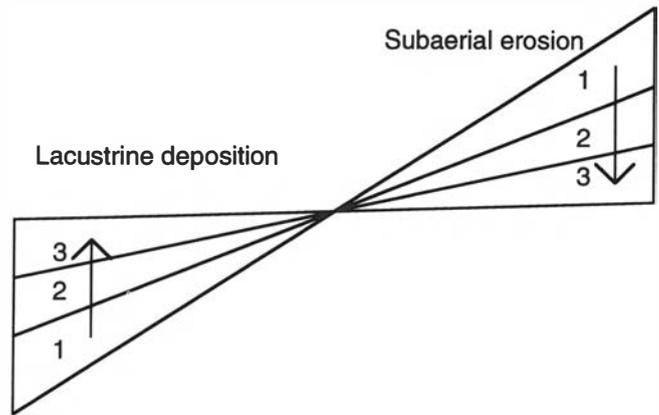


Fig. 7. Schematic model to explain the inverted chronostratigraphy in the lower part of the Grøndalsvatn core section in terms of subaerial erosion and material resedimentation into the lake.

the coarse detritus gyttja of Unit E contains organic material eroded from the lake's surroundings. The inferred pattern of mountain-slope erosion and lake sedimentation corresponding to units E and F (inverted stratigraphy) is shown in Fig. 7. The estimated annual sedimentation rate in the upper part of the Grøndalsvatn core (Fig. 6) varies between 0.5 mm/yr (Unit C) and 0.8 mm/yr (Unit A). The mean annual sedimentation rate in the lower part of the core dominated by avalanche flow deposits (Unit E and F) has been estimated as being approximately 7 mm/yr.

Conclusions

The study indicates that subaerial mass-flow avalanches have descended into Grøndalsvatn lake between at least 2910 ± 60 and 2590 ± 60 ^{14}C yr BP (1170 ± 770 cal. BC). There is evidence of a probable short glacial period between 2590 ± 60 and 2140 ± 60 ^{14}C yr BP (330–60 cal. BC). After the latter date, the inflow of glacial meltwater to the lake ceased and most likely no glaciers existed on the Ålfotbreen plateau at that time. There is some indication of possible minor glaciers in the lake's catchment from around 1650 ± 60 ^{14}C yr BP (cal. AD 370–450), but the main recognizable increase in Neoglacial activity on the Ålfotbreen plateau is dated to 910 ± 70 ^{14}C yr BP (cal. AD 1030–1220).

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