RESEARCH ARTICLE

Quick and Musical Ice Sheet Variances in Western Scandinavia 15-40 Kya: A Survey

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Abstract: The inland record of Middle to Late Weichselian dregs and frigid history in Norway demonstrates a progression of four significant ice propels exchanging with quick, extensive ice downturns and interstadial conditions. During every one of the chilly advances the ice sheet extended from coastal/inland situations to the rack regions. The reason for picturing these varieties in glaciation bends developed along nine cuts across from inland to retire, and for understanding of the palaeoclimatic history, is the local Quaternary stratigraphy, in excess of 300 datings, fossil substance and some palaeomagnetic information. The strategies applied as of late for AMS radiocarbon dating of icy dregs with low natural carbon content have given promising outcomes regarding exactness and accuracy, and the aftereffects of such datings were a significant instrument for our recreations and for timing of the ice motions. The fast and cadenced ice vacillations, as recreated in our new model, have been genuinely simultaneous in many pieces of Norway. Ice progresses started and finished at 40, 30 - 28, 24 - 21 and 18 - 15 (14C) Kya. We portray three mediating interstadials from inland destinations: Hattfjelldal I, Hattfjelldal II and Trofors. Our stratigraphical record additionally incorporates numerous signs of high, pre-Holocene, relative ocean levels, recommending a significant glacio-isostatic despondency of western Scandinavia during the interstadials. In our glaciation model we recommend that, notwithstanding precipitation, the bumpy fjord and valley geology, icy isostasy and relative ocean level changes were most likely more significant for the size of the frosty vacillations than were air temperature changes.
Keywords: Glacio-isostatic despondency, Glacio-isostatic despondency, Quaternary stratigraphy

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1. Introduction

Proxy climatic records from terrestrial and deep- sea sediments and ice cores reported during the last decade seriously challenge the view of a relatively continuous ice cover in Scandinavia during the interval 15 - 40 Kya. Seasonally open waters existed at least three times in this period, at 19, 25 and 30 - 35 Kya, along the Norwegian coast and even north to the Fram Strait in the polar North Atlantic Ocean (e.g. Hebbeln et al. 1998), as reviewed by Olsen et al. (2001a). Major ice retreat with ice-free areas reaching far into the inland of southern Norway at 32 - 37 Kya is indicated by 14C dates on sub-till sediments and thermoluminescence (TL) dating of 37 - 40 Kya (calendar years) of aeolian sand. The published record showing similar glacier fluctuations at 30-40 Kya in northern Norway includes both U / Th dating of speleothems from inland caves in Nordland County, TL dating of glaciofluvial sand from various parts of Fennoscandia and accel- erator mass spectrometry (AMS) 14C dating of organic-bearing, sub-till sediments from inland Finnmark County (also reviewed by Olsen et al. 2001a). Our study confirms and extends these results, as well as previously reported interstadials of various ages from the coastal areas (Sandnes, Alesund, Arn0ya, Hamnsund and And- 0ya interstadials), both geographically and with regard to time (Olsen et al. 2001a, 2001b, 2001c). The aim of this review paper is to give a brief presentation of our new glaciation model and summarize the conclusions on the 2-D reconstruc- tions of rapid and rhythmic ice sheet variations at 15-40 Kya in Norway, as obtained from the stratigraphic record, more than 300 dates of various kinds and some palaeomagnetic data. For details and background data, such as utilized methods, stratigraphic data, traces of high sea levels etc., see Olsen et al. (2001a, 2001b, 2001c). The present paper also includes new information on traces of high Middle Weichselian sea levels from Selbu, central Norway, supporting the regional glacial reconstructions. Our conceptual model for glacial variations has been questioned, but has also gained con- siderable support from modern proxy climatic records. Hopefully, this new model will provide new motivation and inspiration for further inves- tigations and discussions of methods, ice sheet fluctuations and their timing.

Norway is characterized by a highly irregular mountainous terrain with a densely dissected coastline and deeply incised fjords and valleys, ideal for rapid ice growth and decay. Considering the westerly position of the mountain areas above 1000 m a.s.l. in Fennoscandia, the initial ice growth during glaciations must have started in central southern Norway, in the high- est mountains along the coast and along the Norwegian-Swedish national border in the north. Conditions favourable for glaciation are enhanced by the short distances to principal moisture sources: the North Atlantic and the Norwegian Sea. However, the long coastline and deep fjords may also have functioned in the opposite sense, with ice flow mainly concentrated along the fjords and at many “entry” points for the sea to destabilize an extensive ice sheet.

2. Methods

The stratigraphical methods employed were the standard ones (clast fabric, grain-size analysis, etc.) used by the Geological Survey of Norway. Some of the more important for the present study are summarized below.

AMS radiocarbon dating of sediment samples with a low organic content and some marine molluscs has been carried out at the R. J. Van de Graaff Laboratory, University of Utrecht. For samples of sediments, dates were obtained from one of four organic fractions, with the majority performed on the NaOH-insoluble fraction (97 of a total of 136). Conventional radiocarbon dating and most AMS datings of shell samples were performed at the Radiological Dating Laboratory in Trondheim, Norway, and at the T. Svedborg Laboratory, Uppsala University, Sweden, respec- tively. All dates used for glaciation curve recon- structions are presented by Olsen et al. (2001a, 2001b). If not otherwise indicated, all ages cited in this paper are in radiocarbon years before the present.

Considering the controversial character of our data compared with previously published data from fjord and inland areas of Norway, first we had to evaluate the dating methods and the established chronology. Statistical treatment of the dates indicated that the mean ages of the four, major, Middle to Late Weichselian interstadials were significantly different at 99 % confidence level (Olsen et al. 2001b). We concluded that the best argument for the reliability of the chronology was the similarity of ages, within a precision of 1 - 3 Ky, for the phases of ice advance and retreat along the nine transects. Therefore, we consider the radiocarbon dating of sediments with a low content of organic carbon, which has been important for the established chronology, to be a useful and reliable tool for the timing of glacial fluctuations in areas where macrofossils are scarce.

To identify marine sediments older than the Holocene at localities situated far inland and high above the present sea level, and even well above the post-glacial marine limit, we have searched for marine fossils, but only seven localities (along transects 3, 6, 7 and 9) have been identified so far. In addition, several such sites close to the coast are reported from south-west Norway (e.g. Larsen et al. 2000). As alternative methods, we have used residues of marine organisms extracted with hexane, and we have determined the content of La and Ce to find a Ce-deficient, lanthanide abundance pattern, which is indicative of a marine depositional environment.

3. Ice Sheet Fluctuations, Sediments and High Relative Sea Levels

Our reconstruction of the ice sheet fluctuations is based on sediment sequences which include a variety of sedimentary facies and a range of depositional environments. The most frequent and qualitatively most important of these com- prise sediments deposited in proglacial environ- ments, which is essential for the ice sheet reconstructions. Sediment successions occurring in caves (e.g. Larsen et al. 1987), and subaerially at the coast or in the inland parts of Norway, are illustrated in a series of idealized logs. Fine-grained laminated cave sediments appear to preserve palaeomagnetic signals, and show evidence of a palaeomagnetic excursion con- sidered to equate with the Mono Lake / Lake Mungo excursion (28 Kya). This is recorded in Skjonghelleren (Larsen et al. 1987) and in other cave sequences. It is also possible that the same excursion is represented in fine-grained sediments in subaerial positions at Fiskelauselva and Sargejohka. A review of this, including a geo- graphic overview with examples of sediment suc- cessions from each of the nine regions studied, is presented by Olsen et al. (2001a, 2001b, 2001c).

Sub-till sediments with marine fossils are mainly found at moderately uplifted sites along the coast. However, some of these are located high above the previously known post-glacial marine limits, such as those recorded from the Hinn0ya and Gryt0ya islands (transect 3). Sim- ilar sediments have recently been found in the inland of central Norway (Selbu) at altitudes 10 - 15 % higher than the post-glacial marine limit. This means that the glacio-isostatic component during the last glaciation was much more pronounced in several places than hitherto realized.

We have also recorded traces of a marine environment based on secondary indications (e.g. Ce deficiency), as described before, at a number of places both close to the coast and farther landward, and at elevations high above the marine limits from the last deglaciation period, e.g. at Rokoberget where marine microfossils have also been recorded recently. This further strengthens the argument for a considerable glacio-isostatic component during most of the Mid to Late Weichselian, because these records of inferred marine sediments encompass most of the ice retreat intervals during the 15 - 40 Kya period.

Conceptual model

Based on the geographical distribution of dated sub-till sediments (subglacial sediments excluded), it is inferred that the Middle to Late Weichselian glaciation in Fennoscandia started at 30 Kya from glaciers located along the Scand- inavian mountain chain. Glacier fluctu- ation curves along all transects, show a high regional consistency. An attempt to reconstruct the 2-D glacier extent in western Scandinavia during alternating major stadial and interstadial episodes in the period 15 - 40 Kya, using all these data. The results indicate multiple glacial advances across the coast to the continental shelf alternating with ice retreats to the inland areas (the Hattfjelldal I, Hattfjelldal II and Trofors interstadials), on which we have based our conceptual model. The importance of this reconstruction is its emphasis on ice instability, with rapid shifts between ice growth and ice recession during the studied time interval.

It is presumed that rapidly fluctuating ice streams, which occurred in many fjord-valleys, fjords and their extension seawards to the adjacent shelves, also had a significant upstream influence on the land-based parts of the ice sheet, and that the major destabilization component was the abrupt changes of ice surface gradients towards the rapidly oscillating ice streams. Even minor changes in sea level, therefore, could have triggered a sequence of processes, which, together

with climatic variations, led to synchronized ice sheet fluctuations and rapid alternations between intervals with extensive glaciation and ice-free conditions in Norway 15 - 40 Kya.

4. Discussion and Conclusions

Our glaciation model, as reviewed here, fits well with a proposed "minimum model" of the geometry and thickness of the Late Weichselian Fennoscandian ice sheet, which suggests a relatively thin, multidomed ice sheet with several minor ice-free areas. The evidence for general ice movement patterns indicates more than one major ice dome. With a typical average net growth rate of 0.1 m/ yr (as typifies the summit area of Greenland during the Holocene), the available time during each ice build-up phase is not sufficiently long to achieve the ice thickness of the classical "maximum model."

This new record of glacier fluctuations on land in Norway during the last Fennoscandian glaciation seems to fit well with recently published information for glacier fluctuations along the west coast of Norway and the North Sea area. However, our data are in even better agreement with ice-rafted debris (IRD) peaks from the Norwegian Sea, and with ice-core data from Greenland, which indicate rapid changes from stadial to interstadial conditions in 500 - 2500 and 5000 - 7000 year intervals during the entire period from 40 - 45 Kya to the Holocene.

The relative sea level, thought to be driven mainly by glacial isostasy, was probably very high along the western Fennoscandian ice sheet margins during the ice retreat intervals between 40 and 15 Kya. The relative sea level in the North Sea area was very low at 30 Kya.

However, this may be explained by very little glacio-isostatic depression close to the margin of the former ice sheet and at the end of an interstadial, and that the global eustatic sea level was low during the entire 15 - 40 Kya interval. Given that the ice recession, which was strongly influenced by calving in the fjord areas, took place at a similar rate during each deglaciation phase, the effect of glacial isostasy indicates that the ice thickness was considerable during all the major ice advances. The glacio-isostatic depression was greatest and, therefore, the ice was thickest during the 21 - 24 Kya interval (Last Glacial Maximum [LGM] 1) and prior to 39 Kya. We suggest that the ice sheet responded to a westerly dominated climate regime during the first part of the last glacial maximum (LGM 1) by building major domes only in the west. This changed to a configuration with a more easterly position for the ice domes and ice divides during the second major Fennoscandian ice sheet extension (LGM 2), which is a well-documented general trend during ice build-up both in northern and southern Fennoscandia and along the southern margins of the Baltic Sea. In the Arkhangelsk area of Russia, the glacial record indicates a single last glacial maximum advance at 16 Kya towards the eastern margins of the Fennoscandian Ice Sheet (Larsen et al. 1999). The difference in glacial development in the west compared to the east may result from several factors, such as different distances to the ice-divide / dome areas and moisture sources, as well as differences in topography. The natural termination of all westward-trending ice advances at the shelf break in the west, compared to the free ice flow on the flat-lying land areas in the east, is another important factor. The record of the glacial history during the late Mid Weichselian (25 - 40 Kya) in the eastern parts of Fennoscandia (Sweden and Finland), briefly reviewed by Olsen et al. (2001a), is not well known. New data from the Sokli area in northern Finland, with three in situ Weichselian interstadial organic beds separated by tills, and with at least one of the interstadials of Mid Weichselian age (Helmens et al. 2000), as well as a new compilation by Arnold et al. (2002) of previously published data, seriously challenge the previous interpretations of a continuous ice cover throughout the Mid and Late Weichselian and call for a reconsideration of the ages and character of the Early and Middle Weichselian glacial fluctuations in eastern Fennoscandia.

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