Rapid adjustments of the western part of the Scandinavian Ice Sheet during the Mid and Late Weichselian – a new model

Lars Olsen, Harald Sveian & Bjørn Bergstrøm

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Regional Quaternary stratigraphy, fossil content (marine mollusc shells, dinocysts, pollen, etc.), some palaeomagnetic data, and more than 200 datings, mostly AMS-^{14}C datings of organic-bearing tills and sub-till waterlain sediments from the northern, central and southern parts of Norway are the basis for construction of nine glaciation curves from the inland to the coast and shelf, and for interpretation of the palaeoclimate. The results show rapid shifts between glacial and interstadial conditions in semi-cycles of five thousand to seven thousand years in the interval from c. 40-45 ka to 10 ka (^{14}C) BP. We describe these glacial variations in a new model which reflects rapid and rythmic glacier fluctuations. The conclusions with regard to number and size (extent) of the glacial and interstadial events are based on stratigraphy, whereas the timing and rapidity of events are based on dates. All these basis data are presented more thoroughly in an accompanying paper (*this volume*). The interstadials are named the Hattfjelldal interstadial I (30-39 ka BP) and II (24-27 ka BP), and the Trofors interstadial (17-21 ka BP). Previously reported interstadials are extended in this study to include larger inland areas, indicating extreme fluctuations several times both in the extent and volume of the ice. Considerable ice retreat with very extensive ice-free areas in several parts of Norway during the last two interstadials (c. 24-27 and c. 17-21 ka BP) have not been reported before, except for preliminary short notices from our studies. The stratigraphical record includes many indications of high pre-Holocene relative sea-levels, suggesting a considerable glacial isostatic depression of western Scandinavia during the interstadials. We suggest that, in addition to precipitation, the mountainous fjord and valley topography, glacial isostasy and relative sea-level changes were probably more important for the size of the glacial fluctuations than the air-temperature changes.

Lars Olsen, Harald Sveian & Bjørn Bergstrøm, Geological Survey of Norway, NO-7491 Trondheim, Norway.
Corresponding author: Lars Olsen (e-mail: lars.olsen@ngu.no)
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Introduction

During the last two to three decades, most climate models for the Last Glacial Maximum (LGM, c.15-25 ka BP) rely on CLIMAP and COHMAP data (CLIMAP 1976, COHMAP 1988, Lowe & Walker 1997), and thus on a relatively continuous ice cover in Scandinavia and extensive adjacent perennial sea-ice cover in the Norwegian Sea during most of the interval 40-15 ka BP. Proxy climatic records from terrestrial and deep-sea sediments and ice cores reported during the last decade seriously challenge these views. It is reported that seasonally open waters existed at least three times in this period, at c. 19, 25 and 30-35 ka BP (^{14}C), along the Norwegian coast and even north to the Fram Strait in the Polar North Atlantic Ocean (Vorren et al. 1988, Mangerud 1991a, b, c, Hebbeln et al. 1994, Valen et al. 1996). The climatic record reconstructed for the last glacial cycle from the Summit ice core on Greenland (Dansgaard et al. 1993), shows rapid shifts on a millenial scale in atmospheric temperature that match the variations in the surface ocean temperatures of the North Atlantic, including the variations during the LGM interval (Bond et al. 1993). This climatic variability is quasi-cyclic, starting with a temperature minimum and a 'Heinrich' event, reflecting abrupt iceberg rafting episodes of the North American Laurentide ice sheet and increased carbonate content in the sediments. Both the Greenland ice record and the North Atlantic records indicate that each 'Heinrich' event and its correlative glacial event is followed by an abrupt warming and subsequent gradual cooling that together constitute a 'Bond' cycle (Lehman 1993). Similar trends with variations in ice-rafted debris (IRD) and carbonate content are documented from the Norwegian Sea, indicating rapid shifts in glacial conditions also along the western margins of the Scandinavian ice sheet (Baumann et al. 1995).

A major ice retreat, with ice-free areas reaching far into the inland of southern Norway c. 32-37 ka BP, indicated by ^{14}C-dates on organic-bearing sub-till sediments, was reported by Thoresen & Bergersen (1983) and Rokoengen et al. (1993a). Thermoluminescence (TL) dating of 37-40 ka (calendar years) BP of aeolian sand, also from inland areas of southern Norway (Bergersen et al. 1991), gives further evidence of considerable Mid-Weichselian ice retreat. The published record showing similar glacier fluctuations at c. 30-40 ka BP in northern Norway includes both U/Th-dating of speleothems from inland caves in Nordland (Lauritzen 1991), TL-dating of

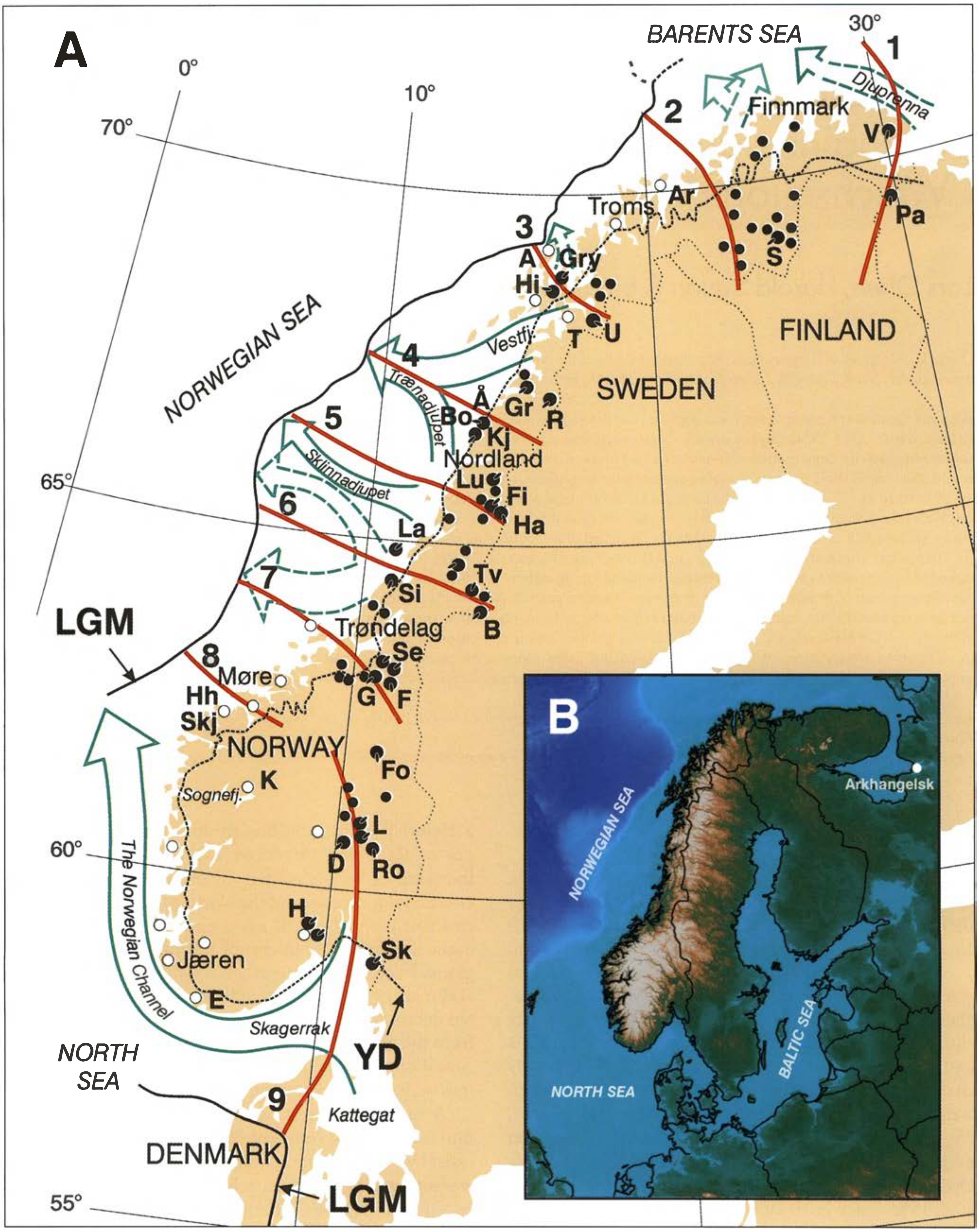


Fig. 1: A) Map with stratigraphical sites (dots) used in this study. Also indicated are sites with comparable information (open circles) from other published or unpublished sources, the western margin of the Scandinavian ice sheet during the Weichsel maximum (LGM) and the Younger Dryas (YD) Stadial, transects for the glaciation curves (Fig. 17), and stratigraphical sites (letters and closed circles with crosslines) referred to in the text; see also Fig. 1 from Olsen et al. (this volume). Positions of the major ice-stream channels - the Djuprenna, Vestfjorden, Trænadjupet, Sklinnadjupet and the Norwegian Channel ice streams - are also indicated (after Ottesen et al. 2000). B) Inset map shows the topography of Fennoscandia (Finland – Norway – Sweden) and adjacent areas. Light colour/shading indicate higher elevations.

glaciofluvial sand and AMS-^{14}C dating of organic-bearing sub-till sediments from inland areas of Finnmark (Olsen 1988, Olsen et al. 1996). The present study confirms and extends these results, as well as previously reported interstadials from the coastal areas (Sandnes, Ålesund, Arnøya, Hamnsund and Andøya interstadials), both geographically and with regard to time.

The aim of this article is to amplify the background data and present a 2-D reconstruction of ice-sheet variations in Norway during the last glaciation (40-15 ka BP) based on mapping of the regional Quaternary stratigraphy (Fig.1), AMS-^{14}C dating of organic-bearing sediments, shell dates and some palaeomagnetic data. These results indicate glacial advances reaching across the coast to the continental shelf and interstadials with ice retreats reaching to the inland areas in the period 40-15 ka BP (Olsen 1993a, b, 1995a, b, 1997a, b). These intervals appear to correlate fairly well with the North Atlantic and Norwegian Sea 'Bond cycles', and describe strong cyclicity. Another important element in this cyclic pattern is the highly productive surface water (HP-zones) indicative of open water conditions in the Polar North Atlantic (Dokken & Hald 1996). Together all these factors are thought to describe strong cyclicity with ice growth mainly during the last part of the HP-zones, and iceberg production and ice retreat indicated by the IRD sediment horizons (Olsen 1997a), on which we have based our conceptual model.

During these studies traces indicative of marine environments have been found at several localities in sub-till sediments situated much higher than the postglacial marine limit in these areas (e.g. Olsen & Grøsfjeld 1999). This evidence, together with all the utilized methods and basis data are presented more thoroughly in an accompanying paper (Olsen et al., *this volume*).

Geological setting

Norway is characterized by a highly irregular mountainous terrain with a densely dissected coastline and deeply incised fjords and valleys (Fig.1), ideal for rapid ice growth and decay. Considering the westerly position of the mountain areas above 900 m a.s.l. in Fennoscandia, the initial ice growth during the last glaciation must have started in central southern Norway, in the highest mountains along the coast and along the Norwegian-Swedish border in the north. Conditions favourable for glaciation are enhanced by the short distances to principal moisture sources, which are the North Atlantic and the Norwegian Sea in the west. However, the long coastline and the deep and long fjords may also have functioned in the opposite direction with many 'entry' points for the sea to destabilize an extensive ice-sheet, such as that which existed during the last glacial maximum.

The deep fjords as well as the long and deep trenches running parallel to the coast on the adjacent shelf, e.g. the Norwegian Channel - Skagerrak Trench, may have functioned as effective calving channels during ice-stream retreat and disintegration. It is likely that the first significant hindrance to rapid ice retreat in the North Sea area would have been the shallower areas of the Kattegat towards the 'outlet' of the Baltic Sea basin. Considerable ice-retreat along the Norwegian coast may therefore have occurred without a major contemporary ice retreat in the Baltic Sea region (Fig.1).

Glacial erosion was more pronounced in most parts of the mainland of Norway than on the adjacent shelves and in the other peripheral zones of the area covered by the Scandinavian ice-sheet. Thus, each major glacial advance has tended to 'clean' the surface of older glacial and non-glacial deposits, leaving only the youngest set of deposits on the ground when the ice melted. However, some exceptions to this general trend exist, e.g. long and complex sediment sequences ('sediment traps') in particular topographical positions. This contrasts with what is found in most peripheral (ice marginal) areas, such as in Germany and Poland, where deposition generally has taken place with little erosion of older sediments. Resedimentation and erosion in these areas, however, may have been strong enough to recirculate old soil remnants, which is considered to be of low risk in most of Norway. This is important for the approach adopted in this article.

Some of the tributary valleys and topographical depressions in Norway make efficient sediment traps during major ice advances, and are considered well suited to the identification and study of ice-dammed lake sediments. Our approach was, first to identify from regional Quaternary geological maps potential localities with preserved glaciolacustrine or other fine-grained sediments covered by till, and then to select those with few or no traces of oxidation and groundwater circulation for AMS-^{14}C dating and detailed studies.

Methods

The stratigraphical methods employed were the standard ones (clast fabric, grain-size analysis, etc.) used by the Geological Survey of Norway (Olsen 1988, 1998). Some of the more important for the present study are summarized below. For more details about these methods, see Olsen et al. (*this volume*).

AMS radiocarbon dating of sediment samples with a low (0.1-1.5 % TOC) organic content and some marine mollusc shell-samples have been carried out at the R.J. Van de Graaff Laboratory at the University of Utrecht (UtC-numbers). 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; Olsen et al., *this volume*). The dating of the other organic fractions (NaOH-soluble fractions, dichlormethane extracts and hexane extracts) was carried out mainly as an age-control for the insoluble fraction. Dating of mollusc shells is used as the age-control for

Table 1

Locality	Transect no.	Field no.	Lab.no.	Fraction	Weight	LOI	TC	TOC	d13C	C14-yrs.	+/- 1sd	
Komagelva	1	501-89	UtC 1795	INS		1.40 %	0.10 %		-27.8	16 420	190	190
Komagelva	1	519-89	UtC 3458	INS		1.86 %			-25.4	14 380	140	140
Leirelva	1	512-89	UtC 1799	INS		4.10 %	0.20 %		-25.7	17 290	170	170
Leirelva	1	512-89	UtC 1800	SOL		4.10 %	0.20 %		-23.5	17 110	160	160
Leirelva	1	513-89	UtC 3460	SOL		3.61 %			-24.2	18 680	170	17
Skjellbekken	1	16-94	UtC 4039	INS					-29.1	34 000	600	600
Skjellbekken	1	18-94	UtC 4040	INS					-26.3	25 860	280	280
Kroktåa	3	7.-98	UtC 7394	INS					-20	13 950	90	90
Mågelva	3	I-8-98	UtC 7456	INS					-20.4	13 890	140	140
Urdalen	3	20.-98	UtC 8458	INS	0.68 mg				-28.4	20 470	110	110
Urdalen	3	21.-98	UtC 8459	INS	0.53 mg				-25.9	27 580	220	220
Meløy	4	14.-98	UtC 8456	INS	0.53 mg				-25.4	17 700	80	80
Kjelddal I	4	16.-98	UtC 8457	INS	0.33 mg				-24.8	18 880	100	100
Kjelddal II	4	18.-98	UtC 8313	INS	1.57 mg				-24.5	24 858	161	161
Grytåga	4	9.-96	UtC 5557	INS					-6.1	35 400	500	500
Risvasselva	4	10.-96	UtC 5558	INS		1.88 %			-21	36 800	600	600
Luktvatnet	5	5.-95	UtC 4715	INS	1.26 mg			0.07 %	-16.1	30 600	300	300
Grane, F.	5	1.-040991	UtC 2215	INS		2.26 %	1.44 %	0.34 %	-21.35	28 000	500	500
Grane, F.	5	3.-040991	UtC 2216	INS		1.15 %	1.02 %	0.14 %	-20.98	19 500	200	200
Grane, F.	5	94-0031	UtC 3466	INS					-20.3	29 400	500	500
Grane, N.	5	94-0030	UtC 3467	INS					-20.1	26 400	400	400
Hattfjelldal	5	1.-280691	UtC 2212	INS			1.23 %		-23.02	27 300	600	600
Hattfjelldal	5	2.-280691	UtC 2213	INS			1.35 %		-19.42	30 500	600	700
Hattfjelldal	5	3.-280691	UtC 2214	INS			1.65 %		-19.18	25 700	600	600
Hattfjelldal	5	10.-95	UtC 4720	INS	2.40 mg			0.10 %	-24.5	28 060	220	220
Hattfjelldal	5	11.-95	UtC 4721	INS	2.02 mg			0.08 %	-22.8	25 370	170	170
Hattfjelldal	5	10.-95	UtC 4802	SOL	1.06 mg			0.50 %	-25	25 980	240	240
Hattfjelldal	5	11.-95	UtC 4804	SOL	1.52 mg			1.40 %	-27.2	25 780	240	240
Hattfjelldal	5	13.-95	UtC 4807	INS	2.40 mg		1.03 %	0.13 %	-22.6	26 720	280	280
Hattfjelldal	5	14.-95	UtC 4809	INS	2.17 mg		1.04 %	0.10 %	-18.2	23 500	240	240
Slettåsen	5	12.-95	UtC 4722	INS	2.31 mg	1.72 %		0.20 %	-10.6	34 900	400	400
Røssvatnet	5	94-0020	UtC 3468	INS					-19.5	31 000	500	500
Røssvatnet	5	94-0023	UtC 3469	INS					-18.0	29 700	500	500
Langstr.bak.	6	1.-97	UtC 5974	INS					*	18 700	500	500
Øyvatnet	6	8.-95	UtC 4718	INS	1.31 mg			0.05 %	-21.1	22 330	150	150
Øyvatnet	6	8.-95	UtC 4800	Hexane	1.75 mg				-27.6	19 340	150	150
Gartland	6	9.-95	UtC 4719	INS	2.32 mg		0.63 %	0.15 %	-23.3	28 000	200	200
Gartland	6	9.-95	UtC 4871	SOL	0.18 mg			0.90 %	-29.5	16 250	190	190
Namsen	6	15.-95	UtC 4811	Hexane	2.03 mg				-29.9	16 110	120	120
Namsen	6	16.-95	UtC 4812	INS	1.33 mg		0.87 %	0.04 %	-21.3	18 580	140	140
Namsen	6	17.-95	UtC 4813	INS	1.36 mg		0.85 %	0.04 %	-21.9	18 020	170	170
Namskogan	6	53-94	UtC 3465	INS					-19.2	28 700	400	400
Ø. Tverråga	6	3.6.-90	UtC 3464	INS		0.72 %			-23.5	17 830	190	190
Nordli	6		UtC 1380	INS		2.50 %	0.58 %		-25.0	41 000	3000	2000
Blåfjellelva II	6	17.-96	UtC 5565	INS					-21.1	19 710	110	110
Blåfjellelva II	6	18.-96	UtC 5566	INS					-21.4	20 040	100	100
Blåfjellelva I	6	2.-90	UtC 3463	INS		1.66 %			-23.1	22 220	240	240
Humm., Sve. Sweden;	6	1.-92	UtC 4814	INS	2.22 mg	0.60 %		0.08 %	-29.1	22 070	170	170
Sitter	7	29-91	UtC 2103	INS			0.70 %		-28.3	30 200	400	400
Sitter	7	7.-95	UtC 4717	INS	2.01 mg			0.07 %	-23.7	21 150	130	130
Sitter (conta.)	7	7.-95	UtC 4799	SOL	0.67 mg			0.70 %	-26.4	12 480	70	70
Myrvang	7	6.-95	UtC 4716	INS	1.06 mg			0.05 %	-24.6	16 770	190	190
Reinåa	7	1.-96	UtC 5549	INS		1.13 %			-18.2	28 700	300	300
Reinåa	7	2.-96	UtC 5550	INS		1.58 %			-17.5	16 850	90	90
Reinåa	7	3.-96	UtC 5551	INS		0.90 %			-17.4	19 880	160	160
Reinåa	7	4.-96	UtC 5552	INS		0.82 %			-16.1	31 600	400	400
Reinåa	7	5.-96	UtC 5553	INS		0.70 %			-15.1	29 280	260	260
Reinåa	7	6.-96	UtC 5554	INS		0.44 %			-16.1	30 900	300	300
Stærneset	7	7.-96	UtC 5555	INS		0.75 %			-15.6	18 820	110	110
Stærneset	7	8.-96	UtC 5556	INS		0.77 %			-11.1	25 240	180	180
Grytdal	7	4.-95	UtC 4714	INS	2.26 mg		0.89 %	0.66 %	-19.9	38 500	700	700
Grytdal	7	11.-96	UtC 5559	INS		0.70 %			-19.4	39 500	800	800
Grytdal	7	12.-96	UtC 5560	INS		0.62 %			-19.2	37 200	600	600
Grytdal	7	13.-96	UtC 5561	INS		0.98 %			-20	41 800	1000	1100
Grytdal	7	14.-96	UtC 5562	INS					-20.8	23 700	200	200
Grytdal	7	15.-96	UtC 5563	INS					-20.4	25 300	260	260

Locality	Transect no.	Field no.	Lab.no.	Fraction	Weight	LOI	TC	TOC	d13C	C14-yrs.	+/- 1sd	
Grytdal	7	16.-96	UtC 5564	INS					-20.5	28 400	300	300
Grytdal	7	4.-97	UtC 6040	INS					-23.8	18 970	150	150
Flora	7	8.-97	UtC 5977	INS					*	17 800	400	400
Flora	7	16.-97	UtC 5978	INS					*	15 920	260	260
Flora	7	19.-97	UtC 5979	INS					*	17 800	400	400
Flora	7	21.-97	UtC 5981	INS					*	16 700	220	220
Flora	7	22.-97	UtC 5982	INS					*	15 620	200	200
Flora	7	24.-97	UtC 5984	INS					*	19 600	280	280
Flora	7	25.-97	UtC 6042	INS					*	19 050	120	120
Flora	7	26.-97	UtC 5985	INS					*	18 000	400	400
Kollsete, S/F	8	18.-97	UtC 6046	INS					*	22 490	180	180
Skjeberg	9	2.-87	UtC 1801	INS		2.20 %			-29.6	19 480	200	200
Skjeberg	9	2.-87	UtC 1802	SOL		2.20 %			-28.7	16 770	190	190
Herlandsdal.	9	2-10/9-94	UtC 4728	INS	2.33 mg		0.42 %	0.20 %	-28.4	32 000	300	300
Herlandsdal.	9	3-10/9-94	UtC 4729	INS	2.38 mg		0.43 %	0.07 %	-28.4	28 300	240	240
Herlandsdal.	9	14.-97	UtC 6045	INS					-29.3	23 250	170	170
Passebekk	9	11.-97	UtC 6044	INS				0.16 %	-29.4	28 600	300	300
Passebekk	9	12.-97	UtC 5987	INS				0.01 %	*	21 000	400	400
Rokoberget	9	1.-210391	UtC 1962	INS		5.20 %			-30.4	47 000	4000	3000
Rokoberget	9	9.-270991	UtC 1963	INS		2.70 %			-29.6	33 800	800	700
Dokka, K.	9	4.-89	UtC 3462	INS		1.20 %			-30.2	26 800	400	400
Dokka, K.	9	1.-290991	UtC 2218	INS		1.07 %	0.20 %		-29.75	18 900	200	200
Mesna, Lh. (subgl.)	9	7.-97	UtC 6041	INS					-27.5	16 030	100	100
Mesna, Lh.	9	4.-270991	UtC 1964	INS		1.60 %			-25.4	36 100	900	800
Mesna, Lh.	9	1.-270991	UtC 2217	INS		1.60 %	0.45 %	0.25 %	-24.95	31 500	700	700
Stampesletta (subgl.)	9	7a.-91	TUa**	SOL					**	c. 16 000	**	**
Stampesletta	9	7.-270991	UtC 1965	INS		1.20 %		0.22 %	-26.9	32 300	500	500
Gråbekken	9	18.-95	UtC 4723	CO3	2.31 mg		5.60 %	1.06 %	-20.7	41 300	900	1000
Folldal	9	19.-95	UtC 4724	CO3	2.28 mg		5.40 %	0.23 %	-20.7	36 300	500	600
Folldal	9	1.-95	UtC 4709	INS	1.26 mg		0.28 %	0.22 %	-22.2	26 260	220	220
Folldal	9	1.-95	UtC 4710	SOL	0.75 mg			1.80 %	-26.2	23 260	160	160

d13C: ratio 13C/12C in per mil with respect to PDB-reference.
* : Estimated d13C-value.
** : Numbers not available; preliminary report (S. Gulliksen, pers. comm. 1995).

AMS-^{14}C dates of sediments (in situ or redeposited in till). These 97 dates are all used for the glaciation curve constructions and are selected from a total of 136 dates of sediment samples. The second column is referring to glaciation curve transects 1-9, 'conta.' indicates contamination by carbon from the overlying unit, but is included as a minimum date, and 'subgl.' indicates subglacially deposited sediments. Only dates from the Geological Survey of Norway's (NGU) own projects are included in this table; see Olsen et al. (this volume) for details about the screening and selection of dates used in the data-base, and for additional background data used during the reconstruction of the regional glacier-fluctuation curves.

coastal sites. Most of the AMS-^{14}C dates of sediments used for glacial curve reconstructions are included in Table 1. Additional dates that were also used are included in Olsen et al. (*this volume*; Table 4).

Conventional radiocarbon dating and AMS-dating of shell-samples were performed at the Radiological Dating Laboratory in Trondheim, Norway (T-numbers; Table 2), and at the T. Svedborg Laboratory, Uppsala University, Sweden (TUa-numbers), respectively. The samples for AMS-dating in Uppsala were prepared and targets produced at the Radiological Dating Laboratory in Trondheim. All ages cited in this article, if not otherwise indicated, are in radiocarbon years before the present (BP).

We have tried to find marine fossils to identify marine sediments older than the Holocene at localities situated far landward and high above the present sea-level, and even high above the late-glacial marine limit, but only five localities (transects 3, 6, 7 and 9; Olsen & Grøsfjeld 1999) have been identified so far. In addition, three such sites close to the coast are reported from SW Norway (Janocko et al. 1998). As alternative methods, we have used residues of marine organisms (molluscs, algae, etc.) extracted with hexane after a procedure described by Hansen (1996), and we have determined the content of La and Ce to find a Ce-deficient lanthanide abundance pattern, which is indicative of marine depositional environment (Roaldset 1980). For details of the Ce-calculations, see Olsen et al. (*this volume*).

Ice-sheet fluctuations

Key sites and crucial stratigraphical information

The reconstruction of the ice-sheet fluctuations in Norway is based on sediment sequences which include a variety of sediment facies and a range of depositional environments. The most frequent and qualitatively most important of these comprise sediments deposited in proglacial environments. Such sediments occur in a

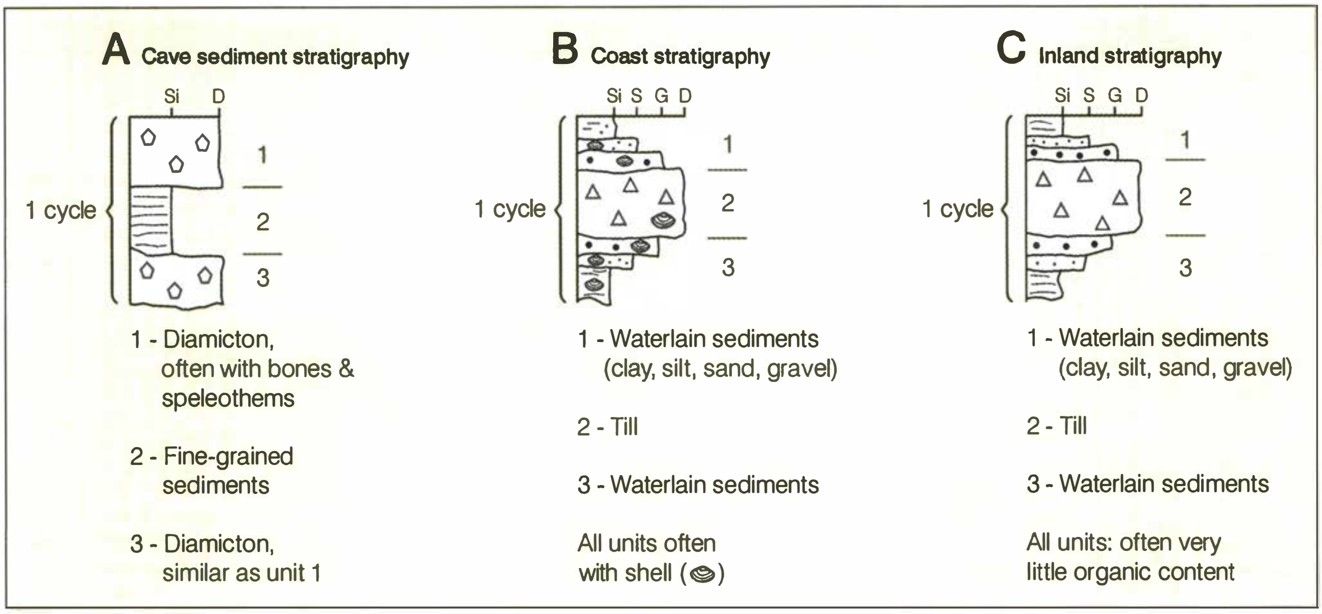


Fig. 2: Simplified logs of generalized stratigraphical successions of sedimentary units which indicate alternating ice free – ice cover – ice-free conditions. Each succession represents one cycle of glacial events. The sediment successions illustrate stratigraphies (A) in caves, (B) subaerially at the coast, and (C) inland.

majority of the localities (Olsen et al., *this volume*), which is essential for the ice-sheet reconstructions.

Sediment successions occurring in caves, and subaerially at the coast or in the inland of Norway, are illustrated in a series of simplified logs (Fig. 2). One such succession is inferred to represent one glacial cycle, with alternating ice free – ice cover – ice-free conditions. One or more of the waterlain sediment sub-facies (clay, silt, sand, gravel, etc.) may be lacking due to erosion or non-deposition, and the tills are not in every case a true basal till. Nevertheless, these are generally the basic elements of all recorded stratigraphies, and some examples of such cave and inland sediment successions are shown in Fig. 3. In the Skjonghelleren cave, three glacial cycles have been recorded (Larsen et al. 1987), but only the two cycles dated to the 40-15 ka BP interval are shown. Three glacial cycles are also recorded at the subaerial inland site at Fiskelauselva, and, as well as at Skjellbekken, where even a fourth (older) cycle may occur.

Fine-grained laminated cave sediments appear to preserve palaeomagnetic signals very well (Valen et al. 1997), and show evidence of a palaeomagnetic excursion considered to equate with the Lake Mungo excursion. This is recorded in Skjonghelleren and in other cave sequences (Larsen et al. 1987, Valen et al. 1996, 1997). Another possibility is that the same excursion is also represented in fine-grained sediments in subaerial positions at Fiskelauselva and Sargejohka (Fig. 3; Løvlie 1994, Løvlie & Ellingsen 1993, Olsen et al. 1996).

A geographic overview with simplified examples of sediment successions from each of the nine regions studied is added in Appendix A. More detailed stratigraphic information is presented in two other papers (Olsen et al., *this volume; and submitted*).

High pre-Holocene stadial to interstadial relative sea-levels

Traces of possible marine conditions indicate that the sea may have reached further landward and to much higher elevations during the Middle to Late Weichselian interstadials than during the Holocene. If so, a considerable glacial isostatic downwarping of the Earth's crust is implied during most of the period c. 15-40 ka BP.

Indications of high relative sea-levels during the last glaciation, recorded at many sites in Norway, include fossil

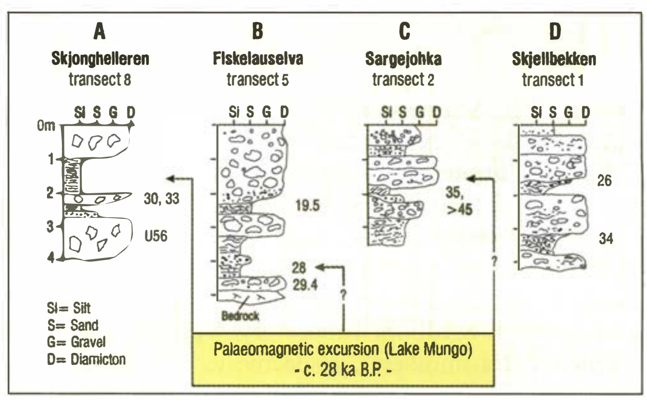


Fig. 3: Logs from four sites with simplified stratigraphies which are inferred to indicate a regional ice advance with deposition of glacio-lacustrine sediments and till c. 28-29 ka BP. The age control is given by radiocarbon dating (ka BP) and the occurrence and possible occurrence of a dated palaeomagnetic signal (Lake Mungo, c. 28 ka BP, e.g. Larsen et al. 1987). Skjonghelleren is a cave located at the coast along transect 8, whereas the other sites are located far inland along transects 5, 2 and 1, respectively (see Fig. 1). The diamictons at Skjonghelleren represent ice-free conditions, whereas diamictons at the other sites represent mainly tills and therefore ice cover. U56 represents a U/Th dating, 56 (cal yr) ka BP.

Table 2

Locality	Transect no.	Field no.	Lab.no.	Mollusc shell	d13C	C14-yrs. +/- 1sd	
Kroktåa, Hinnøya	3	6.-98	UtC 7350	One shell fragment	0.5	12 430	80
Storelva, Grytøya	3	1.-98	UtC 7345	One shell fragment	*	41 660	1500
Mågelva, Hinnøya	3	I-2-98	UtC 7346	One shell fragment	0.3	11 270	80
Mågelva, Hinnøya	3	I-3-98	UtC 7347	One shell fragment	*	11 680	70
Mågelva, Hinnøya	3	I-4-98	UtC 7348	One shell fragment	*	11 060	70
Mågelva, Hinnøya	3	I-5-98	UtC 7349	One shell fragment	0.7	45 560	2400
Meløya, Meløy	4	13.-98	UtC 8310	One shell fragment	2.7	38 200	700
Stamnes, Åmøya	4	M5-92	T-10541	Div. species	*	12 420	105
Bogneset I, Åmøya	4	M4-92	T-10540	Div. species	*	32 100	2600
Bogneset I, Åmøya	4	2.-6/6-93	TUa-947	Div.	*	40 025	965
Bogneset I, Åmøya	4	II-6/7-94	TUa-1239	Arctica islandica, a.o.	*	35 940	1455
Bogneset I, Åmøya	4	III-6/7-94	TUa-1240	Div.	*	28 355	430
Bogneset I, Åmøya	4	IV-6/7-94	TUa-1241	Arctica islandica, a.o.	*	38 090	1675
Skogreina, Meløy	4	1.-5/6-93	TUa-743	Div. species	*	38 545	835
Skogreina, Meløy	4	3.-5/6-93	TUa-946	Div. species	*	37 730	735
Skogreina, Meløy	4	2.-5/6-93	TUa-1092	Div. species	*	38 060	710
Stigen, Meløy	4	19.-98	UtC 8314	One shell fragment	1.1	12 200	60
Åsmoen, Ørnes	4	M7-92	TUa-567	Hiatella arctica	*	28 355	235
Åsmoen, Ørnes	4	05.06.93	TUa-744	Macoma, a.o.	*	12 520	85
Mosvollelva, Ørnes	4	08.07.94	TUa-1094	Fragm. of one species	*	29 075	370
Vargvika, Meløy	4	M3-92	T-10797	Div. species	*	12 450	195
Gammalmunnåga, M.	4	M2-92	T-10539	Hiatella, Mya, Macoma	*	> 44.800	
Ytresjøen, Meløy	4	22.-98	UtC 8315	Fragm. of one species	0.4	28 720	240
Ytresjøen, Meløy	4	23.-98	UtC 8316	One shell fragment	1.9	35 500	600
Vassdal ferry quay	4	1.-6/6-93	TUa-944	Div. species	*	35 280	575
Vassdal, Meløy	4	M1-92	T-10796	Div. species	*	30 610	3950
Sandvika, Meløy	4	12.-98	UtC 8309	One shell fragment	0.3	12 600	60
Neverdalsvatnet, Meløy	4	1.-7/7-94	T-11785	Chlamys islandica	*	12 520	205
Nattmålsåga, Meløy	4	1.-14/9-95	T-12567	Div. species	*	11 975	155
Fonndalen, Meløy	4	21.-96	UtC 5465	Fragm. of one species	0.66	11 990	60
Aspåsen, Meløy	4	1.-27/7-95	TUa-1386	Div. species	*	36 455	530
Oldra, Meløy	4	2.-30/9-93	TUa-745	Div. species	*	32 510	395
Oldra, Meløy	4	1.-20/7-95	TUa-1385	Mya truncata	*	33 040	315
Oldra II, Meløy	4	3.-20/7-95	TUa-1387	One shell fragment	*	33 975	515
Kjelddal I, Meløy	4	15.-98	UtC 8311	One shell fragment	1.4	35 800	600
Kjelddal II, Meløy	4	17.-98	UtC 8312	One shell fragment	-1	33 700	400
Grytåga, Fauske	4	19.-96	UtC 5463	Fragm. of one species	0.78	41 460	900
Hundkjerka, Hommelstø	5	4.-6/9-94	TUa-1093	Div. species	*	46 340	1620
Langstrandbakken	6	1.-14/7-95	T-12564	Div. species	*	36 950	2700
Sitter, Flatanger	6	1.-17/7-95	UtC 4726	One shell fragment	2.5	12 490	70
Myrvang, Trøndelag	6	28.-96	UtC 5414	Div.	-1.35	12 070	60
Gjevika, Osen	7	2.-6/9-91	T-11962	Macoma calcarea	*	12 325	215
Osen, Trøndelag	7	5.-22/9-94	TUa-1238	One shell fragment	*	39 140	2425
Follafoss, Trøndelag	7	1.-20/5-92	TUa-1260	One shell fragment	*	46 905	4020
Follafoss, Trøndelag	7	2.-21/5-92	TUa-1261	One shell fragment	*	47 565	4680

d13C: ratio 13C/12C in per mil with respect to PDB-reference.
* : Estimated d13C-value.

Radiocarbon dates (conventional and AMS) of marine mollusc shells. Only dates relevant for the glaciation curve constructions are included. The total number of dates is 45 (30 dates > 15 ka BP), and 9 of these are conventional dates (with T-refr.). The numerical ages are reduced by a reservoir age of 440 years. See the main text for further details.

marine fauna (e.g. mollusc shells, dinoflagellates, etc.), remnants of disintegrated marine organisms and lanthanide distributions indicating marine environments (see 'Methods' above). 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 late-/postglacial marine limits, such as those recorded from the Hinnøya and Grytøya islands (see Appendix A, *transect 3*; and Fig. 6). This means that the glacial isostatic component or other tectonic components during the last glaciation were much more pronounced than realized so far in several places.

Secondary indications of marine conditions include organic material extracted with hexane as a solvent (Hansen 1996), and a lanthanide distribution pattern with deficiency of Ce compared to La and to terrestrial conditions (Roaldset 1980). We have recorded such traces of marine environment at a number of places both close to the coast and further landward, and at elevations high above the marine limits from the last deglaciation period, e.g. at Rokoberget (Rokoengen et al. 1993a; Table 3, and Figs. 4-5) where marine microfossils have also been recorded recently (Olsen & Grøsfjeld 1999). This further strengthens the argument for a considerable gla-

Table 3

Locality no.	Locality name	Sea level (m a.s.l.) 40-15 ka BP	ML	Age (BP) of the 40-15 ka sea-level	40-15 ka sea-level in % of late-glacial ML
1	Leirelva, Finnmark*	111	85	19 ka ?	130
2	Grytøya, Troms	130	70	30-40 ka	186
3	Hinnøya, Troms-Nordland	160	70	12-15 ka	229
4	Valnesfjord, Nordland	75	110	36-41 ka	68
5	Åsmoen, Nordland	60	90	28 ka	67
6	Luktvatnet, Nordland*	146	120	31 ka	122
7	Hattfjelldal, Nordland*	260	140	24-35 ka	186
8	Domåsen, N-Trøndelag*	220	160	c. 18-19 ka?	138
9	Namsen, N-Trøndelag	179	142	18-19 ka	126
10	Øyvatnet, N-Trøndelag*	70	148	19 ka	48
11	Sitter, N-Trøndelag	45	120	21 ka; 30 ka	35
12	Sæterelva, S-Trøndelag	95	140	39 ka	68
13	Reinåa, N-Trøndelag*	280	200	19-31 ka	140
14	Grytdal, S-Trøndelag*	260	160	19-28 ka	163
15	Brattvåg, Møre & R.	20	60	28-38 ka	33
16	Jæren, Rogaland	200	25	30-40 ka	800
17	Herlandsdalen, Telemark*	250	175	28-32 ka	143
18	Rokoberget, Hedmark	235	190	34 ka	123
19	Lillehammer, Oppland*	140	185	31-36 ka ?	75
20	Gudbrandsdalen*	240	185	35 ka (TL)	130

Examples of high relative sea-levels or minimum marine transgressions during the interval 40-15 ka (^{14}C) BP versus late-glacial marine limit (ML). The maximum relative sea-levels from these areas during the 40-15 ka BP age-interval are not known. Marine conditions inferred from secondary indicators are indicated by an asterisk (*). See the main text for further explanations. Loc. 1 is after Olsen et al. (1996), loc. 15 after Larsen et al. (1987), loc. 16 after Andersen et al. (1991), loc. 18 after Rokoengen et al. (1993a), loc. 19 after Olsen (1985b, 1995a, b), and loc. 20 after Olsen (1985a) and Bergersen et al. (1991). TL; age based on TL dating, but adjusted to ^{14}C-yrs.

cial isostatic component during the last glaciation, because these records of inferred marine sediments encompass all the ice-retreat intervals during the 15-40 ka BP period (Olsen et al., *this volume*).

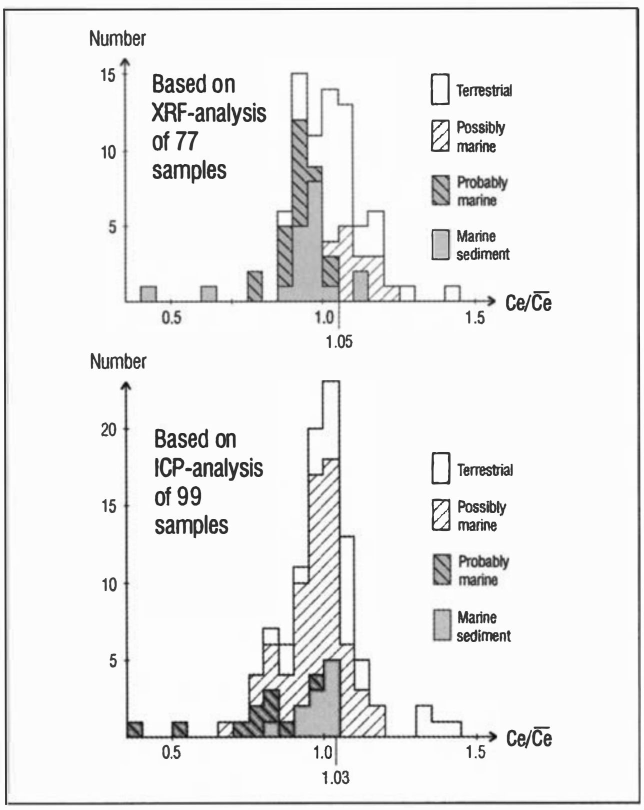


Fig. 4: Histograms showing the deficiency of cerium (Ce) in marine versus terrestrial sediments from different parts of Norway. The assignments marine (1), probable marine (2), possible marine (3) and terrestrial sediments (4) are based on the occurrence of (1) marine fossils or (2) dissolved remains of such fossils, (3) waterlain sediments and lack of evidence of any damming conditions (bedrock thresholds, sediments or ice), and (4) all other cases. Most of the XRF- and all the ICP-analysed samples (fraction < 2 µm) of certain and probable marine sediments give values at c.1.0 and lower, whereas the range of terrestrial values in both cases extends to c. 1.4, which clearly indicates a Ce deficiency in the marine sediments. See Olsen et al. (this volume) for details of the Ce and $Ce_n/\underline{Ce}$ calculations and for further explanations.

Description of ice-sheet fluctuations in different regions of Norway

Simplified logs of sediment successions along all nine transects (Fig. 1) are illustrated in a series of figures (Figs. 6 - 16) and put in a geographical context in Appendix A (see also Olsen et al., *this volume*). Glacier-fluctuation curves along all transects are shown in Fig. 17. Some information is also included from SW-Norway, but the data are insufficiently robust to justify the construction of a glacier-fluctuation curve. Several attempts to construct such curves covering the Mid- and Late Weichselian have previously been presented from this area (e.g. Mangerud et al. 1981, Andersen 1987, Mangerud 1991a, b, c, Larsen & Sejrup 1990, Sejrup et al. 1998, 1999), but all of these are poorly constrained due to a lack of field data from areas proximal to the late-glacial Younger Dryas – Allerød ice marginal position. Nevertheless, the high quality of dates and stratigraphical records from the coast of SW-

Norway make these data important also as a basis of correlation for our reconstructions.

An attempt to reconstruct the glacial 2-D extension during six major stadial and interstadial episodes in the period 15-40 ka (^{14}C) BP, using all these data, is indicated in Fig. 18.

Glaciation model

The results of this study underpin a model of variations in 2-D dimensions of the ice for western Scandinavia during the last glaciation. The importance of the model is its emphasis on ice instability, with rapid shifts between ice growth and ice recession in intervals with durations of a few thousand years during the period 10-40 ka (^{14}C) BP. The behaviour can be likened to the action of a "yo-yo", with strong action (ice advance) quickly followed by a strong reaction (ice retreat), whereas moderate advance was followed by moderate decay. This is strikingly similar to what is indicated by the glacial variations recorded in the ice-cores from Greenland and stadial-interstadial shifts recorded in North Atlantic sediments (Dansgaard et al. 1993, Bond et al. 1993).
Given the geological setting described above, the main components of our model are:

1) Ice build-up occurred contemporaneously in many areas where the influence of suitable topography and high precipitation, in combination with a sufficiently low summer and annual mean temperatures, favoured rapid glacier formation. Small local ice domes continued to grow until they coalesced with more dominant ice domes. Subsequently a full ice-sheet was developed, probably with more than one central ice dome. However, full glaciation occurred only if the ice-growth conditions were stable for a sufficiently long period. In this study we propose that "sufficiently long periods" may have been shorter than 5000-7000 years, which is much shorter than previously realized.

2) The fjord valleys, the fjords and their extension seawards to the adjacent shelves functioned as ideal channels for ice-stream formation, and this probably characterized the glacier development in most of these areas, at least in most of the major fjord systems. It is known that a major ice stream existed in the Norwegian Channel both during the Mid- and Late Weichselian (Longva & Thorsnes 1997, Sejrup et al. 1998, 2000).

4) Considerable glacial isostatic downwarping of the Earth's crust in most parts of Scandinavia during the last glaciation led to very high regional stadial/interstadial relative sea-levels in the fjord areas. Consequently, with such high, contemporaneous sea-levels, the marine-based parts of the ice sheet mainly developed as more or less separate ice streams with extremely rapid advance and retreat, as we know can occur in West Antarctica today (Denton & Hughes 1981).

5) We presume that the rapidly fluctuating ice streams 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 rapid alternations between intervals with extensive glaciation and extensive ice-free areas.

6) The model presented here fits well with a proposed "minimum model" of the geometry and thickness of the Late Weichselian Scandinavian ice sheet, which suggests a relatively thin, multidomed ice sheet with several minor ice-free areas (e.g. Nesje et al. 1988, 1994, Brook et al. 1996). It does not fit so well with the classical 'maximum model' of a land mass entirely covered by a thick ice sheet and dominated by a central ice dome (e.g. Vorren 1977, Andersen 1981, Boulton et al. 1985, Holmlund & Fastook 1995). The evidence for general ice movement patterns indicates more than one major ice dome. With a typical net growth rate of 0.1 m/year (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 'maximum model'.

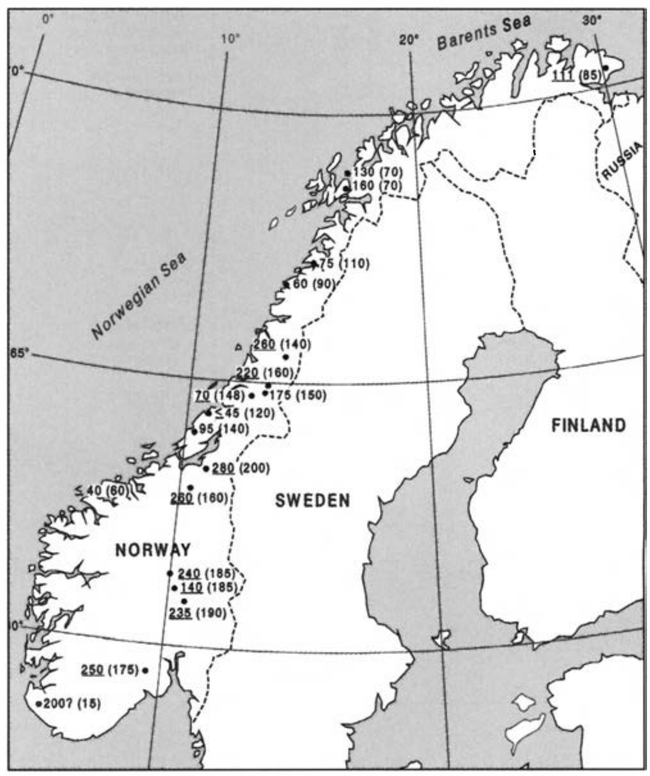
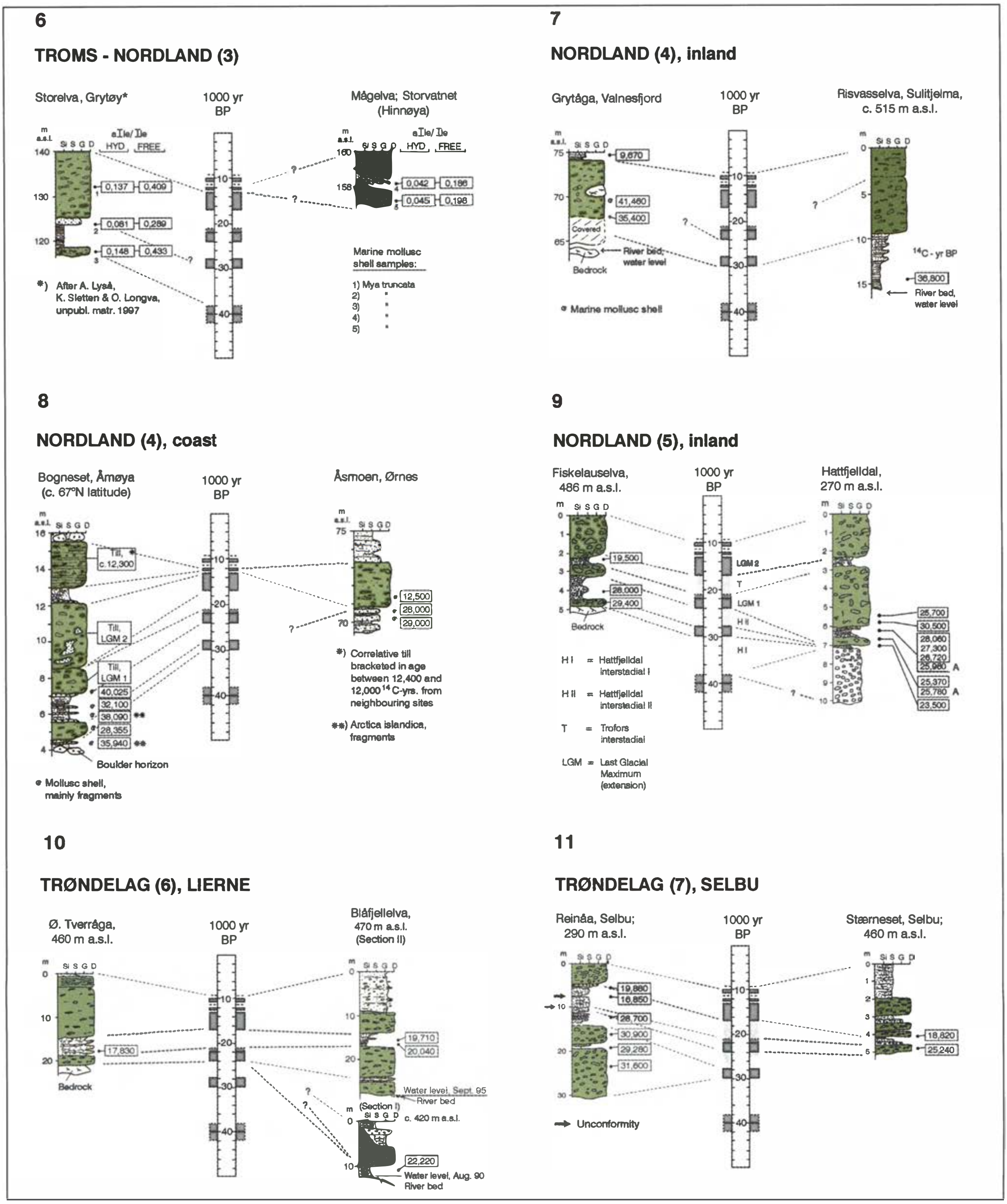
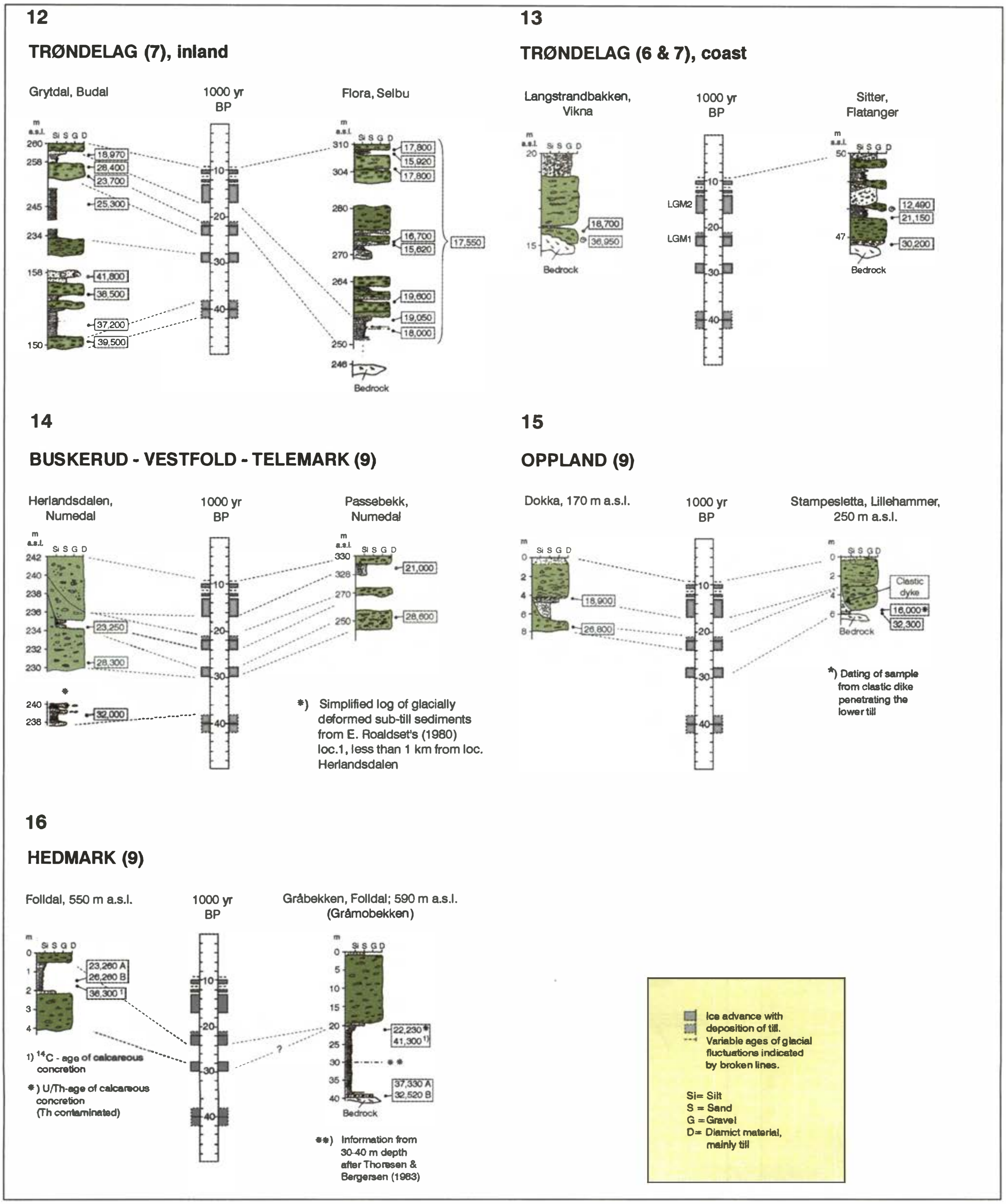


Fig. 5: Map with location (dots) and numerical values showing the altitude (in m a.s.l.) of highly raised sediments, or traces of environments, thought to be of marine origin from the last glaciation c. 15-40 ka BP. The interpretation is, in several cases, based on secondary indicators (numbers underlined), such as organic matter extracted from the sediments using hexane as a solvent and/or a Ce deficiency as indicated in Fig. 4. For comparison, the late-/postglacial marine limit in each area is shown in parantheses.



Figs. 6-16: The boxes along the vertical time-scale in the middle of the illustration indicate intervals of regional ice advances, with local glacial variations or ice-margin fluctuations occurring at or between the ages indicated by horizontal broken lines. Suggested correlations are also indicated (broken lines). Logs indicating simplified sedimentary successions from various sites are shown. Fig. 6: Sites along transect 3 at the Grytøya and Hinnøya islands, southern Troms (see Fig.1). Results of amino acid analyses are indicated with sample points adjacent to the stratigraphical columns. Fig. 7: Sites in the Valnesfjord area (Gr - Grytåga) and at Sulitjelma (R - Risvasselva) inland along transect 4. Legend as in Fig. 6, but the numerical ages here and in Figs. 8-16 indicate ^{14}C-ages (not calibrated to calendar years) of sediments and shells, not amino acid measurements. Fig. 8: Sites along the coast of Nordland along transect 4. Fig. 9: Sites inland in Nordland along transect 5. Together, these sites include sedimentary units which represent all the main episodes shown in Figs. 18 & 19D. Dating results marked by the capital letter A indicate the numerical age of the soluble (SOL) organic fractions. Those without denotation represent the insoluble



(INS) fractions. After Olsen (1997a). Fig. 10: Sites inland in Nord-Trøndelag along transect 6. Fig. 11: Sites inland in Sør-Trøndelag along transect 7. Fig. 12: Additional sites inland in Trøndelag along transect 7 (G and F in Fig.1). All the main glacial and ice-free episodes in the reconstructed regional glacier-fluctuation model for the interval 15-40 ka BP are thought to be represented at the Grytdal site. Fig. 13: Sites along the coast of Trøndelag along transect 6. The two last glacial maximum ice extensions are thought to be represented by tills at these sites, i.e., LGM 1 represented at Sitter, and possibly at Langstrandbakken, where LGM 2 also occurs. Fig. 14: Sites inland in Buskerud, Vestfold and Telemark (H in Fig.1). Fig. 15: Sites at Dokka and Lillehammer (Stampesletta), in Oppland (D and L in Fig.1). Fig. 16: Sites in eastern Folldal, in the northern parts of Hedmark (Fo in Fig.1). The Weichselian Scandinavian ice sheet may have covered the Folldal area continuously during the last glacial maximum extension, without any significant ice retreat at c. 19-20 ka BP as is thought to have occurred in the other areas studied.

Discussion and conclusions

Considering the controversial character of our data compared with previously-published data from fjord and inland areas of Norway, it is important first to discuss the dating methods used. We have done this, with a discussion focused on dating material and a more thorough examination of all the utilized methods presented in a separate accompanying paper (Olsen et al., *this volume*). Some general considerations are included here, and subsequently, we will discuss the consequences of the data in terms of glacial fluctuations.

Dating method - problems and prospects

Using AMS-^{14}C dating of organic-bearing sediments as a basic method for the reconstruction of Middle to Late Weichselian glacial variations, in the way we have attempted, involves both advantages and possible serious problems. Although they are often restricted to so-called 'sediment traps', a major advantage is that such sediments occur in most regions, and it is fairly 'easy' to find enough sites to attempt such reconstructions. We have tried to test the reliability of the ages achieved for the sediments in different ways, such as by dating more than one organic fraction, and comparing the results with each other (App. C). Other dating methods (e.g. U/Th, luminescence, amino acid analysis, palaeomagnetic measurements) or radiocarbon dating of macrofossils are also used as controls in some cases, but in most cases this has not been possible. A fairly comprehensive examination of the accuracy and precision of the AMS-^{14}C dates of sediments is presented in Olsen et al. (*this volume*). The best argument for the reliability of the method is the similarity of ages, wit-

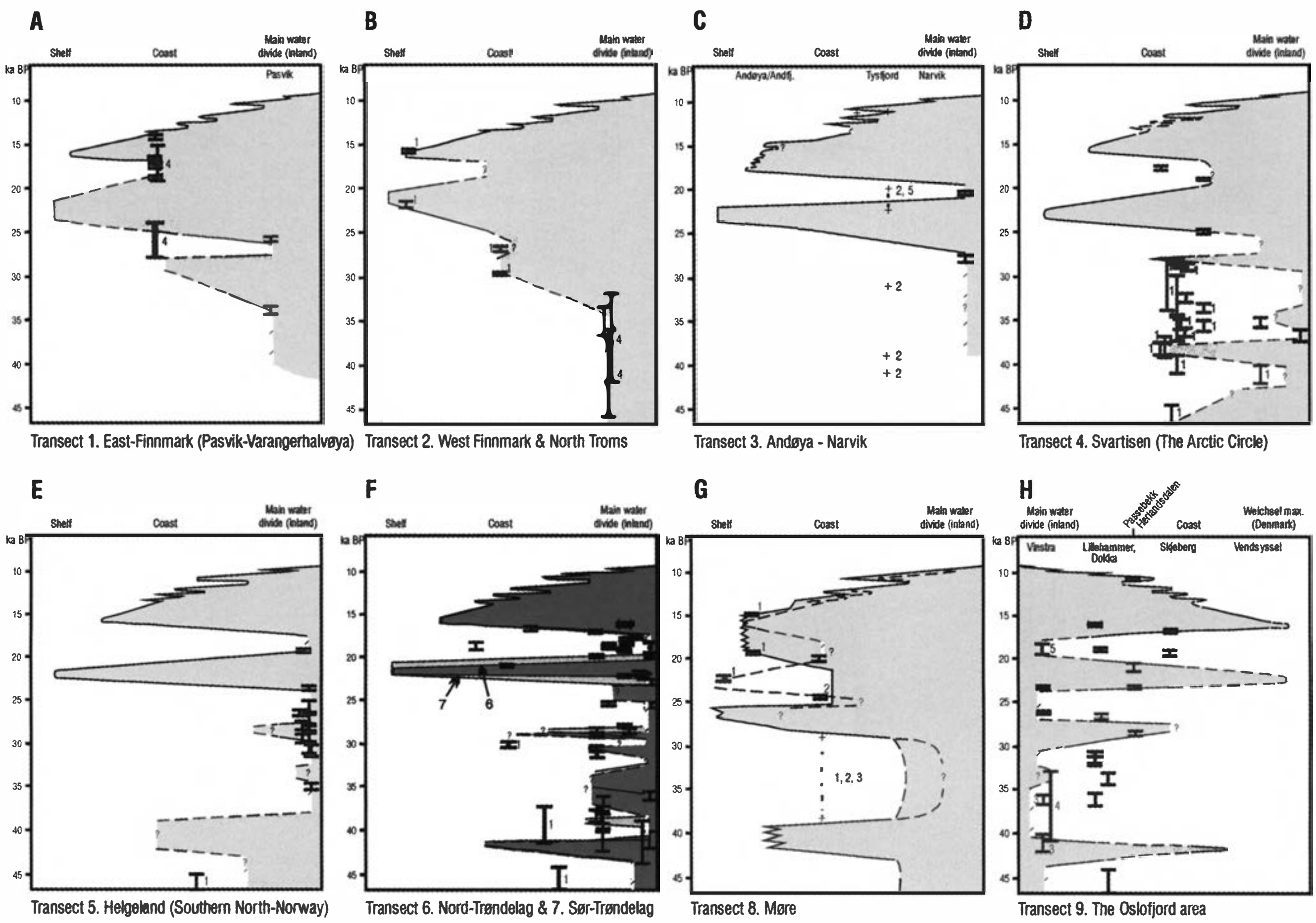


Fig. 17: Glacial curves along the transects shown in Fig.1. All transects are shown with normalized lengths, i.e. all transects have been given equal length. Dates used during these reconstructions are indicated within ± 1δ precision, as vertical rods. The majority of the dates are AMS-^{14}C of sediments (uncalibrated to calendar years). Other dates also included are marked separately: (1) ^{14}C of shell, (2) ^{14}C of bone, and (3) ^{14}C of calcareous concretion. Luminescence dates of sediments (4) and U/Th-dates of calcareous concretions (5) are also included for comparison. Note that these are given in proxy calendar years and are not directly comparable to the ^{14}C dates. A) Glacial curve along transect 1, B) transect 2, C) transect 3, D) transect 4, E) transect 5, F) transects 6 & 7, G) transects 8, and H) transect 9. The glacial curve shown for transect 8 is after Valen et al. (1996), with addition of a stippled line indicating our proposed alternative interpretation with two Late Weichsel maximum glacial extensions. See Fig. 19D for further comparison between the glacial curves. Grey shading indicates ice cover.

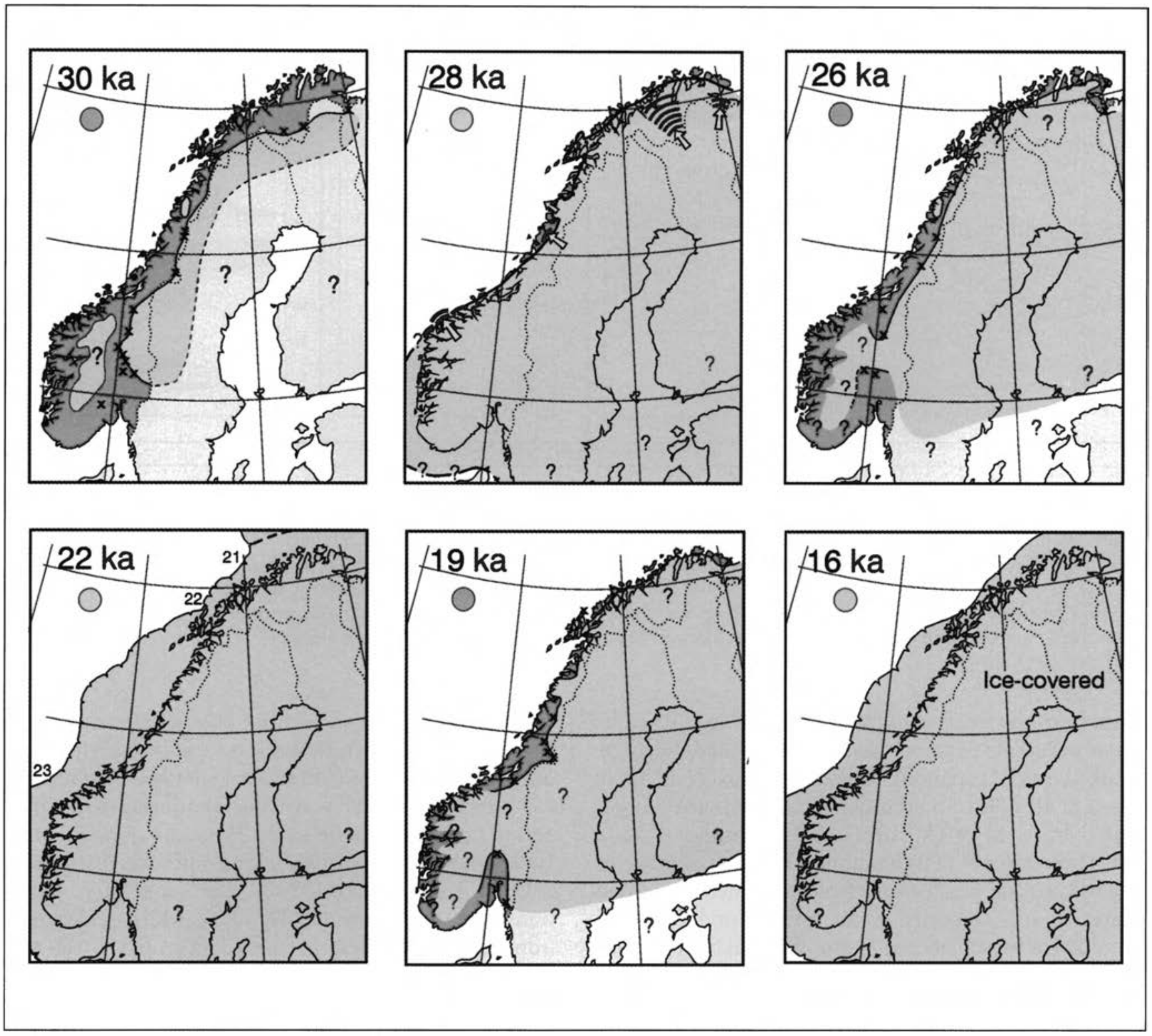


Fig. 18: Maps showing the glacial extension (medium grey) and ice-free areas (dark grey) during six major episodes in the period 15-40 ka (^{14}C) BP. These episodes are characterized by ice advances (medium grey circles) and ice retreats (dark grey circles), respectively. At c. 28-29 ka BP: Major ice advances occurred in at least four different areas (open arrows and circle contour fragments en échelon). The glacial variations in some areas, particularly in eastern Fennoscandia and the Baltic Sea area during these episodes, are considered uncertain (light grey and/or ?) in these reconstructions. After Olsen (1997a).

hin a precision of 1-3 ka, for the phases of ice advance and retreat along the nine transects shown in Figs. 1, 17 & 19D.

We realize that the dating methods used have to be tested more rigorously, at least if the aim is to evaluate the ages at a millennium or sub-millennium scale. Statistical treatment of the dates indicates that the mean ages of the four major Middle to Late Weichselian interstadials (Fig. 19D) are significantly different at a 99 % confidence level (Olsen et al., *this volume*). However, even if the mean ages of the ice-free intervals that we have recorded are approximately correct, we still have several problems to deal with before firmer conclusions can be drawn on dating quality and a more comprehensive assessment of palaeoclimatic and environmental changes. For example, one of these problems is to understand and explain the lack of marine mollusc shells with numerical ages in the interval 13.4 - 27 ka BP along the Norwegian coast. No radiocarbon dates of shells, but numerous ^{14}C and AMS-^{14}C dates of organic and organic-bearing sediments, ^{14}C-dates of animal bones, luminescence-dates of sediments and U/Th-dates of calcareous concretions in cave-sediments indicate significant ice-retreat in the fjord areas of Norway during parts of the Late Weichselian maximum, c. 15-25 ka BP (Vorren et al. 1988, Olsen 1993a, Olsen et al. 1996, Valen et al. 1996, Nese 1996, Lauritzen et al. 1996, S.E. Lauritzen, pers. comm. 1996). The lack of shell-

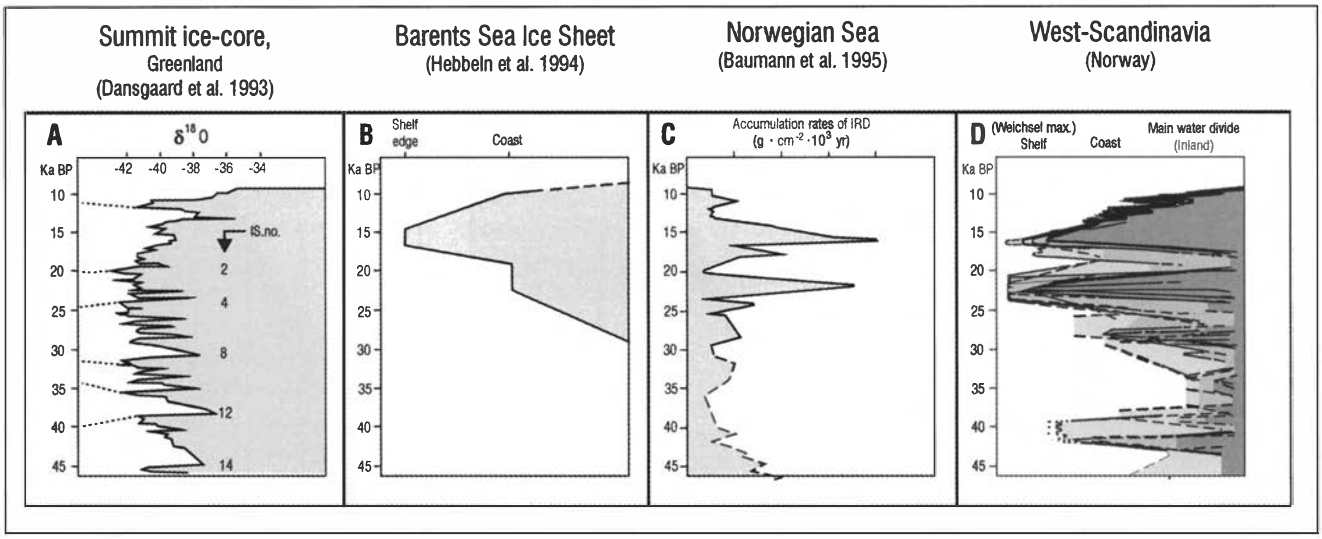


Fig.19: Comparison between various data which indicate proxy glacial and climatic variations in the vicinity of Norway to the north and west. A) $\delta^{18}O$-data from the Summit ice core from Greenland (the GISP-project, Dansgaard et al. 1993); B) Glaciation curve representing the Barents Sea ice sheet (grey) during the last glacial maximum (Hebbeln et al. 1994); C) IRD accumulation data from the Norwegian Sea (Baumann et al. 1995), and D) Glaciation curve based on nine transects from inland to coast/shelf in Norway (Olsen 1997a). In this complex curve we have chosen an alternative curve development for transect 8 compared to the significantly deviating one presented by Valen et al. (1996). See text and Fig. 17 for further explanation. All time scales are shown in ^{14}C-yrs. (see Olsen et.al., this volume)

dates from the interval c. 16.4 - 21 ka BP in the southwestern Barents Sea area has been explained partly by sea-ice cover throughout the year (Vorren et al. 1990, Olsen et al. 1996). In accordance with hypotheses presented by Hald et al. (1991) and Steinsund & Hald (1994), we suggest that dissolution of calcareous shells, due to cold and acidic water from high melt-water discharge and/or CO_2 rich water formed under sea-ice, should also be considered as a possible cause for some of this scarcity of shells. We also suggest that these factors, i.e. sea-ice/fjord-ice cover throughout the year and dissolution of calcareous shells, should be considered, and tested in the future, as causes of the apparent lack of shells with ^{14}C-ages of c. 18-20 ka BP from the fjord areas of Norway.

Glacial fluctuations – with comparison to Greenland and the Nordic Seas

This new approach to detailed mapping and dating of glacier fluctuations on land in Norway during the Middle and Late Weichselian Scandinavian glaciation has given information which is partly in conflict with the well-established model (Vorren 1977, Andersen 1981, Denton and Hughes 1981, Mangerud 1991a, b, c). The new data fits better with recently published information for glacier fluctuations along the west coast of Norway and the North Sea area (Larsen et al. 1987, Vorren et al. 1988, Alm 1993, Sejrup et al. 1994, Valen et al. 1996), but our data are even more comprehensive, and indicate much stronger fluctuations and much more rhythmic and rapid changes in glacier volume than previously realized. The stratigraphies and datings presented here are in good agreement with ice-core data from Greenland (Fig. 19A, D), which indicate rapidly changing conditions from stadial to interstadial environments in 500-2500 and 5000-7000 year intervals during the entire period from 40-45 ka BP to the Holocene (Johnsen et al. 1992, Dansgaard et al. 1993). We emphasize that in Fig. 19D we have constructed an alternative curve along transect 8, also shown in Fig. 17G, which is different from the recently published curve presented by Valen et al. (1996). Our alternative curve between 30 and 15 ka BP is not in conflict with the basic data presented by Valen et al. (1996), but fits better with the regional data we present and other regional data we refer to in this article (e.g. Fig. 19A, B, C & D).

The main interacting components that result in the triggering of an IRD event, or a 'Heinrich' event, are, as suggested by Andrews (1998): (i) changes in global temperature and accumulation; (ii) changes in relative sea-level at the tidewater margins of the world's ice sheets; and (iii) changes in the basal thermal regime of the ice close to these margins. All these components are probably important in association with ice-sheet collapse. The single component which we can best evaluate based on our data is the relative sea-level. We have found that the relative sea-level, thought to be driven mainly by glacial isostasy, was probably very high along the western Scandinavian ice-sheet margins during the ice-retreat intervals between 40 and 15 ka BP (Fig. 5; and Table 3). However, the relative sea-level in the North Sea area was very low at c. 30 ka BP (Rokoengen et al. 1993b), and the global eustatic sea-level was low during the entire 15-40 ka BP interval (e.g. Shackleton 1987). Our model of the glacial fluctu-

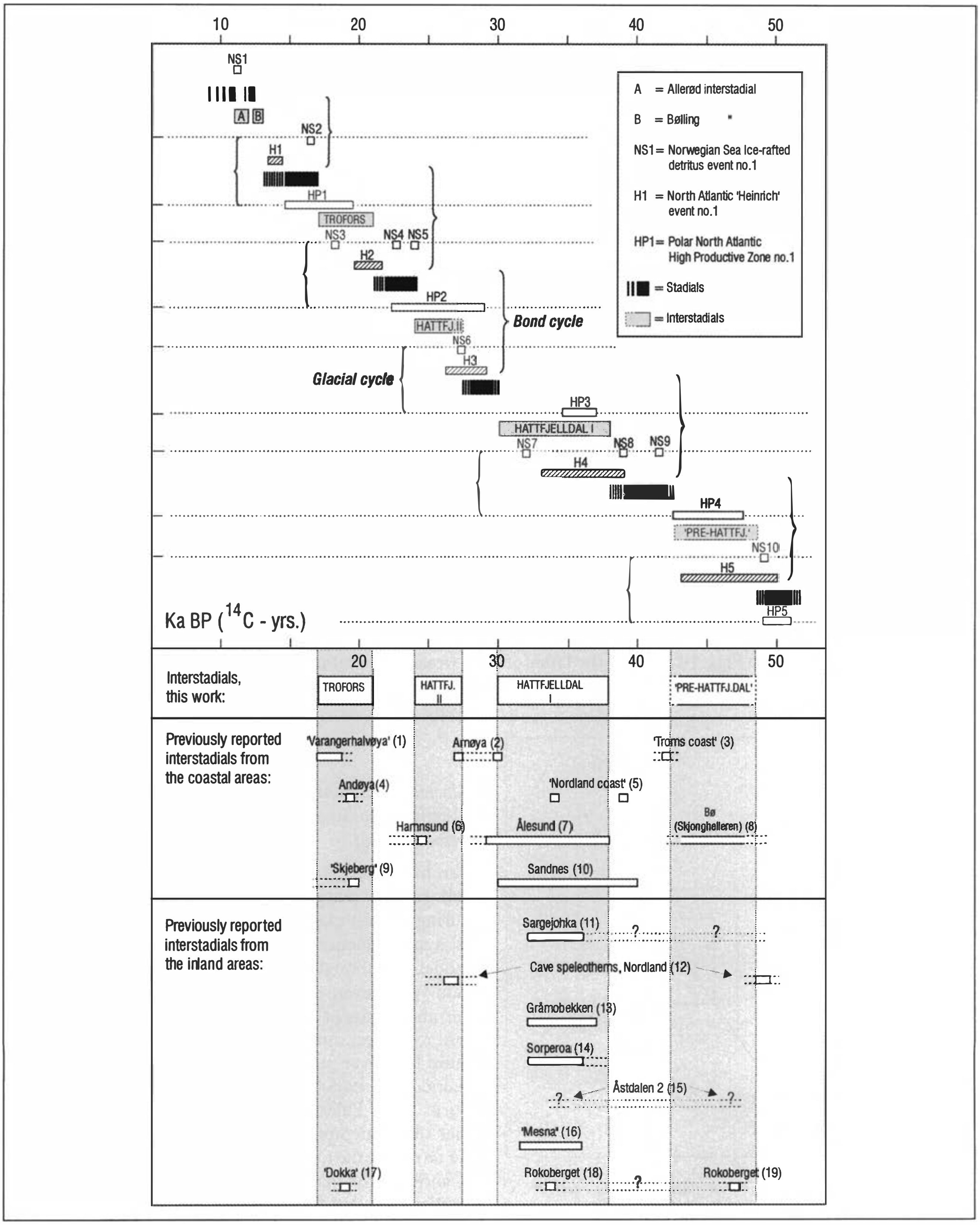


Fig.20: Age intervals and possible relationship between various sediments and events in Norway and adjacent seas. Norwegian Sea ice-rafted detritus 'NS' events are after Baumann et al. (1995), North Atlantic 'Heinrich' events are after Bond et al. (1993), and 'High Productive' zones are those described by Dokken & Hald (1996). Previously reported interstadials are from (1) Olsen et al. (1996); (2) Andreassen et al. (1985); (3) Vorren et al. (1981); (4) Vorren et al. (1988); (5) Rasmussen (1981, 1984); (6) Valen et al. (1996); (7) Mangerud et al. (1981), Larsen et al. (1987); (8) Larsen et al. (1987); (9) Olsen (1993a, b, 1995a, b); (10) Feyling-Hanssen (1971, 1974), Andersen et al. (1991); (11) Olsen (1988), Olsen et al. (1996); (12) Lauritzen (1991); (13) Thoresen & Bergersen (1983); (14) Bergersen et al. (1991); (15) Haldorsen et al. (1992); (16) Olsen (1993a, b, 1995a, b), Rokoengen et al. (1993a); (17) Olsen (1993a, b, 1995a, b); (18) and (19) Rokoengen et al. (1993a).

ations during the Mid- and Late Weichselian indicates a stadial-interstadial semi-cyclicity of 5-7 ka (Figs. 19D & 21), and we postulate a glacial isostatic loading operating on characteristic relaxation time-scales of c. 3 ka, similar to those suggested for the Laurentide ice sheet (Andrews & Peltier 1989). If this occurred, then the short time intervals available for ice growth and decay, and the contrasting sea-level records landward (fjord areas) and seaward (North Sea), suggest rapid relative sea-level changes. During such conditions, with rapid ice loading creating abrupt rises in relative sea-level, this component would probably give a major contribution to the collapse of the ice-sheet on the shelves, and, together with climatic ameliorations, trigger a cascade of responses along the coast, particulary in the major fjord areas. The instability of the marine-based parts would also have a significant destabilization effect on the westerly located land-based parts of the ice-sheet, and this is a major component of the conceptual ice-sheet growth and decay model ("yo-yo" model) presented above.

In the light of these considerations it is interesting to note that our data also fit well with the Barents Ice Sheet fluctuations during the last glacial maximum (Fig. 19B, D; and Hebbeln et al. 1994) and sediment core data from the North Atlantic and the Norwegian Sea (Bond et al. 1993, Baumann et al. 1995, Dokken & Hald 1996), as indicated in Figs. 19 & 20. In the latter of these illustrations (Fig. 20) we have used the dated intervals of ice-rafted detritus, 'NS' (Norwegian Sea IRD) and 'Heinrich' layers, and the dated zones of highly productive surface water (HP-zones), from the cited references. Fig. 20 illustrates how the ice-growth periods generally started during the open water 'HP-zones', mainly during the latter parts of these, and partly overlap with the ice-rafted detritus events and the 'Heinrich' layers. This is the case for all four major ice-growth intervals between 40 and 15 ka BP, and we take this as a strong argument for the potential of our approach, because the intervals of IRD in the Norwegian Sea (the NS events) are likely to have a close relationship with the glacier margin fluctuations along the Norwegian coast and onto the adjacent shelves (Fig. 19C, D; and Baumann et al. 1995).

An important consequence of these results is that the duration of glacier extension beyond the coastline to the the shelf areas must have been short, probably less than 2000-3000 years during each ice advance. Only NS3 and NS7 fit distinctly within the interstadials and do not overlap with major regional stadials (Fig. 20). This may suggest that these IRD events result from medium-size ice growth in the coastal mountains, with offshore glacier extension during very short intervals at c. 18.2 and 32 ka ago. With a longer duration of the glacier margin in an 'offshore' position, there would probably have been a weaker correlation than we have found between glacial growth periods and the Norwegian Sea IRD ('NS') events.

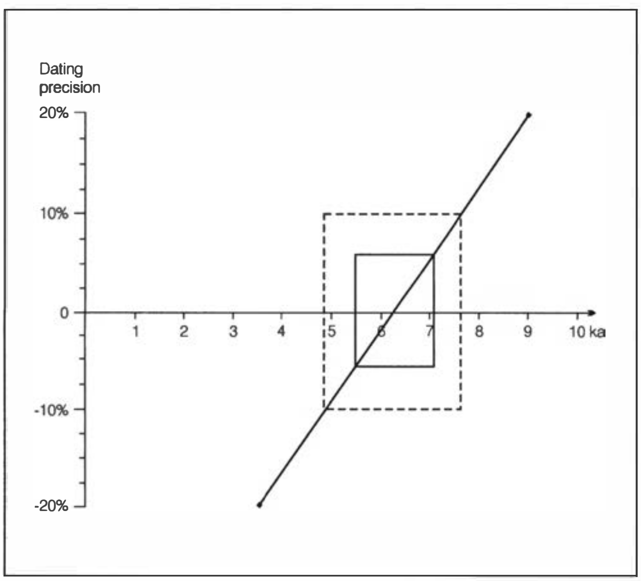


Fig.21: Length of semi-cyclicity of four glacial advance – retreat repetitions during the 40-15 ka BP interval. The dating precision is tested (Olsen et al., this volume) and found to deviate < 6 % from the arithmetric mean in 13 of 14 replicate tests. 6 %-precision of the arithmetic mean of the 'cycles' (6.2 ka) is indicated by the inner box, whereas the outer stippled box (included for comparison) indicate 10 % precision. The diagonal line indicates the same in one dimension, and this line is extended to even show 20 % precision, which is much less precise than any of the cases we have examined.

Glacial fluctuations – with comparison to southern and eastern Fennoscandia, including the Baltic Sea and northwestern Russia

The history of glacial fluctuations along the southern and eastern margins of the Fennoscandian ice-sheet during the last glacial maximum has to be reconsidered as a consequence of the new results and glaciation model. It is thought that the first ice advance during the Late Weichselian maximum did not reach to the southernmost parts of Sweden before 21 ka BP, and a significant ice retreat during the broad Late Weichselian maximum has never previously been reported from this area (Lundqvist 1986, Mangerud 1991a,b,c, Andersen & Borns 1994, Ehlers 1995). However, it is quite possible that the contemporary ice-margin during the inferred ice retreat in the Oslofjord-region at c. 19 ka BP (Figs. 1, 2) ended in the shallow Kattegat basin and southernmost Sweden, and that the ice-retreat did not include the Baltic Sea area during this period. We suggest that the ice sheet responded to a more westerly dominated climate regime during the first part of the last glacial maximum (LGM 1) by building major domes in the west. This changed to a configuration with a more easterly position for ice domes and the ice divides during the second, major Scandinavian/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 (Ljungner 1943, Lundqvist 1969, 1981, 1986, Bergersen & Garnes 1971, 1981, Garnes & Bergersen 1977, Fagerlind 1981, Olsen 1985a, 1988, 1993b, Hirvas et al. 1988, Houmark-Nielsen 1989, Kleman 1992, Ehlers 1996, Ehlers et al. 1995, Olsen et al. 1996). This indicates that a major part of the ice-sheet in eastern Fennoscandia remained as a more or less continuous ice sheet during the considerable ice retreat in the west at c. 19-20 ka BP. This is also in good agreement with recently documented evidence of the last glacial events in the Arkhangelsk area of Russia, which indicates a single last glacial maximum advance at c. 16 ka BP towards the eastern margins of the Weichselian Fennoscandian Ice Sheet (Larsen et al. 1999). A late LGM ice advance in the east, as reported from the Arkhangelsk area, suggests that ice build-up with ice-growth centres mainly in the western Fennoscandian mountains (e.g. during LGM 1, c. 22 ka BP) effectively prevented ice extension in the east. We speculate that the relatively high surface of the remaining ice-sheet over the eastern part of central and northern Fennoscandia after the c. 19-20 ka BP ice retreat in the west, may have been an important factor to initiate the rapid build-up of ice in the eastern part of Fennoscandia and neighbouring parts of Russia, which resulted in the maximum ice extension towards the east during LGM 2.

The glacial variations during the late Mid-Weichselian between 40 and 25 ka BP in the eastern parts of Fennoscandia (Sweden & Finland) are uncertain, but numerous ^{14}C-dated organic-bearing sediments and luminescence-dated, waterlain sub-till sediments have given numerical ages of 30-50 ka BP (Lagerbäck 1988, pers. comm. 1996, Lagerbäck & Robertsson 1988, Hirvas et al. 1988, Mejdahl 1990, 1991, Nenonen et al. 1996). These indicate possible ice-free conditions in extensive areas, even in the central and northern parts of eastern Fennoscandia, during the late Mid-Weichselian, but this interpretation remains speculative. It can be concluded that, should a late Middle Weichselian interstadial be represented in the data reported here, then this gives rise to a major correlation problem, because all interpretations of Weichselian ice-free intervals in northern and central parts of Sweden and Finland previously presented suggest an Early Weichselian age (Lundqvist 1986, Lagerbäck 1988, Lagerbäck & Robertsson 1988, 1996, Hirvas et al. 1988, Nenonen 1995, Nenonen et al. 1996, Satkunas & Robertsson 1996). 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), seriously challenge these interpretations 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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Appendix A

Geographical overview: description of ice-sheet fluctuations in different regions of Norway, based on stratigraphy and dates. Examples of stratigraphic successions are included in Figs. 3, 6-16.

Northern Norway.- Simplified stratigraphic successions from Skjellbekken (Pasvik) and Sargejohka, Finnmark (Pa and S in Fig. 1, and Fig. 3) indicate deposition of till during an ice advance towards the coast along *transects 1 and 2* (Figs. 1, 17A & 17B) between 34 and 26 ka BP. A disturbed palaeomagnetic signal in the lowermost part of the till at Sargejohka may possibly correlate with the Lake Mungo magnetic excursion at c. 28 ka BP. Therefore, the ice advance traced at Pasvik and at Sargejohka is thought to have occurred c. 28-30 ka BP. It is not known whether this ice advance crossed the coastline, but no correlative glacial unit has so far been reported from the outer coast in this region, except for one possible deposit at Arnøy, northern Troms (Ar in Fig. 1; Andreassen et al. 1985). Therefore, the 28-30 ka ice advance may well have ended at the coast in northernmost Norway. However, the same ice advance - or a younger one - towards the last glacial maximum position along transect 2 (Figs. 1 & 17B) crossed the coastline after c. 27 ka BP and reached the maximum position (LGM 1) on the continental shelf c. 21 ka BP. This is based on stratigraphies and ^{14}C-dating of redeposited marine mollusc shells in till from Arnøy, northern Troms (Andreassen et al. 1985), and from sediment cores from the southwestern Barents Sea shelf (Hald et al. 1990, Vorren et al. 1990). It is not known, however, whether this ice advance also reached a maximum position along transect 1 in the northeast, because only one major advance of the last glacial ice has so far been recorded at Varangerhalvøya (V in Fig.1), and this ice advance (LGM 2) probably occurred shortly after an interval of ice retreat or ice marginal stillstand at c. 17-19 ka BP (Table 1, and Olsen et al. 1996).

The stratigraphical information along *transect 3* (Figs. 1 & 17C) is based mainly on data from sub-till sediments in Urdalen (U in Fig. 1; Olsen et al., *this volume*), cave sediments in Tysfjord (T in Fig. 1; Nese 1996, S.E. Lauritzen, pers. comm. 1996), dating of mollusc shell in till at Langøya (Rasmussen 1984), and sedimentary successions from Andøya (A in Fig.1; Vorren et al. 1988, Møller et al. 1992, Alm 1993). The reported data indicate glaciomarine sedimentation at Bleik on the northernmost part of Andøya at c. 40 ka BP. However, there is so far no reported ice advance at 28-30 ka BP in these areas. The major ice advance to the maximum extension (LGM 1) is represented by the Bleik Moraines dated to c. 22 ka BP (Møller et al. 1992), and was followed by a rapid and considerable ice retreat with deposition of glaciomarine sediments on the northern part of Andøya by c. 19.5 ka BP (Vorren et al. 1988). In the Vestfjorden area, this ice retreat may have reached as far east as Tysfjord c. 20-21 ka BP (T in Fig.1, and Nese 1996), and subsequently, a glacial readvance occurred after c. 19 ka BP and reached almost to the maximum position (LGM 2). We have also used information from newly recorded late-glacial and Middle Weichselian sediments at the Hinnøya and Grytøya islands (Fig. 6) located in the central part of transect 3. The age range of these additional sediments is limited, but the occurrence of *in situ* marine sediments between shell-bearing tills in positions 120-160 m a.s.l., i.e. high above the postglacial marine limit (c. 70 m a.s.l.), is information of wider significance (see p.43) than just for the late-glacial period (Hinnøya) or an interval during the Middle Weichselian (Grytøya).

Key sites for reconstruction of a glaciation curve along *transect 4* (Fig. 17D) will be described in another report (Olsen in prep.a). The data from these sites indicate an ice retreat almost to the border between Norway and Sweden at c. 35-39 ka BP (R in Fig. 1, and Fig. 7), and then an ice advance towards the outer coast occurred shortly after c. 28.4 ka BP (Fig. 8). This was followed by a limited ice retreat, and subsequently, two major ice advances (LGM 1 and LGM 2) towards the LGM position. It is not known how far landwards the ice retreated in this area between these two major advances, but the ice retreat may well have ended (with the ice margin) in the inner fjord area during minimum extension.

Simplified stratigraphic successions with key information along *transect 5* (Fig. 17E) have been presented by Olsen (1997a). Tills and ^{14}C-ages of underlying and intercalated organic-bearing sediments (Fig. 9) indicate ice advances between c. 28 and 29.4 ka BP, between 23.5 and 19.5 ka BP, and after 19.5 ka BP, and considerable ice retreat almost to the Swedish border between these ice advances (Hattfjelldal interstadial II and Trofors interstadial), and also prior to c. 29.4 ka BP (Hattfjelldal interstadial I). The numerical ages obtained from the lower stratigraphical units at Fiskelauselva (Fig. 9) are supported by the occurrence of a disturbed palaeomagnetic signal which may possibly correlate with the Lake Mungo magnetic excursion (Fig. 3, and Løvlie 1994). This palaeomagnetic excursion is also thought to be represented in cave sediments deposited during ice-dammed or ice-cover conditions a few kilometres to the southwest of this site (Valen et al. 1997).

The proxy climatic record from the interstadial complex c. 30-40 ka ago, i.e. the interval named Sargejohka and Arnøya interstadials along transect 2, 'Nordland coast' interstadial along transects 3 - 5, and Hattfjelldal (I) interstadial in the inland along transect 5, indicate sub-Arctic conditions. Characteristic vegetational elements were dwarf birches (*Betula nana*), fern (Pteridophyta and Polypodiaceae) and wormwood (*Artemisia*) in the inland areas, whereas marine mollusc species as *Arctica islandica*, indicating temperate Atlantic water, occurred along the coast at least as far north as to the 67°N latitude (Olsen et al. 1996, Olsen & Selvik in prep., Olsen in prep.a; and Table 2, TUa-1239 & TUa-1241).

The climatic conditions that prevailed during the interval from 21 to 19 ka BP at Andøya in the outer coastal part along transect 3, are inferred from pollen-stratigraphical data obtained from lacustrine sediments and thought to represent low to middle Arctic, interstadial conditions (Vorren et al. 1988, Alm 1993). This was followed by climatic deterioration and glacial advance at c. 18.8-18.5 ka BP, climatic amelioration at c. 18 ka BP, and renewed climatic depressions with glacial advances at c. 16.8-16 and after 15 ka BP. The main humidity character, also based on the vegetational indicators, of the interval from c. 22 to 12 ka BP is described as arid by Alm (1993).

Proxy climatic indicators from the Hattfjelldal (II) interstadial dated to c. 24-27 ka BP and the Trofors interstadial dated to c. 17-21 ka BP, which is represented in the inland of Nordland, are too sparse to say much more than that these intervals were probably characterized by partly ice-free Arctic to sub-Artic conditions, with considerable glacier volumes possibly remaining in some highland valleys and mountain areas.

Central Norway.- At Blåfjellelva (B in Fig. 1; and Fig. 17F) along *transect 6*, and close to the border between Norway and Sweden in central Norway, ^{14}C-datings and sediments in river sections indicate two major ice advances during the last glacial maximum period. These occurred between c. 20 and 22 ka BP, and shortly after 17.8-19.7 ka BP, as indicated in three simplified stratigraphical logs (Fig. 10). Similar stratigraphic successions and ^{14}C-datings are recorded from Namdalen further to the NW, and also from the Selbu area along *transect 7* to the SW (Se in Fig. 1). The simplified logs from two such sites indicate till deposition during ice advances at c. 30 ka BP, between 29.3 and 28.7 ka BP, between 25.2 and 19.9 ka BP, and shortly after c. 16.9-18.8 ka BP (Fig. 11). Significant ice retreats between these advances reached at least to Selbu, and probably several kilometres further landwards as indicated from stratigraphic successions to the east (Stærneset) and southeast (Flora) of Selbu. Stratigraphy and ^{14}C-datings from Grytdal (Fig. 12, and G in Fig. 1) indicate deposition of till during ice advances between c. 39.5 and 38.5 ka BP, between 37.2 and 28.4 ka BP, between 23.7 and 19 ka BP, and shortly after c. 19 ka BP. At Flora (Fig. 12, and F in Fig. 1), a complex glacial stratigraphy and the average numerical age of eight ^{14}C-datings indicate a major ice advance shortly after c. 17.6 ka BP.

Sedimentary successions and ^{14}C-datings from the coast along transects 6 and 7 (Fig. 1) indicate one or possibly two ice advances at Sitter (Si) between c. 30.2 and 21.1 ka BP, followed by a considerable ice retreat phase between c.18.7 and 21.1 ka BP. Subsequently, the last major ice advance at Langstrandbakken (La) occurred after c. 18.7 ka BP (Fig. 13). Glacial deposits indicating ice marginal oscillations during the last deglaciation on the outer Trøndelag coast are dated to 12-12.5 ka BP (Sveian & Solli 1997, Olsen & Riiber, in press), as at Sitter (Fig. 13).

The pollen record from central Norway for the interstadial intervals between 40-45 and 15 ka BP is so far very sparse, and cannot provide precise data on the palaeoclimate conditions. However, marine molluscs of this age from the coastal areas and palaeomagnetic susceptibility from soils developed during the Middle to Late Weichselian interstadials, give some background data for preliminary palaeoclimatic interpretations. For example, shell fragments of the temperate Atlantic water indicator *Arctica islandica*, dated to c. 37-40 ka BP, have been found in sub-till sediments at the coast of Trøndelag, along transect 6 (Bergstrøm & Riiber, in press), and the palaeorainfall, based on palaeomagnetic susceptibility data, is inferred to be generally low (arid) during all Middle and Late Weichselian interstadials in central Norway (Olsen 1997b, Olsen et al., *this volume*).

West and southwest Norway.- Along *transect 8* (Figs. 1 & 17G) Larsen et al. (1987), Larsen & Ward (1992) and Valen et al. (1996) have reported stratigraphies and various dates from cave sediments and fjord valley deposits indicating several ice advances and retreats on the coast in the period 12-45 ka BP. However, they have not reported field evidence or dates supporting a double advance model for the last glacial maximum between 15 and 25 ka BP. Firstly, an ice advance crossed the outer coastline at c. 40 ka BP (Larsen et al. 1987), and then the ice retreated by c. 29-38 ka BP, an episode known as the Ålesund interstadial (Mangerud et al. 1981). Subsequently, a second ice advance crossed the outer coast at c. 28-29 ka BP (Larsen et al. 1987). This advance, which is considered to represent the LGM by e.g. Sejrup et al. (1999), was followed by an ice retreat phase at c. 24.4-24.5 ka BP, known as the Hamnsund interstadial (Valen et al. 1996), and finally, a single ice advance during the traditional LGM-interval (15-25 ka BP). The latter interpretation is not compatible with the glacial reconstruction along other transects presented here, where two major ice advances are separated by a considerable ice retreat during the last glacial maximum at c. 20-18 ka BP (Olsen 1997a), with the exception of transects 1 and 2, where there is evidence for only a single glacial maximum ice advance. However, even in the coastal zone along transect 8, at least one conventional ^{14}C-dating of c. 20 ka BP has been obtained from soil layers protected underneath boulders in the blockfield of the mountain Gamlemsveten (J. Mangerud, unpublished material 1981), indicating ice retreat and considerably reduced ice volume subsequent to a more extensive phase of ice advance. This is also in agreement with the ice-sheet model presented by Nesje et al. (1988, 1994), who describes an ice sheet with a reduced ice-surface elevation during the youngest part of the last glacial maximum. In our opinion, the data published from this region so far, allow alternative glaciation curves to be constructed. We have therefore presented an alternative curve for the period between 30 and 15 ka BP, using all of the data mentioned above (Fig. 17G).

At Kollsete in the vicinity of Sogndal in the inner part of Sognefjorden (K in Fig. 1), organic 'bulk' material from glaciolacustrine sediments, covered by a thick till, and overlying gyttja deposits correlated with the Bø interstadial (Andersen et al. 1983, Aa & Sønstegaard

1997), has been AMS-^{14}C dated to c. 22.5 ka BP (Table 1). This indicates that the last major ice sheet advanced in the Sognefjord area at or after c. 22.5 ka BP.

At Jæren, on the southwesternmost tip of Norway (Fig. 1), marine clays lying far (up to 250 m) above the postglacial marine limit have been described by several authors (e.g. Grimnæs 1910, Bergersen & Follestad 1971, Feyling-Hanssen 1971, 1974, Garnes 1976). These clays were deposited during the Sandnes interstadial, dated to c. 30-40 ka BP (Feyling-Hanssen 1971, 1974, Andersen et al. 1991).

The ice-sheet oscillations during the last glacial maximum phase in the area between Sognefjorden and Jæren are not recorded from onland sites; only offshore data indicate ice advances shortly prior to c. 22-23 ka BP and after 18.8 ka BP, separated by an ice retreat interval at 18.8-22 ka BP (Rise & Rokoengen 1984, Sejrup et al. 1994). However, onland data indicate that two major ice advances crossed the Jæren area after the Sandnes interstadial. The oldest of these was trending northwards across the area from the Norwegian Channel, whereas the younger ice advance crossed the area from the east to the North Sea in the west (Janocko et al. 1998). At Egersund (E in Fig. 1) in the south, which is reported by Bakkelid & Skjøthaug (1984) and Anundsen & Gabrielsen (1990) as a litho-isostatic subsidence area (0.3 – 1mm/yr), marine sediments located less than 7 m a.s.l. and dated to slightly older than 18.5 ka BP indicate an interval of reduced ice extension in the middle of the last glacial maximum period. These sediments bear no sign of having been overridden by glaciers, which might suggest that the Egersund-area has been ice-free since 18.5 ka BP (Schistad & Anundsen 1994). However, this is in conflict with all modern reconstructions of the Late Weichselian Scandinavian ice-sheet fluctuations, which suggest continuous ice-cover in this area during the Late Weichselian from the LGM interval to the late-glacial period (e.g. Sejrup et al. 1998, 2000).

Climatic conditions during the Ålesund interstadial (29-38 ka BP) are well documented from the Skjonghelleren cave (Skj in Fig. 1), with the occurrence of a rich assemblage of fossil bones from sea and land animals, as well as bones of birds (Larsen et al. 1987). Based on these fauna remains, the prevailing climate in this interval at the coast along transect 8 (Fig. 1) is thought to have been similar to the coastal area of northernmost parts of Norway today (Larsen et al. 1987). The climatic conditions that prevailed during the Hamnsund interstadial (c. 24.4-24.5 ka BP), also at the coast along transect 8, are not known (Valen et al. 1996), as the reported finds of bones from seal and little auk may indicate a wide range of climatic conditions, from boreal to Arctic.

Southeast Norway.- In Herlandsdalen (H along *transect 9* in Fig.1), a tributary valley to the major valley Numedalen in southeast Norway, Roaldset (1980) reported sub-till clay which, based on the lanthanide distribution in the clay, she inferred to be of marine origin (see 'Methods' and 'High sea-levels' in the main text). She also correlated the interval of clay deposition with the Sandnes interstadial, dated to c. 20-50 ka BP (Feyling-Hanssen 1971, 1974), which was later dated more precisely to c. 30-40 ka BP (Andersen et al. 1991). New reconnaissance studies in this area by the present authors (Bergstrøm & Olsen; cf. Bergstrøm 1999) have provided new AMS-^{14}C dates which support and extend Roaldset's (1980) ideas. In Herlandsdalen, and at Passebekk, a tributary valley to the Numedalen valley (Lågendalen) a few kilometres further upstream in a proximal direction relative to the ice margin oscillations, tills indicate ice advances shortly after c. 28.3-28.6 ka BP, between 23.3 and 21 ka BP, and after c. 21 ka BP (Fig. 14). Inferred marine and glaciofluvial sediments deposited prior to and between these advances indicate significant ice retreat phases.

Larger ice-sheet fluctuations are implied by sedimentary evidence, dated by AMS-^{14}C dating from Dokka, Rokoberget and Lillehammer further landward in central southeastern Norway in the NE (D, Ro & L in Fig. 1, and Figs. 15 & 17H). In this area, tills with confining radiocarbon dates indicate ice advances shortly after c. 31-32.3 ka BP, between 26.8 and 18.9 ka BP, and after 18.9 ka BP. Clastic dykes starting at the base of the uppermost till and penetrating the underlying till at Mesna and Stampesletta, Lillehammer, give radiocarbon ages of c. 16 ka BP (Fig. 15, and Table 1). This indicates a last major ice advance approximately at that time, a conclusion supported by similar evidence from the coast at Skjeberg (Sk in Fig. 1). In the latter area the last major ice advance seems to have crossed the coastline shortly after c. 16.8-19.5 ka BP (Table 1).

In the area of the present water-shed and the classical glacial maximum ice divide zone in central southern Norway, sediments and dates indicate a major ice retreat during the Gråmobekken and Sorperoa interstadials c. 30-40 ka BP (Thoresen & Bergersen 1983, Bergersen et al. 1991). These intervals may correlate with the Ålesund and the Sandnes interstadials recorded on the west and southwest coast, respectively (Mangerud et al. 1981, Andersen et al. 1991), and they may also correlate with the Hattfjelldal interstadial I in Nordland (Olsen 1997a).

Interstadial 2 in Åstdalen, which is located at 600-700 m a.s.l. and some 20 km NE of Lillehammer (L in Fig. 1), is represented by gravel deposits, subaerial pedogenesis and an ice-wedge cast, and is inferred to have been a cold interval with permafrost (Haldorsen et al. 1992). The age of this interstadial is unknown, but it follows a glacial advance after the early Middle Weichselian Åstdalen interstadial 1. It may therefore also correlate with the Gråmobekken - Sorperoa - Hattfjelldal (I) interstadial.

New studies in the eastern Folldal area (Fo in Fig. 1) have provided data (Olsen in prep.b), including tills, glaciolacustrine sediments and datings, which indicate an ice advance towards the last glacial maximum extension shortly after c. 23.3-26.3 ka BP (Fig. 16). An U/Th-dating of c. 22 ka BP (calendar years) of a calcareous concretion at Gråbekken might have indicated ice-free conditions in the interval 18-20 ka BP (^{14}C-years), but the sample is considered unreliable because of Th contamination (very low $^{230}Th/^{232}Th$-ratio). However, based on stratigraphic correlations and matching of curves also the magnetic susceptibility pattern of the uppermost part of the sub-till sediments at the nearby locality Gråbekken supports the idea of ice-free conditions in the 18-20 ka BP interval (Olsen 1997b). Nevertheless, we consider these results to be provisional and the measurements should be re-examined and extended before a final conclusion in terms of age interpretation should be given. Therefore, we conclude that there is so far no proper record, of any trace of ice-free conditions indicating ice retreat in this area in the middle of the last glacial maximum (15-25 ka BP). This is contrary to the evidence and indications dealt with for almost all other areas described in this article. Consequently, the southeast central area around the present water-shed and the classical last glacial maximum ice divide zone may be one of very few extensive areas in Norway where an ice body of a considerable size remained during the short-lived interstadial c. 18-20 ka BP, which is named the Andøya interstadial at the outer coast of northernmost Nordland (Vorren et al. 1988) and the Trofors interstadial in the inland of southern Nordland (Olsen 1997a).

The indicators of proxy climatic conditions during the Middle and Late Weichselian interstadials in southeast Norway encompass mainly pollen and macroscopic plant remains from Gråmobekken (c. 32-37 ka BP) and Rokoberget (c. 34 ka BP) interstadial sediments (Thoresen & Bergersen 1983, Rokoengen et al. 1993a). These indicate grass-dominated, almost treeless vegetation developed during sub-Artic to Arctic-alpine, tundra-like conditions.

Palaeomagnetic susceptibility data from Folldal from soils correlated with the interstadial c. 26 ka BP, and possibly also with the youngest interstadial, c. 20 ka BP, indicate arid conditions during this/these interval(s). The palaeotemperature from these intervals in southeast Norway are not known.

Appendix B

Summary of the main stratigraphic evidence

- The majority of 136 AMS-^{14}C dates of organic-bearing tills and sub-till waterlain sediments with TOC content of 0.1-1.8 % were carried out on the alkaline insoluble organic fraction, with less than 6 % of the dates considered to give ages significantly too young (Table 1; and Olsen et al., *this volume*).
- The major glacial variations in the interval 15-40 ka (^{14}C) BP, summarized in six maps (Fig. 18) and nine transects from inland to coast (Figs. 1, 17 & 19D), suggest the existence of extensive ice-free areas during several intervals, which alternated with periods of rapid ice-growth. Data mainly from other sources are used in two of the curves (3 & 8). A regional description of the glacial history, including examples of Quaternary stratigraphy and dates from key sites used during these constructions, are presented briefly in Appendix A and illustrated in Figs. 3, 6 - 16.
- All the major glacial fluctuations are represented in each region and along each transect (Fig. 17), except for the glacial advance dated to around or shortly before 40 ka BP. Only indirect evidence for this episode, in the high sea-levels north of the Arctic Circle, has been found, suggesting that glacial extension during this event was not large, but locally with considerable ice-thickness in the north.
- Stadials occurred at (1) around or shortly before 40 ka BP, following an interstadial dated to older than c. 43 ka BP, (2) c. 28-29 ka BP, (3) c. 21-24 ka BP, and (4) c. 14.5-17 ka BP.
- The three intervening interstadials are preliminary named *the Hattfjelldal interstadial I (30-39 ka BP)*, the *Hattfjelldal interstadial II (24-27 ka BP)*, and the *Trofors interstadial (17-21 ka BP)*. These are represented by waterlain sediments and radiocarbon-dated organic materials at coastal sites, and also at several sites in the inland areas of Norway (Olsen 1997a).
- The climate during these interstadials is thought to have been cold and dry during the two youngest intervals (Olsen 1997b), whereas temperate Atlantic surface water, reflected in the records of the mollusc *Arctica islandica*, prevailed during the Hattfjelldal interstadial I, c. 35-38 ka BP, and reached at least north to 67°N along the coast (Olsen in prep.a) at the same time as dwarf birches and ferns grew in the Hattfjelldal inland region in the southeastern part of Nordland (Olsen & Selvik in prep.). Low to middle Arctic, interstadial conditions prevailed from 21 to 19 ka BP at northern Andøya, northern Nordland (Alm 1993), whereas sub-Artic to Arctic-alpine tundra conditions seem to have dominated in most parts of Norway during the interstadial complex between c. 30-38 ka BP. The climate during the interval 24-27 ka BP (Hattfjelldal interstadial II) is thought to have been colder than during the older interstadial (Hattfjelldal interstadial I), but possibly slightly warmer than during the youngest interstadial (Trofors interstadial).
- Marine shells at the coast and traces of marine organisms in sediments from inner fjord and adjacent inland areas indicate high relative interstadial sea-levels in most of the period 15-40 ka BP (Table 3, and Figs. 4-5). Some of these data show relative sea-levels much higher than those inferred from the late-glacial - postglacial marine limit in these areas (Olsen & Grøsfjeld 1999), and these data may illustrate the overall deglaciation sea – land dynamics at the coast of Norway during most of the last glaciation, i.e. rapid ice-retreat during phases of considerable glacial isostatic downwarping of the crust of the Earth, and, consequently, very high contemporary relative sea-levels.

Appendix C

Evaluation of dates:

Testing of AMS-^{14}C dating of organic-bearing sediments (*in situ* or redeposited in till). Two test methods have been used and the results are evaluated here. More tests are included in Olsen et al. (*this volume*).

Test no. 1

Description : Dating of different organic fractions (INS, insoluble; SOL, soluble; dichlormethane and hexane extractions).

Result: AMS-^{14}C (INS): 77 of 81 dates from inferred subaerially deposited sediments (in situ or redeposited in till) with no visual traces of oxidation give numerical ages which are supposed to be correct (within +/- 10 % of inferred age) based on stratigraphy and general considerations on the glacial history. AMS-^{14}C (SOL): 10 of 17 dates from inferred subaerially deposited sediments (in situ or redeposited in till) give significantly too low numerical ages. AMS-^{14}C (dichlormethane): 13 of 13 dates give significantly too low numerical ages, all of this fraction derive from secondary input. AMS-^{14}C (hexane): 2 of 2 dates give possible correct ages, also based on general considerations.

Interpretation and evaluation: AMS-^{14}C (INS): Most stable dating results, possible less than 6 % with significantly too low age estimates. AMS-^{14}C (SOL): Often contaminated by young carbon in cases where small amounts of material (< 0.90 mg C) are used for AMS measurements; unreliable as a single dating fraction, but may be useful together with dating of other fractions, e.g. the INS-fraction. AMS-^{14}C (dichlormethane): 100 % secondary input through groundwater circulation. Useful if the objective is to test whether such input has occurred or not occurred. AMS-14C (hexane): Potentially good for dating of preserved traces of marine organisms.

Test no. 2

Description: Matching of glacial curves, postulating that the glacial events in the north and the south occurred approximately contemporarily, i.e. events occurred within the range of dating precision of +/- 3-5 %, which is approximately +/- 1000 years around 20 ka BP.

Result: Glacial curves along nine transects (see Figs.1, 17 and 19D). The curves are based mainly on numerical ages achieved from AMS-^{14}C dating of INS-fractions of sediments, and the major ice-advances read from the curves match within +/- 2000 years or less in most (8 of 9) of the curves.

Interpretation and evaluation: A very good match between eight of nine glacial curves strongly suggests that the majority of the numerical ages achieved are insignificantly biased and probably almost correct. However, this conclusion is fully based on the validity of the postulate of approximately contemporary events in the N and the S. The only significant deviation from this conclusion is the curve from Møre, western Norway (no.8, Figs.1 & 17G), which is also shown to deviate from other proxy climatic and glacial variation records from adjacent areas (Fig.19). Therefore, we have presented a better-fit alternative curve for this area (Fig.17G).