Methods and stratigraphies used to reconstruct Mid- and Late Weichselian palaeoenvironmental and palaeoclimatic changes in Norway

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A review is presented on the comprehensive stratigraphic database and the methods used for palaeoclimatic and palaeoenvironmental interpretations in Norway during the Mid- to Late Weichselian time interval. The reconstructions are based on 9 transects from inland to coast and are underpinned by more than 300 dates, which provide a coherent chronology of the stratigraphic successions and of the main events. Raised marine sediments suggest that considerable glacial isostasy combined with ice-sheet instability affected several areas, the sea reaching far inland during phases of significant ice retreat dated to between 45 and 17 ka (^{14}C) BP. Magnetic susceptibility records obtained from paleosols proved useful both as a tool for correlation and as a palaeoprecipitation indicator, a parameter that is notoriously difficult to estimate. These data, in combination with biostratigraphic information (animal bones, shells, dinoflagellates, pollen, macro plant remains, etc.), suggest tentatively that the climatic conditions during the interstadials between 45 and 17 ka (^{14}C) BP varied between dry low and middle Arctic, dry subarctic tundra to more humid subarctic, and Boreal conditions during the older part of this interval.

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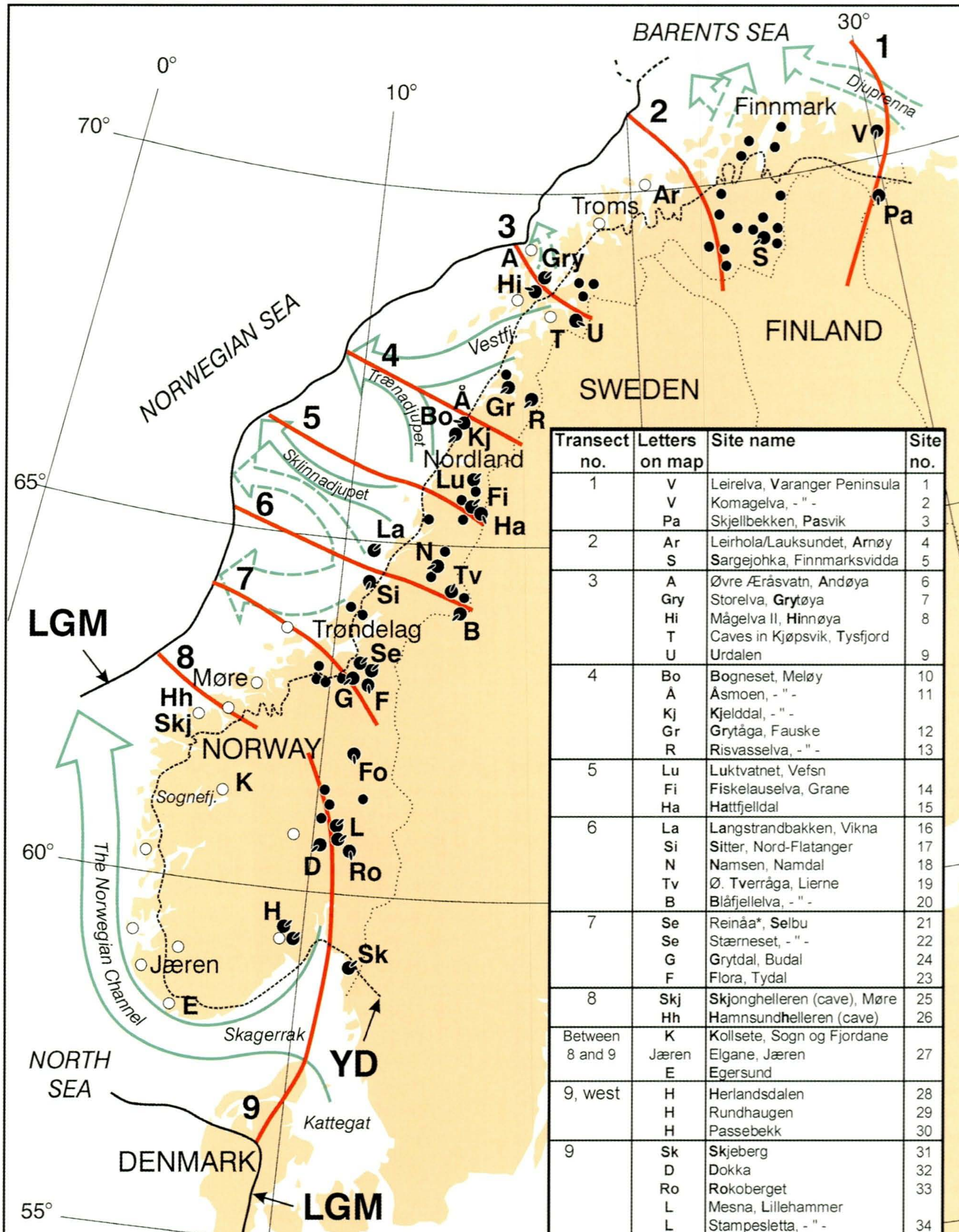
Introduction

In this paper we describe the methodology and key stratigraphies (Fig. 1) underpinning new palaeoenvironmental and palaeoclimatic reconstructions for the Mid- and Late Weichselian of onshore areas of Norway. The dating methods employed, the regional glacial history and reconstructions of curves representing glacier fluctuations are presented in two linked papers (Olsen et al. 2001a, b).

The main aim of this work has been to review the stratigraphical data available in order to better constrain reconstructions of glacial, palaeoenvironmental and palaeoclimatic variations in Norway during the time interval 40-15 ka BP. The relative importance of the data used, in terms of numbers of localities and lithological units, is illustrated in Fig. 2 (see also Table 6). The regional timing of events is based mainly on ^{14}C-dating of bulk organic sediments, supplemented with a significant contribution of ^{14}C-dates obtained from shells and other organic-bearing materials (Olsen et al. 2001a). The most important data used for palaeoclimatic and palaeoenvironmental interpretations are pollen 'assemblage' data and marine mollusc assemblages, fairly robust data for these proxies being available from c. 20% of the localities.

The stratigraphical data have been synthesised from records obtained from all over the country, but the reconstructions focused along 9 transects from inland to coast (Fig.1). Most of the original data came to light as a result of Quaternary stratigraphical mapping by the Geological Survey of Norway. Information from other published sources, particularly those from the areas covered by profiles 3 and 8, is also employed. The most comprehensive data-sets for the time range 22-15 ka BP, including detailed microfossil (pollen, insects, etc.) and macrofossil (macroalgae) records, are those from Andøya (K.-D. Vorren 1978, T.O. Vorren et al. 1988, Alm 1993). These data are included in the database both as primary information for the reconstructions and as a control dataset (Table 4: Olsen et al. 2001a). Dates of mammoth bones indicate ice-free conditions in Southeast Norway c. 30-40 ka BP (Heintz 1974, Bergersen & Garnes 1981, Bergersen 1991, Idland 1992), and data from cave sediments covering the time range from 20 to more than 45 ka BP from North Norway and West Norway have also been considered (Larsen et al. 1987, Lauritzen et al. 1996, Nese 1996, Nese & Lauritzen 1996, Valen et al. 1996, 1997). Middle Weichselian mollusc shells, foraminifera and pollen 'assemblages' from highly uplifted *in situ* marine sediments at Høgjæren, Southwest Norway (Andersen et al. 1987, 1991, Janocko et al. 1998), have also been included (Table 4: Olsen et al. 2001a).



Transect no.	Letters on map	Site name	Site no.
1	V	Leirelva, **V**aranger Peninsula	1
	V	Komagelva, - " -	2
	Pa	Skjellbekken, **Pa**svik	3
2	Ar	Leirhola/Lauksundet, **Ar**nøy	4
	S	**S**argejohka, Finnmarksvidda	5
3	A	Øvre Æråsvatn, **A**ndøya	6
	Gry	Storelva, **Gry**tøya	7
	Hi	Mågelva II, **Hi**nnøya	8
	T	Caves in Kjøpsvik, Tysfjord	
	U	Urdalen	9
4	Bo	**Bo**gneset, Meløy	10
	Å	**Å**smoen, - " -	11
	Kj	**Kj**elddal, - " -	
	Gr	**Gr**ytåga, Fauske	12
	R	**R**isvasselva, - " -	13
5	Lu	**Lu**ktvatnet, Vefsn	
	Fi	**Fi**skelauselva, Grane	14
	Ha	**Ha**ttfjelldal	15
6	La	**La**ngstrandbakken, Vikna	16
	Si	**Si**tter, Nord-Flatanger	17
	N	**N**amsen, Namdal	18
	Tv	Ø. **Tv**erråga, Lierne	19
	B	**B**låfjellelva, - " -	20
7	Se	Reinåa*, **Se**lbu	21
	Se	Stærneset, - " -	22
	G	**G**rytdal, Budal	24
	F	**F**lora, Tydal	23
8	Skj	**Skj**onghelleren (cave), Møre	25
	Hh	**H**amnsund**h**elleren (cave)	26
Between 8 and 9	K	**K**ollsete, Sogn og Fjordane	
	Jæren	Elgane, Jæren	27
	E	**E**gersund	
9, west	H	**H**erlandsdalen	28
	H	**H**undhaugen	29
	H	**H**assebekk	30
9	Sk	**Sk**jeberg	31
	D	**D**okka	32
	Ro	**Ro**koberget	33
	L	Mesna, **L**illehammer	
	L	Stampesletta, - " -	34
	Fo	Gråbekken, **Fo**lldal	35
	Fo	**Fo**lldal	36

Fig. 1. 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 Last Glacial maximum (LGM) and the Younger Dryas (YD) stadial, profiles for the glaciation curves, letters indicating stratigraphical sites referred to in the inset table and in the main text, and position of the most prominent ice streams (the least pronounced indicated by broken lines).

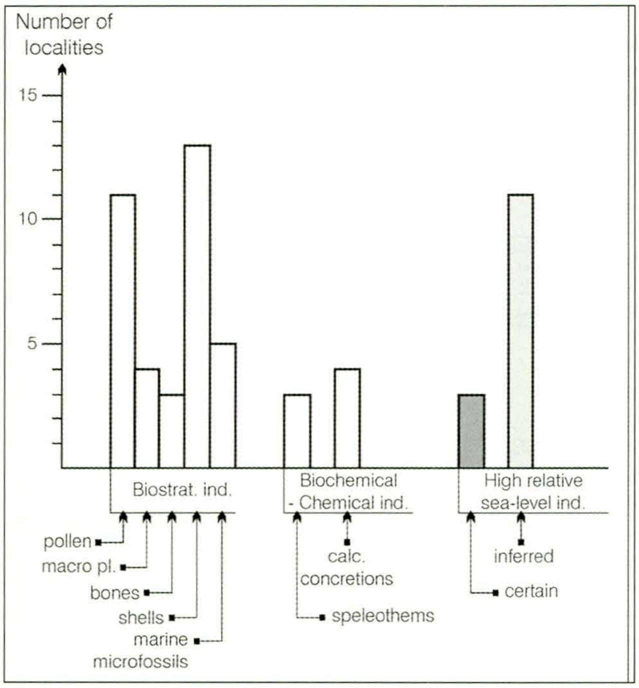


Fig. 2. Distribution of palaeoclimatic and palaeoenvironmental indicators used in our study. Most indicators are used in only one or two stratigraphical units at each site, but shells occur often in several units, e.g., at Bogneset, northern Norway, where shells occur in 5 different stratigraphic units.

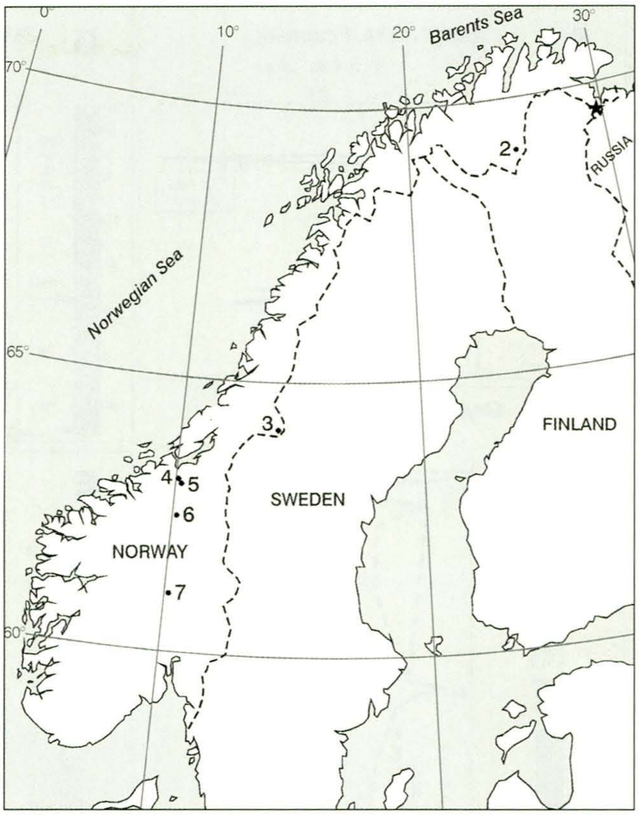


Fig. 3. Map with location of modern soil and paleosol sites referred to in this study. Names of sites are: ★= Pasvik (four modern soil sites), 2= Sargejohka, 3= Blåfjellelva, 4= Støren (modern soil site), 5= Grytdal, 6= Folldal; and 7= Mesna (modern and paleosol site). After Olsen (1997b).

Indicators of palaeoclimatic and palaeoenvironmental conditions

Magnetic susceptibility

Pedogenic magnetic susceptibility (MS) is a specific soil property which has been used to record and correlate paleosols, even within the context of Norwegian glacial stratigraphic sequences (Olsen 1997b, 1998; Figs. 3 & 5). It may also be an important indicator of proxy climate, as suggested for soil horizons in loess successions in eastern Europe and China (Kukla et al. 1988). The increase in MS values, which frequently occurs in the transition between loess and loess soils, occurs in a similar manner, independent of scale, in studied profiles from Norwegian soils developed in diverse parent materials (Olsen 1997b, 1998).

We have used MS measured in podsols which have developed under comparable topographical conditions in different areas, in a preliminary manner as an indicator of palaeorainfall (Olsen 1997b; Fig. 4 & Table 1). The general idea of this approach is that heavy minerals, including magnetite and other magnetic minerals, are gradually enriched downwards, e.g. in the B-horizon of podsols, during repeated rainfall events. The more rain that falls on the ground and the more times that water drainage or seepage through the sediments occurs, the more magnetic minerals accumulate in the B-horizon, and therefore, the higher MS values will be produced. In addition, there may exist a component of fine-grained magnetic minerals (e.g., maghemite and magnetite) which result from general pedogenetic processes (e.g., Banerjee 1995). It is conceivable that repeated rainfall cycles and drainage through the soils, followed by intervals of dry conditions, will increase the rate of the soil-forming processes, and therefore also increase the production of magnetic minerals. For details of the method, see Olsen (1998).

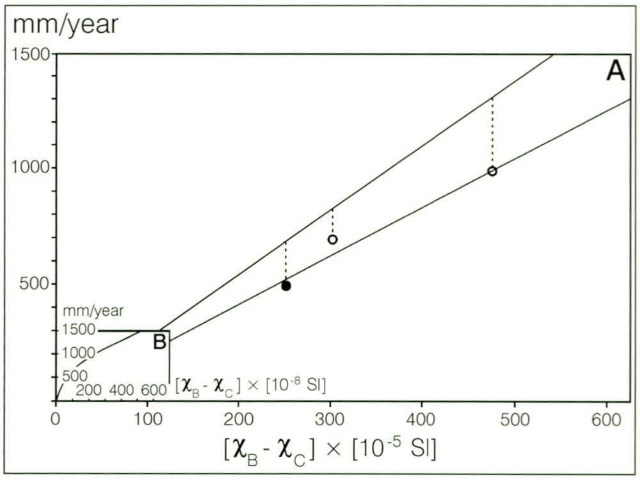


Fig. 4. (A) Suggested approximately linear relationship between modern rainfall (precipitation) and pedogenic magnetic susceptibility of young soils from single sites (open circles) and averaged value from several sites (closed circle). (B) Similar curve based on more comprehensive data from loess soils in the temperate zone around the world; inferred from data in Maher & Thompson (1995). χ_B and χ_C are explained in Table 1. After Olsen (1997b).

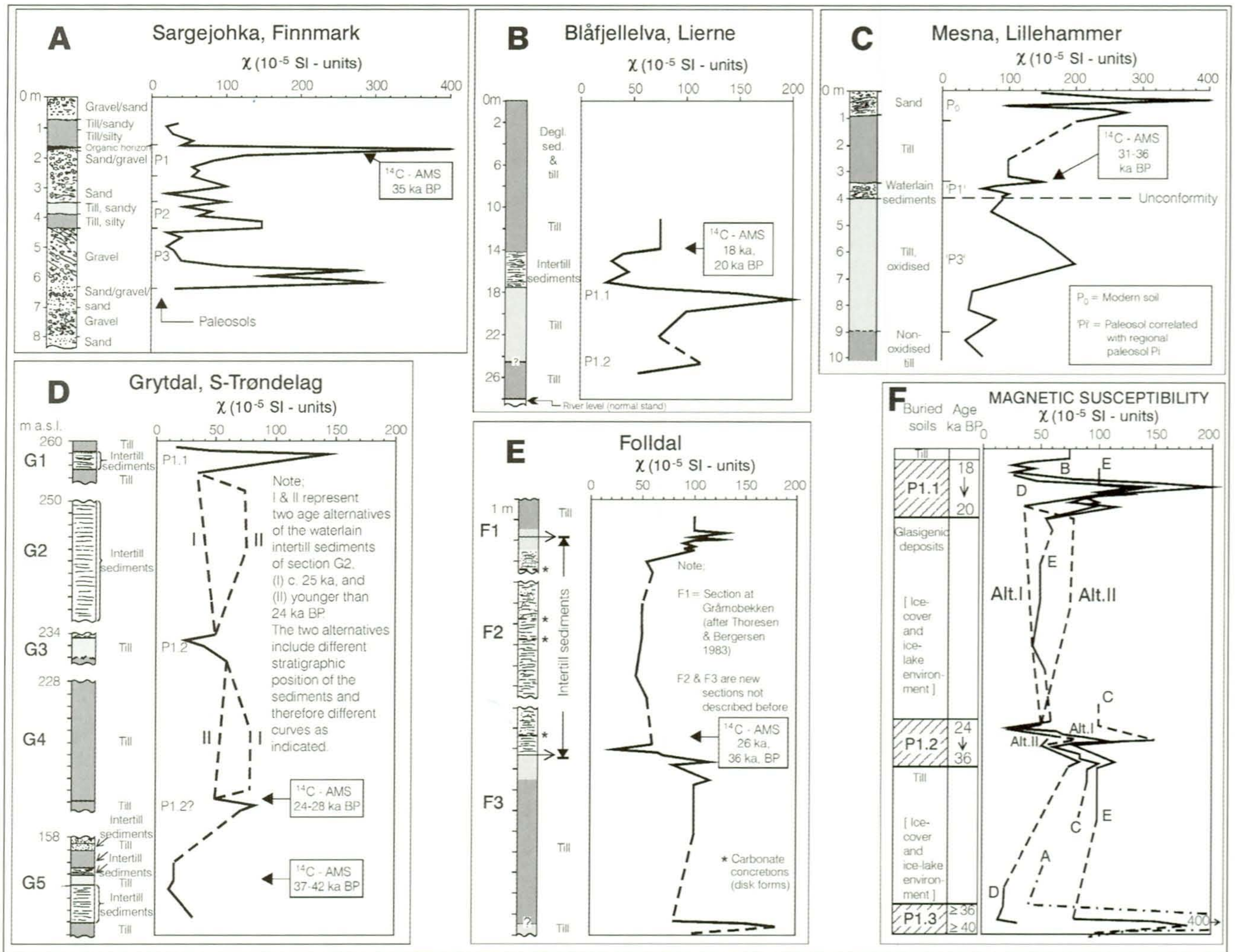


Fig. 5. Magnetic susceptibility from the stratigraphies at Sargejohka (A), Blåfjellelva (B), Mesna (C), Grytdal (D) and Folldal (E), and all curves plotted in the same diagram (F; after Olsen 1997b). All curves are based on c. 500 gram samples. Numerical ages are based on AMS-^{14}C dates of soils and correlated sediments.

Table 1. Annual mean precipitation inferred from magnetic susceptibility (χ) in paleosols (buried soils). A linear relationship is assumed between annual mean precipitation and increase in magnetic susceptibility in different soils. Basic suppositions are particularly the relationship between the modern soil and precipitation in Pasvik (4 sites), Støren (1 site) and Lillehammer (1 site). χ_B = maximum χ in the soil B horizon, and χ_C = minimum or average χ in the soil C horizon. After Olsen (1997b).

Site	Soil	Period	Age, ka BP	XB - XC	Precip. mm/year	Precip., today
Pasvik	p0	Holocene	10	250	540 - 700	500
Støren	p0	Holocene	9	470	1000 - 1300	500 - 1000
Lillehammer	p0	Holocene	9	300	700 - 850	700 - 800
Sargejohka	p1	Sargejohka i.s.	> 35	300	650 - 830	300
Lierne	p1.1	Trofors i.s.	17 - 21	130	280 - 365	300 - 500
Lierne	p1.2	Hattfjelldal i.s. I	30 - 40	60	125 - 175	300 - 500
Grytdal	p1.1?	Hattfjelldal i.s. II	24 - 28	115	255 - 320	500 - 1000
Grytdal	p1.2	Hattfjelldal i.s. I	30 - 37	65	145 - 190	500 - 1000
Folldal	p1.1	Trofors i.s.	17 - 21	80	175 - 225	300 - 500
Folldal	p1.2	Gråmobekken i.s.	26 - 36	40	90 - 125	300 - 500
Folldal	p1.3	pre-Gråmob. i.s.	> 36	100	220 - 285	300 - 500
Lillehammer	p1	Gråmobekken i.s.	31 - 36	240	525 - 675	700 - 800

Table 2. Middle and Late Weichselian interstadials (> 15 ka BP) in Norway, with examples of palynomorph data (pollen & spores) expressed as AP versus NAP, and interpretation of climatic conditions.

Location & reference	Material	Environment	Organic content; % LOI, TC or TOC	AP-unident.-NAP%	Inferred climate, characteristic vegetation	Ice-free interval, assigned age, BP
Sargejohka (Olsen et al. 1996) *Transect 2*	Gyttja silt	Terrestrial - fluvial - lacustrine	1.2 (LOI)	20 - 0 - 80	Subarctic tundra, treeless vegetation, but dwarf birches occur frequently. Grasses and sedges dominate. Wormwood (Artemisia) reaches 5%.	***Sargejohka interstadial;*** 35,000 - > 45,000 ^{14}C-yr
N. Æråsvatnet (Vorren et al. 1988)	Algal silt	Marine	12-13 (LOI)	5 - 0 - 95	High Arctic climate in the younger part, Middle to Low Arctic, with Betula nana, Ericales, Rubiaceae, etc. in the older part.	***'Andøya interstadial';*** 18,000 -18,500; 19,000 - 19,500; and 20,000 - 21,000 ^{14}C-yr (Øv. Æråsvatnet ; Alm 1993)
	Hiatus					
Transect 3	Algal silt	Marine	3-4 (LOI)	10 - 0 - 90	Maritime Middle Arctic (Oxyria, Cyperaceae) to continental Low Arctic climate (Artemisia, Betula n.)	
Bogneset (Olsen, in prep.) *Transect 4*	Silt	Glaciomarine			*(preliminary results)* Maritime Subarctic conditions, with scattered trees (Betula sp.).	***'Ålesund interstadial';*** 28,000 - 39,000 ^{14}C-yr
Hattfjelldal (Olsen, in prep.)	Silt - sand	Gl.fluv. - gl.lac.; possible marine influence (Ce-def., marine algae?)	1.4 (TC)	33 - 33 - 33; (some resed. pollen)	*(preliminary results)* Subarctic tundra, treeless vegetation, but dwarf birches occur frequently. Grasses and sedges dominate. Isolated areas with ferns.	***Hattfjelldal interstadial II;*** 24,000 - 27,000 ^{14}C-yr
Transect 5	Silt - sand	Gl.fluv. - fluv. - gl.lac. - lac., marine influ.?	1.7 (TC)	60 - 14 - 26; (some resed. pollen)	*(preliminary results)* Subarctic tundra, scattered trees, decid. & conif. trees, some ferns.	***Hattfjelldal interstadial I;*** 30,000 - > 35,000 ^{14}C-yr
Kollsete (Aa & Sønstegaard 1997)	Gyttja	Gl.lac. - lac.		> 90 % NAP, some resed. or longtransported tree-pollen	Subarctic - Arctic tundra, dom. by dwarf birches and grasses. July temp. at least 3-4°C lower than today.	***'Bø interstadial';*** c. 43,500 - > 50,000 ^{14}C-yr
Rokoberget (Rokoengen et al. 1993)	Sandy silt	Gl.lac. - gl.marine (Ce-def. & dinocysts)	2.7 (LOI)	8.5 - 31.5 - 60	Subarctic climate, tundra conditions combined with seashore vegetation, dominated by grass.	***Rokoberget interstadial, y. part;*** c. 34,000 ^{14}C-yr
	Hiatus					
Transect 9	Clayey silt	Gl.lac. - gl.marine (?)	3.0 (LOI)	13 - 20 - 67	Similar as the younger part	***Rokoberget interstadial, o. part;*** c. 47,000 ^{14}C-yr
Gråbekken (Gråmobekken; Thoresen & Bergersen 1983)	Clay-silt/ sand/ gravel	Glaciolac./ glaciofluv.	3.0 (LOI)	30 - 0 - 70; some resed. or longtransported tree-pollen.	Subarctic climate, open tundra veg., scattered birches. Mainly herbs, as Poaceae, Artemisia (6%), Thalictrum and Cyperaceae.	***Gråmobekken interstadial;*** c. 32,000 - 40,000 ^{14}C-yr
Djupdalsbekken (Thoresen & Bergersen 1983)	Till, with resed. org.	Resed. material: Gl.lac. - gl.fluv.	1.8 (LOI)	10 - 0 - 90	Slightly different, with more wet conditions and much more shrubs than at Gråbekken.	***Gråmobekken interstadial, o. part;*** > 40,000 ^{14}C-yr
Folldal (Olsen, in prep.)	Clay - silt	Glaciolacustrine	0.2 (TOC)	Mainly resed. pollen	*(preliminary results)*	***'Hattfjelldal interstadial II';*** 24,000 - 27,000
Transect 9	Silt - sand	Gl.lac.	0.2 (TOC)	Similar as at Djupdalsbekken	*(preliminary results)* As at the nearby Djupdalsbekken locality.	***Gråmobekken interstadial, o. part;*** > 40,000 ^{14}C-yr
Øv. Åstbrua gravel pit (Haldorsen et al. 1992)	Soil	Subaerial cond., weathering and permafrost		No organics found	Permafrost conditions with ice wedge formation, proximity to a glacier in both ends of the interval	***Øv. Åstbrua interstadial 2;*** Mid Weichselian.
Transect 9	Sand/ silty clay	Gl.lac.	Plant macrofossils up to 2 cm length recorded	40 - 0 - 60; mosses and twigs of Salix are found	Open, treeless tundra vegetation dominated by grass. Dwarf birches occur commonly. Artemisia up to 12%.	***Øv. Åstbrua interstadial 1;*** > 48,000, probably early Mid Weichs.

Pollen data and plant remains

Pollen analysis has been performed on samples from sediments below and between till units, and on some selected samples from basal parts of lodgement tills. The samples were treated with HF and acetolysis as described in Fægri & Iversen (1989). *Lycopodium* tablets were added to allow absolute pollen analysis (Stockmarr 1972).

In order to make sense of the considerable amount of data shown in a typical pollen diagram, it is necessary to

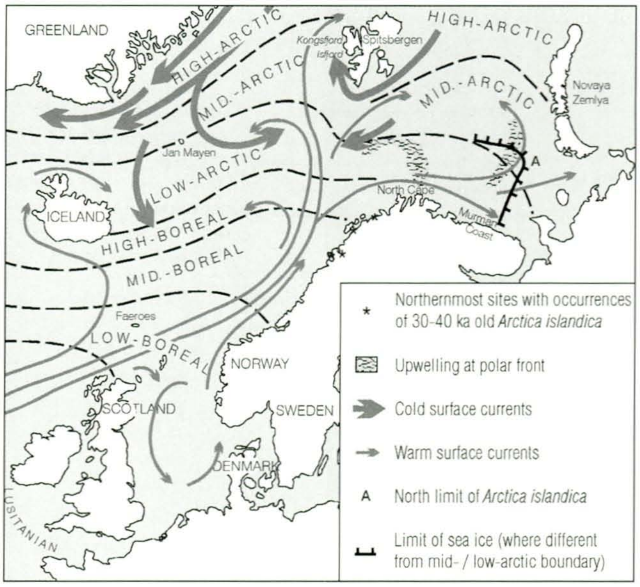


Fig. 6. Northernmost sites with occurrences of *Arctica islandica* from the interval 30,000 – 40,000 ^{14}C-yr BP in Norway. See the main text for further details. Additional map information modified from Peacock (1989).

divide the diagram into pollen-stratigraphic units characterised by distinctive groups of pollen types. In this way, a series of *pollen zones* and *local pollen assemblage zones* is created (Lowe & Walker 1997). Our data, however, in most cases are too sparse to encourage such subdivisions. The pollen data generally show homogeneous terrestrial taxa represented in a few samples with low pollen concentrations (commonly less than 100-200 pollen grains/cm^3). Therefore, we usually describe the pollen data from each interstadial which is represented at a particular stratigraphic site, as one local pollen assemblage zone. Sediments of various grain size and genesis are used in this work. Comparisons of pollen data, including pollen concentrations, between sites are therefore mainly tentative.

The pollen concentrations in gyttja sediments from the Sargejohka (35,000 -> 45,000 BP) and the Rokoberget interstadial complexes (34,000 -> 47,000 BP) reached up to 3x10^4 and almost 3x10^5 pollen grains/cm^3, respectively (Rokoengen et al. 1993, Olsen et al. 1996). The samples from the sediments from the interval 17,000 - 35,000 BP (Table 2) have much lower organic contents and pollen concentrations, mainly less than 100 pollen grains/cm^3. Due to variable preservation, the frequency of unidentified pollen grains varies, but it is commonly less than 5-10%. However, in a few cases it is up to 30-35%.

Samples selected for a preliminary examination of plant remains (macro and micro) were prepared following standard methods for separation of foraminifers (e.g., Steinsund & Hald 1994). A micro-/stereoscope with a magnification up to 50 times was used during examination, which resulted in, e.g., a frequency distribution of twigs, tissue, leaves, etc., but no detailed data on species level are available, except for some few cases where such data have been reported (e.g., at Sargejohka; cf. Olsen et al. 1996; and at Rokoberget; cf. Rokoengen et al. 1993).

Marine mollusc shells and marine microfossils

Shell material from the time interval 40-15 ka BP occurs mainly as broken shells, mostly small fragments of *Mya truncata, Hiatella arctica, Macoma calcarea, Arctica islandica, Chlamys islandica, Balanus sp.* and *Mytilus edulis*, which are the common components of many lateglacial, marine, shell-fauna assemblages from Norwegian coastal sites. It is worth noting that during the interval 40-35 ka BP, Arctica islandica, the typical Atlantic cool-temperate water indicator, is recorded in the sediment sequences up to at least 67-68°N, and perhaps as far north as Tromsø, at 69°N (Vorren et al. 1981); see Fig. 6. There is also a noticeable lack of shells in sediments from onland positions during the time interval 27-17 ka BP.

Samples from some of the sediments were prepared for dinoflagellate analysis. Standard procedures for the preparation and analysis of dinoflagellates (Barss & Williams 1973) were adopted. Only one site revealed a dinoflagellate content adequate for palaeoenvironmental

Dinoflagellates	Sample nos. 1-6/7-94	1-2/10-92	2-2/10-92	3A-2/10-92	3B-2/10-92	% of normalised average
Operculodinium centrocarpum	94			2		40.4 %
Protoperidinium spp. (cf. P. conicoides)		1	4	38	11	49.8 %
Protoperidinium spp.						0 %
Spiniferites spp. indet.				2		1.9 %
Bitectatodinium tep ikiense						0 %
Peridinium faeroense						0 %
Unidentified dinoflag. cysts	3	0	0	7	1	8.0 %
Sum, dinocysts	97	1	4	49	12	100 %
Sum, markers	915	90	385	410	1194	
Dry material (grams)	2.180	18.522	16.761	19.009	5.130	
Productivity (no. of dino-cysts per gram dry sed.)	677	8	9	88	27	
Other microfossils:						
Foraminifera	2	4	3	53	9	
Pollen 1			7	2		
Spores		1	1			Age range:
^{14}C-ages (shell, from the same sed. samples)	c. 36,000	c. 40,000	c. 38,000	c. 32,000	c. 28,000	28,000 - 40,000 BP

Table 3. Palynomorphs, mainly dinoflagellates, recorded in the Middle and Late Weichselian sediments at Bogneset, Åmøya, North Norway. The number of dinoflagellate cysts and other microfossils are indicated. ^{14}C-ages of shells are included.

Dinoflagellates	Sitter 1-11/7-95	Sitter 1-17/7-95	Oldra 1-20/7-95	Rokoberget 2-27/9-91	Rokoberget 4-11/3-90	Namsen 2-10/10-95	Grytdal 1-15/10-96
Operculodinium centrocarpum	72		4				
Protoperidinium spp. (cf. P. conicoides)	1		5				
Protoperidinium spp.				2			
Spiniferites spp. indet.							
Bitectatodinium tepikiense	1						
Peridinium faeroense	1						
Unidentified dinoflag. cysts	2			2	1	2	> 2
Sum, dinocysts	77	0	9	4	1	2	some
Sum, markers	870	825	1220	124	87		
Dry material (grams)	1.955	1.455	1.314	9.667	8.499	10.296	21.632
Productivity (no. of dino-cysts per gram dry sed.)	630	0	78	46	19		
Other microfossils:							
Foraminifera			1				
Marine algae			3				
Pollen	1	1	11	8	2		
Spores			27	12			
^{14}C-ages (INS or shell, from the same sed.)	c. 21,000	c. 30,000	c. 33,000 (shell)	c. 34,000	c. 47,000	c. 18,500	c. 39,500 ^{14}C-yr BP

Table 4. Palynomorphs, mainly dinoflagellates, recorded in the Middle and Late Weichselian sediments from selected sites in Norway. The number of dinoflagellate cysts and other microfossils are indicated. ^{14}C-ages of sediments (and one shell) are also included.

and palaeoclimatic interpretations (Table 3), but even sparse data on palynomorphs may provide useful, qualitative distinctions between marine and terrestrial conditions (Table 4). The reason for this is that most of the sediment sequences that we have checked for dinoflagellates have been located in more inland positions and lack not only other marine microfossils, but marine macrofossils as well. A check for the presence of dinoflagellates has therefore been employed to establish whether some sequences may still have accumulated under marine conditions (Olsen & Grøsfjeld 1999).

Calcareous concretions in sediments

The calcareous concretions encountered in this study are thought to have been formed during conditions of high groundwater flow with a steep hydrostatic gradient and an initial 'bulge' with high concentrations of dissolved carbonate. Such conditions are found, for example, in glaciofluvial environments, with a typical depositional temperature of c. 0°C (e.g., Dionne & Cailleux 1972). As these concretions most probably are formed close to the groundwater table, they are considered to reflect the position of the groundwater table at the time of formation. Such concretions need ice-free conditions to be produced, and are therefore important geological indicators for ice retreat.

It should be noted that although the age of formation of concretions may be almost as old as the sediment itself, it may also be much younger. ^{14}C-dating of concretions may even give numerical ages higher than the sediment because of the possible 'reservoir' age of the CO_3 (hardwater effect). However, such dates, in combination with dates obtained from other dating methods (e.g., U/Th, luminescence, etc.), may still prove useful.

Animal bones

Bones of mammoth from Gudbrandsdalen, Southeast Norway, ^{14}C-dated to c. 45,000 yr BP and redated by the U/Th method to c. 43,000 - 53,000 cal yr BP, suggest that mammoths may have lived in ice-free valleys in Norway during the Mid Weichselian (Heintz 1974, Bergersen & Garnes 1981, Bergersen 1991, Idland 1992). A rich bone assemblage of several thousand bones derived from different kinds of animals (birds, foxes, rabbits, etc.) in cave sediments from the same period are known from coastal West Norway (Larsen et al. 1987). Bones of other animals (e.g., bear, wolf, etc.) have also been reported from caves in North Norway (Lauritzen et al. 1996, Nese 1996, Nese & Lauritzen 1996), and these are dated to between 20,000 and 30,000 yr BP. The animals represented in the cave faunas indicate climatic conditions similar to the present conditions on Svalbard and in the northernmost part of Norway. These data are used both for control dates (Olsen et al. 2001a) as well as indicators of the palaeoenvironmental conditions at the time.

Stratigraphy and stratigraphical considerations

Sediment facies and depositional environments

Reconstruction of ice-sheet fluctuations in Norway is based on complex stratigraphic sequences which include a variety of sediment facies originating from a range of depositional environments. The most frequent and qualitatively most important of these are illustrated in Table 5. Sediments deposited in proglacial environments occur in a majority of the localities. The glaciolacustrine sediment facies A and B1 are represented mainly by sub-facies (a) comprising laminated clay, silt and sand, alternating with sub-facies (b)

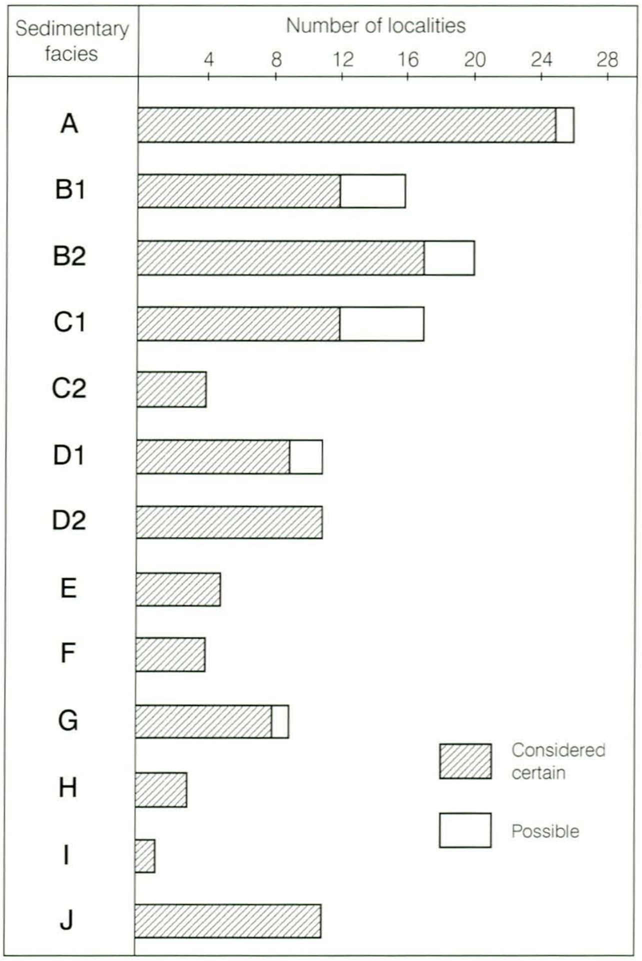


Fig. 7. Distribution of the most frequently occurring sediment facies represented in the sub-till sediments in our study. Most of the sediment facies (A, B1, C, D, F & G) are dominated by clay, silt and fine sand, and most of these are inferred to represent proglacial environments (A-D). For description of sedimentary environment, see Table 5.

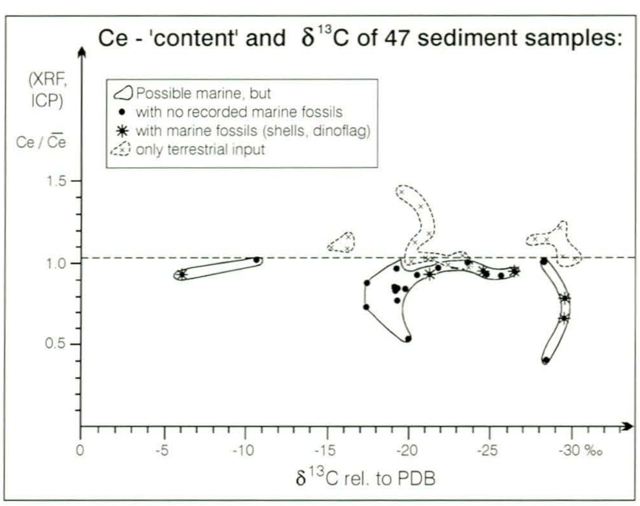


Fig. 8. Ce-content' (expressed as $Ce_n/\underline{Ce}$ – ratio) and $\delta^{13}C$ of 47 selected sediment samples. See the main text for description of calculation procedure for $Ce_n/\underline{Ce}$. Note that all the samples with a certain or inferred significant input of marine sediments have a $Ce_n/\underline{Ce}$ ratio of c. 1.0 or less, which indicate sediments depleted in Ce.

Table 5. Sediment facies and depositional environment inferred from the studied stratigraphic successions.

Sediment facies		Sedimentary environment	Comments
A		Proglacial; glaciolacustrine	Ice-dammed lake; mainly laminated sand, silt & clay
B	B1	Proglacial; glaciolacustrine	Ice-lake; mainly laminated sand, silt & clay
	B2	Proglacial; glaciofluvial	Various kinds of deposits; mainly sand
C	C1	Proglacial; glaciomarine	Uplifted above lateglacial & Holocene marine limit; silt & clay, with clasts; no marine fossils
	C2	Proglacial; glaciomarine	As C1, but with marine fossils (shells, dinoflag)
D	D1	Proglacial; glaciomarine	Lower than lateglacial & Holocene marine limit; silt & clay, with clasts; no marine fossils
	D2	Proglacial; glaciomarine	As D1, but with marine fossils (shells, dinoflag)
E		Fluvial	Mainly gravel & sand
F		Lacustrine	Silt & fine sand
G		Marine	All sites are from onshore areas and therefore uplifted compared to the present sea-level; silt & clay
H		Terrestrial organic env.	Gyttja, peat, etc.
I		Aeolian environment	Sand
J		Other subaerial conditions	Subaerial cave environment; pedogenesis, etc.

which consists of massive clay, silt or sand, whereas the glaciofluvial sediment facies B2 includes several sub-facies of sand and gravel. These sediment facies types (A, B1, B2) are the most common facies in our database for the inland areas (Fig. 7). In coastal areas it is glaciomarine facies D1 and D2, as well as marine facies G, that are the most common sediment types.

Glaciomarine facies C1 and C2, which are recorded at high altitudes in inner fjord valleys at some 20 localities, are qualitatively important because they indicate both certain (C2) and probable (C1), high, contemporary, relative sea levels (see next paragraph), in turn indicating substantial glacial isostatic depression of the land.

High relative sea-levels

The occurrence of pre-Holocene marine sediments at localities situated far inland and much higher than the present sea level is highly significant, especially those which lie well above the lateglacial marine limit. Only three sequences containing marine macrofossils (shells) and five with marine microfossils (foraminifera, dinocysts, algae) have been found so far (Olsen & Grøsfjeld 1999), though a number of other sequences may contain trace quantities of marine fossils. To establish whether waterlain sediments accumulated under marine conditions, although the sequences lack obvious marine fossils, organic matter was extracted from residues of relict marine organisms using hexane as described by Olsen et al. (2001a). The content of *La* and *Ce* has also been measured to determine the extent of the Ce-deficient lanthanide

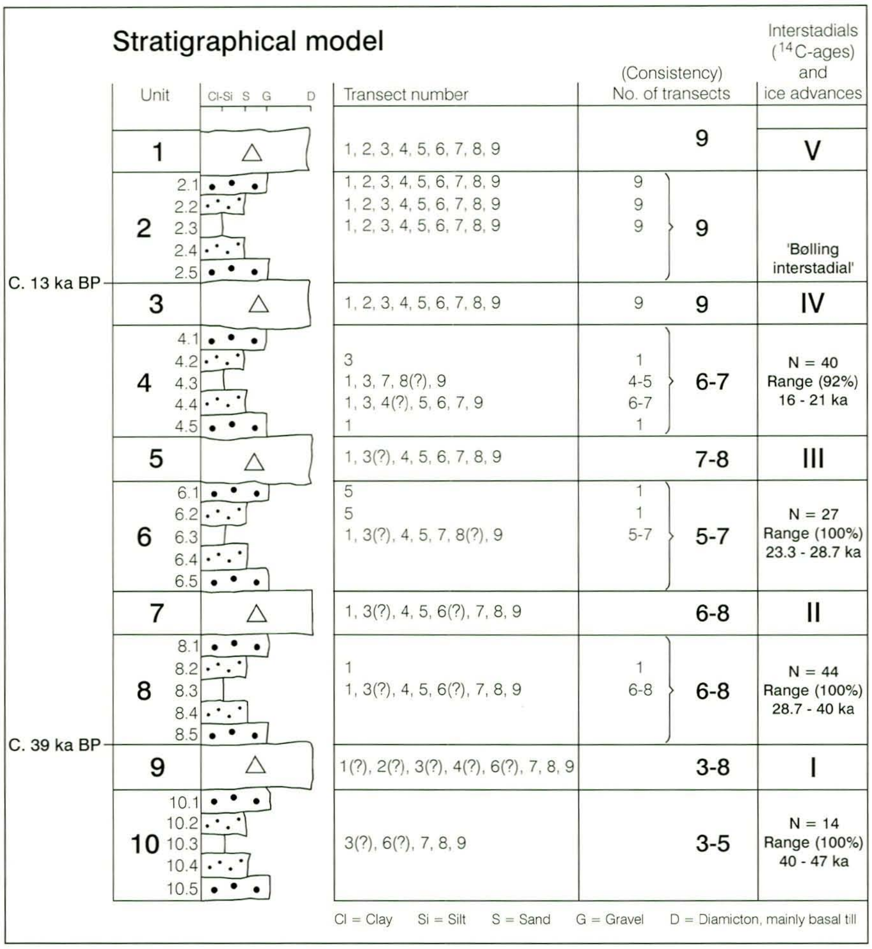


Fig. 9. Outline of the generalised regional stratigraphy representing the interval 10-15 to 40-45 ka BP. The chronology refers to ^{14}C-yr. Unit 1 may include several subunits of tills and waterlain sediments, and is supposed to represent all lateglacial stadial and interstadial events after c. 12.3 ka BP. Unit 2 represents the first regional, lateglacial, ice-retreat phase recorded in onshore positions along the coast of Norway. Unit 3 represents the second, major ice advance (LGM 2) during the Late Weichselian. Units 1, 2 & 3 occur along all nine profiles. Unit 4 represents the ice retreat between the two major ice advances during the Late Weichselian. So far, this unit is not recorded along profile 2. Unit 5 represents the Late Weichselian maximum (LGM 1). It is probably represented along all profiles, but as unit 4 is lacking in profile 2, unit 5 cannot be properly distinguished from the overlying unit 3. Units 6, 7 & 8 also occur in most profiles, whereas units 9 & 10 are considered less well dated, with the exception of profiles 7, 8 & 9 where these units are dated more accurately.

(Olsen et al. 2001a), which is an indicator of a marine depositional environment (Roaldset 1980). Other parameters also used to identify probable marine conditions, as, e.g., C/N ratio, Cl and Br content, will be discussed in another paper (Olsen, in prep.).

Generalised stratigraphy

A generalised stratigraphy of the Mid- and Late Weichselian of Norway is illustrated in Fig. 9. The stratigraphical model includes units of tills alternating with waterlain sediments. Units 3 – 10 represent the interval 40-15 ka (^{14}C) BP. The generalised stratigraphy is based on more than 100 localities from onshore areas and spread over most parts of Norway. Almost 50 of these localities, with representatives from all nine transects (Fig. 1), are included as examples in Table 6, and 36 key stratigraphic successions are shown as simplified logs (Figs. 10 and 11). The localities comprising excavated sections, cores and exposures along rivers and roads are grouped according to their occurrence along each of the nine transects from distal (left) to proximal (right), and are presented from north to south.

Regional overview

There is a strong regional consistency in the stratigraphic scheme depicted in Table 6 and Figs. 9-11. The major ice advances I – IV of the interval 40-15 ka BP are represented in at least six of the nine transects, except for ice advance I which is dated to c. 40 ka BP, which is less pronounced in our data. However, ice advance I may also be represented in more than the two places west of the main watershed (transects 7 & 8) where it is recorded. Evidence of a very high relative sea level along transect 9, during deposition of unit 8 at Herlandsdalen, Passebekk and Mesna, and at Rokoberget c. 233 m a.s.l. (Olsen & Grøsfjeld 1999; lateglacial marine limit c. 190 m a.s.l.; at this site where the sediments are depleted in Ce and contain some marine dinoflagellate cysts (Table 4)), indicates significant glacial isostasy and the occurrence of an extensive ice-body corresponding to unit 9. Till recorded for this glacial episode, called the Mesna Till, occurs at Lillehammer (Olsen 1985). This suggests that a significant ice advance at c. 40 ka ago may also have occurred in southeastern Norway. The same argument may be made for stratigraphic evidence for sites along transects 3, 4, 5 and 6, which indicates that this ice advance may have been a very extensive one (at least south of Vestfjorden, Fig. 1). The intervening interstadial episodes also seem to be equally well represented over the region as a whole.

Sites along transect 1

Leirelva. - This site is represented by an exposed c. 10 m-high river section reaching up to 120 m a.s.l. and located at 70° 17' N and 30° 16' E, with map reference 2435 I (scale

Table 6. Localities (sites) with generalised stratigraphic units, sediment facies, utilised dating methods and comments on dating, correlation and indicators of climate and environment. The numerical ages of the mentioned dates refer to Olsen et al. (2001a, b), and references therein. For location of profiles, stratigraphic framework and sediment facies, see Figs. 1 & 9 and Table 5. Locality "Æråsvatnet" is described as "N. Æråsvatnet" in Table 2 and "Lake Nedre Æråsvatn" in the main text.

Transect no.	Location & reference	Str. units	Facies	14C	TL	OSL	U-ser.	AA ratio	Pal. Mag.	Comments
1	Komagelva	3								
	(Olsen et al. 1996)	4	B2	INS, SOL		x				Ce-deficiency (0.88)
1	Leirelva	3								
	(Olsen et al. 1996)	4	A	INS, SOL	x	x				Ce-def. (0.90)
1	Skjellbekken, Pasvik	3, 5								
	(Olsen, unpubl.)	6	B2	INS						
		7								
		8	B2	INS						
2	Lauksundet, Arnøya (Andreassen et al. 1985)	3, 5		x						shell, resed.
2	Leirhola, Arnøya	3, 5, 7								
	(Andreassen et al. 1985)	8	D2/G	x						shell
2	Slettaelva	3, 5, 7		x				x		shell, pollen, resed.
	(Vorren et al. 1981)	8?								
2	Sargejohka	3, 5, 7							x (unit 7)	Lake Mungo? (c. 28 ka BP)
	(Olsen 1988, Olsen et al. 1996)	8	E/F	INS, macro						pollen, palaeosol
2	Kautokeino	3, 5, 7								
	(Olsen 1988, Olsen & Often 1996)	8	B1/B2		x					resed.
3	Bleik, Andøya	4	D2	x				x		shell, foraminifera
	(Møller et al. 1992)	6?, 8?	D2	x						shell
3	Øvre Æråsvatnet (Alm 1993)	4	B1/F	SOL, INS, macro						pollen, insects
3	Æråsvatnet	3?								
	(T.O. Vorren et al. 1988)	4	D2/G	SOL, INS, macro						pollen, algae
3	Endletvatnet	3								
	(K.D. Vorren 1978)	4	D2/G	SOL, INS						pollen
3	Storelva, Grytøya	3, 5, 7, 9								
		10	A/C2	x				x		shell
3	Mågelva, Hinnøya	3, 5, 7, 9		x				x		shell, resed. (unit 10)
		10	(A/C2)							
3	Cave, Kjøpsvik	4	subaerial	x			x			bones, calc. concretion
	(Lauritzen et al. 1996)	8, 10	subaerial	x			x			bones, calc. concretion
4	Bogneset I & II	3, 4?, 5	D1/B2							
	(Olsen, in prep.)	6	D2/G	x						resed. shell, dinoflag.
		7		x						resed. shell, dinoflag.
		8	D2/G	x				x		shell, dinoflag.
		9?								
4	Grytåga	5, 7		x, INS						resed. shell, Ce-def. (0.94)
	(Olsen, in prep.)	8?	D2/G							
4	Risvasselva	3, 5, 7								
	(Olsen, in prep.)	8	A	INS						Ce-def., resed. (0.93)
4	Caves, Rana	6	subaerial	CO_3						calc. concretions
	(Lauritzen, pers.	8	subaerial	CO_3						calc. concretions
	comm. 1998)	10?	subaerial	CO_3						calc. concretions
5	Hundkjerka	3, 5, 7, 9								
	(Olsen, unpubl.)	10	D2	x						resed. shell
5	Fisklauselva	3								
	(Olsen 1997a)	4	B1/B2	INS						
		5								
		6	A	INS					x	
		7		INS						reworked org. (unit 8)
		8	A/B1							
5	Hattfjelldal &	3								
	Slettåsen	4	B2							
	(Olsen 1997a,	5		INS						resed. org.
	in prep.)	6	B2/C1	INS						pollen, Ce-def. (0.93),
		7		INS						possible marine algae
		8	B2/C1	INS						pollen, Ce-def. (0.94)

Table 6. (continued)

Transect no.	Location & reference	Str. units	Facies	14C	TL	OSL	U-ser.	AA ratio	Pal. Mag.	Comments
6	Langstrandbakken,	3								
	Vikna	4	D1/B2	INS						
		5, 7		x						shell, resed. (unit 8)
		8	D2/G							
6	Østre Tverråga	3								
	(Olsen et al.,	4	A	INS						
	in prep.)	5, 7								
6	Gran, Nordli	3, 5, 7								
	(Olsen et al.,	8	B1	INS						resed. org. (unit 10)
	in prep.)	9, 10	B1/E/F							
6	Blåfjellelva I & II	3								
	(Olsen et al.,	4	A	INS						
	in prep.)	5, 6, 7								
6 & 7	Sitter, Flatanger	3		INS						reworked org. (unit 4),
		4	D1							dinoflag.
		5, 7		INS						reworked org. (unit 8)
		8	B1/D1/G?							
7	Sæterelva, Osen	3, 5, 7		x						shell, resed. (unit 8)
	(Olsen & Riiber,	8	D1							
	in prep.)									
7	Reinåa, Selbu	3								
		4	B2/C1?	INS						Ce-def. (0.87)
		hiatus								
		6	B1/C1?	INS						Ce-def. (0.72)
		7								
		8	B2/C1?	INS						
7	Stærneset, Selbu	3		INS						reworked org. (unit 4)
		4	A/B2/C1?							Ce-def. (0.83)
		5		INS						reworked org. (unit 6)
		6	A/B2							
7	Grytdal, Gauldal	3								
		4	A (C1)	INS						Ce-def. (0.88)
		5		INS						reworked org. (unit 6)
		6	A (C1)	INS						Ce-def. (0.87)
		7		INS						reworked org. (unit 8)
		8	B1/C1/D1	INS						Ce-def. (0.53)
		9		INS						reworked org. (unit 10)
		10	B1/C1/D1	INS						Ce-def. (0.77)
7	Flora, Selbu/Tydal	3		INS						
		4	A/C1	INS						
8	Skjonghelleren	2, 6	subaerial	x			x			bones, speleothems
	(Larsen et al. 1987)	7	A (subgl.)						x	Lake Mungo? (c. 28 ka BP)
		8	subaerial							
		9	A (subgl.)						x	LaChamp? (c. 40 - 42 ka BP)
		10	subaerial				x			speleothems
8	Hamnsundhelleren	5?	A (subgl.)							
	(Valen et al. 1998)	6	subaerial	x						bones (from unit 6 & 8)
		7	A (subgl.)						x	Lake Mungo? (c. 28 ka BP)
		8	subaerial							
8	Gamlemsveten	4?	subaerial	x						block field, soil, bulk org.
	(J. Mangerud, pers.									
	comm. 1981)									
8	Kortgarden	3, 5		x						shell, resed. (unit 6?)
	(Follestad 1990)	6?	D2/G							
8	Skorgenes, Vestnes	3, 5, 7?								
	(Larsen & Ward	8, 9?	B2/D1							
	1992)	10?	B2/D1			x				
8	Kollsete, Sogndal	3, 5?								
	(Aa & Sønstegaard	4, 6?	A	INS						hiatus between units 6 & 10
	1997, in prep.)	10	A/F	x; SOL						pollen
9	Skjeberg, Halden	3								
	(Olsen 1995, 1998)	4	D1	INS						
9	Herlandsdalen,	5								
	Numedalen	6	B1/C1	INS						Ce-def. (0.79)
		7		INS						reworked org. (unit 8)
		8	C1	INS						Ce-def. (0.36)

Table 6. (continued)

Transect no.	Location & reference	Str. units	Facies	14C	TL	OSL	U-ser.	AA ratio	Pal. Mag.	Comments
9	Passebekk,	3								
	Numedalen	4	A (C1)	INS						Ce-def. (0.77)
		5, 6, 7		INS						resed. org. (unit 8),
		8	A/C1							Ce-def. (0.97)
9	Rokoberget	3, 5, 6, 7								
	(Rokoengen et al.	8	C2	INS						pollen, Ce-def. (0.66),
	1993)	10	C1/C2?	INS						dinoflag.
9	Dokka	3								
	(Olsen 1995, 1998)	4	B1/B2	INS						
		5		INS						reworked org. (unit 6),
		6?	B1							Ce-def. (0.98)
9	Stampesletta,	3								unit 4?, clastic dyke from
	Lillehammer	4?	A (subgl.)	SOL						contact between units 3 & 5.
	(Olsen 1995, 1998)	5, 7		INS						reworked org. (unit 8)
		8	B1/C1?							
9	Mesna, Lillehammer	3								unit 4?, clastic dyke from
	(Olsen 1985, 1995,	4?	A (subgl.)	INS						contact between units 3 & 5/7
	1998)	5, 7								
		8	B1/D1?	INS						Ce-def. (0.93)
		9								
9	Sorperoa, Vinstra	8	subaerial		x					eolian sand
	(Bergersen et al.	9?								
	1991)	10?								
9	Grå(mo)bekken,	3, 5, 7?								
	Folldal (Thoresen &	4?, 6	A				x			calc. concretions
	Bergersen 1983)	8	B2/E	x; SOL, INS			x			pollen, calc. concret.
9	Djupdalsbekken,	3, 5, 7?								
	Folldal	4?, 6	A							pollen, resed. (unit 8)
	(Thoresen &	8	B2/E							
	Bergersen 1983)	9?								
9	Folldal	3, 5, 7?								
	(Olsen, unpubl.)	4?, 6	A	INS, SOL,						pollen, resed. (unit 8?),
		8?	B2/E	CO3						calc. concretions
		9?								

1:50,000) and UTM coordinates 972005. The upper part of the stratigraphy consists of silty ice-dammed sediments overlain by a thin lodgement till and with deglaciation sediments on top (Figs. 10 & 11). AMS radiocarbon dates of both soluble and insoluble fractions, as well as TL and OSL dates of bulk samples from the sub-till silt, indicate an early Late Weichselian age. This also implies a probable Late Glacial Maximum (LGM) age (LGM 2) for the overlying till (Fig. 11; Olsen et al. 1996).

Komagelva. - An exposed 6 m-high river section reaching up to 55 m a.s.l. represents this site, which is located at c. 70° 16' N and 30° 20' E, map refr. 2435 I, 996985. The section comprises sand units overlain by glaciofluvial gravel and a lodgement till with a deglaciation sediment sequence on top (Fig. 11). OSL dating of a sand lense in the gravel and AMS radiocarbon dates from reworked sediments in the lowermost part of the overlying till, indicate an age of around 16-17 ka BP. The till may therefore represent a very early ice advance during the last deglaciation or, as we consider most likely, it may represent a second ice advance during the LGM interval (LGM 2) (Olsen et al. 1996).

Skjellbekken. - This site comprises the sections of 16 machine-excavated trenches of up to 2 by 5 m width and length, and 4-5 m depth, and located within an area of c. 3 km^2. The main site is located at c. 69° 23' N and 29° 27' E, map refr. 2433 IV, 965998, and a log from this site reaching up to 125 m a.s.l. is shown in Fig. 11. AMS radiocarbon dates of the insoluble fraction of sediments at two stratigraphical levels separated and overlain by lodgement tills, together with the data from Komagelva and Leirelva, indicate a highly unstable ice sheet, with at least three ice advances separated by ice-retreat periods during the late Middle Weichselian and LGM interval.

Sites along transect 2

Leirhola. - Two stratigraphies from sections on the island Arnøy, northern Troms, have been described by Andreassen et al. (1985). A simplified log from the Leirhola site, located at c. 70° 03' N and 20° 28' E, map refr. 1635 II, 803713, is shown in Fig. 11. The stratigraphy with two basal tills with ^{14}C-dated shells from this and the neighbouring Lauksundet site indicate the occurrence of at least two ice advances after 30 ka BP. The oldest of these may have occurred shortly after 30 ka BP, followed by an ice retreat before 27 ka BP, and subsequently an ice advance during the LGM interval, with a maximum ice extension at the shelf edge c. 21 ka BP (LGM 1) (Hald et al. 1990).

Sargejohka. - This site comprises c. 20 machine-exca-

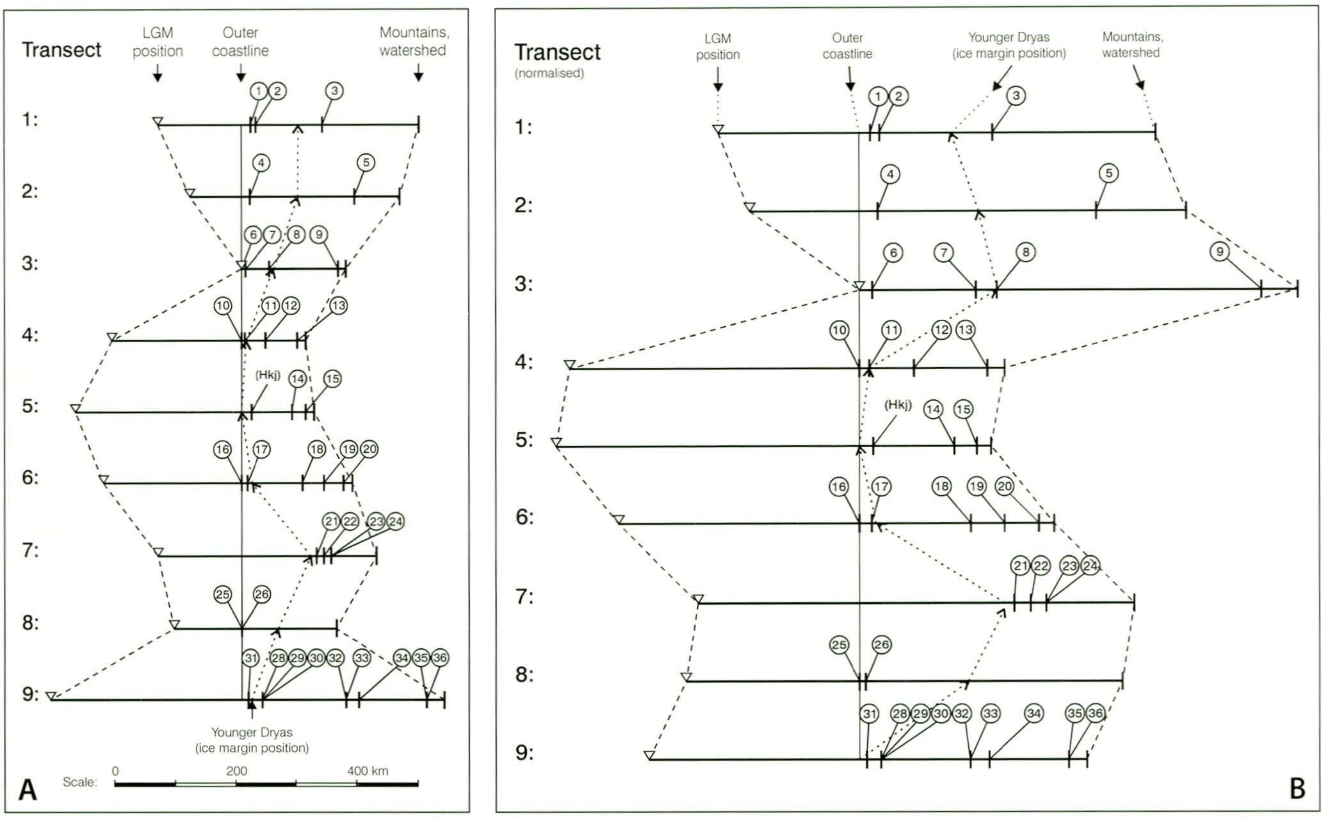


Fig. 10. Stratigraphic sites projected on to their associated transects. For location of transects, see the main text (Fig. 1). The numbers refer to the sites with stratigraphic successions which are shown in Fig. 11. True lengths of transects according to the map, Fig. 1, are indicated in Fig. A, whereas normalised lengths are indicated in Fig. B. Note that no sites from the continental shelf are included here.

vated trenches and sections and some 25 percussion drillings (Olsen et al. 1996). The uppermost part of the stratigraphy is illustrated in Fig. 11, and the location is at c. 69° 07' N and 24° 47' E, map refr. 2033 III, 118693. At least two ice advances represented by tills occurred after c. 35 ka BP and the oldest of these may have an age of c. 28 ka BP, due to the occurrence of a possible palaeomagnetic excursion which may correspond to the Lake Mungo excursion (age, c. 28 ka BP) in the basal part of the lower till (Løvlie & Ellingsen 1993, Olsen et al. 1996).

Kautokeino.* - This site is represented by several sections in a gravel pit in the village of Kautokeino on western Finnmarksvidda, map refr. 1832 I, 819550, approximately at the same latitude, but c. 80 km west of Sargejohka (Olsen 1988, Olsen et al. 1996). TL dates of resedimented, sub-till, glaciolacustrine/glaciofluvial sediments yielded ages in the interval 37-41 ka BP, which together with the overall stratigraphy indicate a similar ice retreat - ice advance history as at Sargejohka. The Kautokeino site is included in Table 6.

*) The sites indicated by an asterisk are included in Table 6, but not in Fig. 11.

Sites along transect 3

Bleik.* – This site, comprising a moraine complex with associated glacigenic and marine sediments in northwestern Andøya, has been described by Møller et al. (1992). The location is at c. 69° 16' N and 15° 57' E, map refr. 1233 I, 370845. The site is included in Table 6 and is supposed to represent the only LGM ice-marginal position on land in Norway. According to Møller et al. (1992), this LGM event culminated at c. 22 ka BP at Bleik. This site is located only 4 km distally (NW) from the Nedre Æråsvatn and Øvre Æråsvatn sites which are also included in our reference database (Tables 2 & 6, and Fig. 11).

Lake Nedre Æråsvatn.* – Corings in lake basins on northern Andøya (Fig. 1) have yielded important information on the Late Weichselian glacial and climatic history in this region (Table 6). The bottom sediments of Lake Nedre Æråsvatn (35 m a.s.l.), map refr. 1233 I, 416842, were deposited at c. 20,000 yr BP, and subsequently compacted by a glacier advance at c. 18,500 – 19,000 yr BP (T.Vorren et al. 1988). Data from Nedre Æråsvatn is included in Table 2. The final deglaciation of both this lake and the nearby Lake Endletvatn occurred at c. 18,000 – 18,500 yr BP (K.-D.Vorren 1978, T.Vorren et al. 1988).

Lake Øvre Æråsvatn. – Øvre Æråsvatn is situated close to Nedre Æråsvatn, but slightly higher (44 m a.s.l.). Its location is at c. 69° 15' N and 16° 03' E, map refr. 1233 I, 410835. Litho- and biostratigraphical data, supplemented by an extensive series of radiocarbon dates, have been reported by Alm (1993). Dating of the bottom sediments yielded an age of 21,000 – 21,800 yr BP (Fig. 11), and only a terrestrial input has been recorded in the Øvre Æråsvatn lake sediments. This is in contrast to the nearby lake Nedre Æråsvatn, where marine sediments were deposited during the interval 15,500 – 19,500 yr BP, indicating a high relative sea level (T. Vorren et al. 1988). The Øvre Æråsvatn sediments, with their position slightly distally to Nedre Æråsvatn, have not been overrun by any glacier after 21,800 yr BP, which is also in contrast to the Nedre Æråsvatn sediments. The glacier advance at c. 18,500-19,000 yr BP, mentioned above, must therefore have ended somewhere between these two sites.

Storelva. – This site is represented by an exposed river section of 20 by 25 m width and height, respectively, and reaching up to c. 140 m a.s.l. Its location is at c. 68° 53′ N and 16° 35′ E, map refr. 1332 IV, 634434. A sequence of 5-6 m of upward-coarsening, inferred shallow-marine sediments is here overlain by a 12-15 m-thick till. The altitude of these sediments high above the lateglacial marine limit (c. 70 m a.s.l.) requires special attention to the possibility of open-sea conditions. The alternative environment would be sedimentation in an ice-dammed lake with redeposition of glacially transported marine fossils. However, fabric analyses from the uppermost part of the underlying till and the basal part of the overlying till indicate northerly directed ice movements, which most likely would have helped to maintain an open bay to the sea in the E-NE during deposition of the shallow-water sediments. Therefore, we think that the altitude may be explained by glacial isostasy and that the sediments are of shallow-marine origin (Olsen & Grøsfjeld 1999). Radiocarbon dating and amino-acid analysis of a shell of the bivalve *Mya truncata* from the marine sediments yielded a middle Middle Weichselian age (Fig. 11), which indicates that unloading of a thick ice body and deglaciation occurred shortly before this time.

Mågelva. – This site comprises several road sections of 1.5 – 2.5 m height. These reveal a stratigraphy which includes tills and redeposited marine sediments from the Middle and Late Weichselian (Table 6, and Olsen et al. 2001b). One of the sections, Mågelva II, reaches up to c. 162 m a.s.l. (Fig. 11). Its position is at c. 68° 39′ N and 16° 26′ E, map refr. 1332 III, 585171. A ^{14}C-dating of *Mya truncata* from the lower till indicates a slightly older but possibly correlative age to the Storelva marine sediments (Fig. 11). If that is the case, then this shell may also have its origin from a position high above the lateglacial marine limit (c. 70 m a.s.l., also in this area). However, other sections at the Mågelva site, also reaching almost 160 m a.s.l., include sediments with lateglacial marine fossils which must have been glacially transported to this altitude, implying that older marine fossils may have a similar history (Olsen & Grøsfjeld 1999). The Mågelva stratigraphy indicates at least two ice advances with deposition of till after 46,000 yr BP and before the lateglacial, ice-front oscillations in this area.

Storsteinshola.* – The occurrence and dating of animal bones and calcareous concretions from a cave (Storsteinshola), map refr. 1331 III, 573549, at Kjøpsvik in Tysfjord (Fig. 1) indicate ice-free conditions at c. 20, 33 and 45 ka BP (Table 6; Lauritzen et al. 1996, Olsen et al. 2001a).

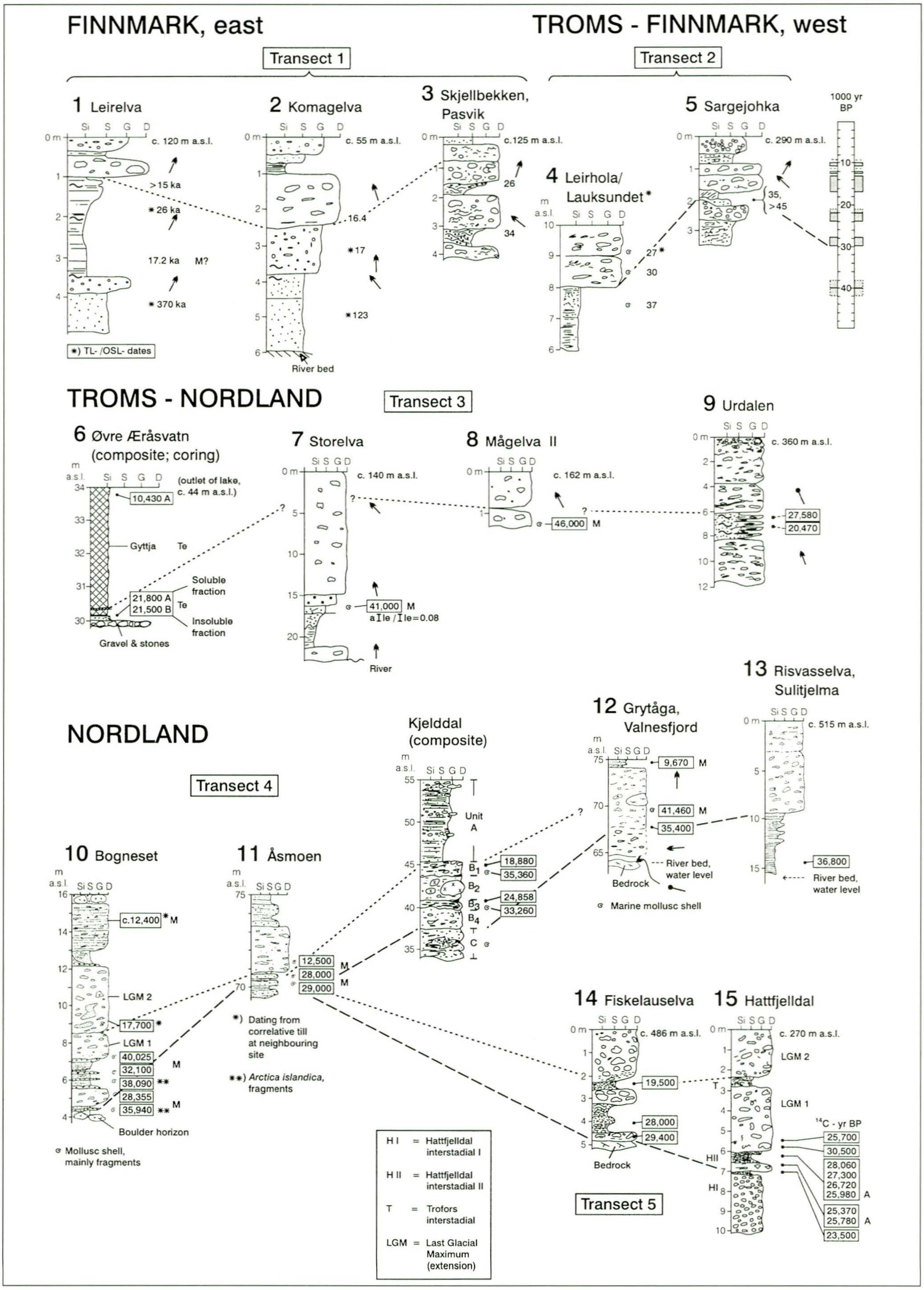
Urdalen. – A 10-12 m-high road section reaching up to 360 m a.s.l., and with a location at c. 68° 49′ N and 18° 00′ E, map refr. 1431 IV, 219992, represents this site. The stratigraphy comprises two major till units, an upper coarse-grained, brownish-grey till with a transition to a stony, glaciofluvial sediment on top, and a lower till which is mainly a compact, fine-grained, bluish-grey, lodgement till of typical regional type (e.g., Olsen 1985a, b, Reite 1993). The lower till is separated into two main parts by a 2-3 m-thick, intercalated, glacially deformed sediment complex of diamictic silty sand, alternating with zones of dark grey and light grey silt laminae in up to 10-15 cm-thick bands. The silty sand of this complex shows a massive structure, whereas the deformed, dark and light silt laminae have a structure which resembles that of a stromatolite. AMS radiocarbon dating of the insoluble fraction of bulk-organic deposits from the sediment complex yielded ages of c. 20.5 (dark silt laminae) and 27.5 ka BP (massive diamictic silty sand), the oldest age in the youngest stratigraphic position (Fig. 11). The reverse age conditions may have been caused by glacial activity (erosion – redeposition or glacial tectonics). The bluish-grey till, including the diamictic beds within the sediment complex, may thus represent at least two, and possibly three ice advances over this area, i.e. one prior to 27.5 ka BP, possibly also one between 27.5 and 20.5 (LGM 1), and the last after 20.5 ka BP (LGM 2).

Sites along transect 4

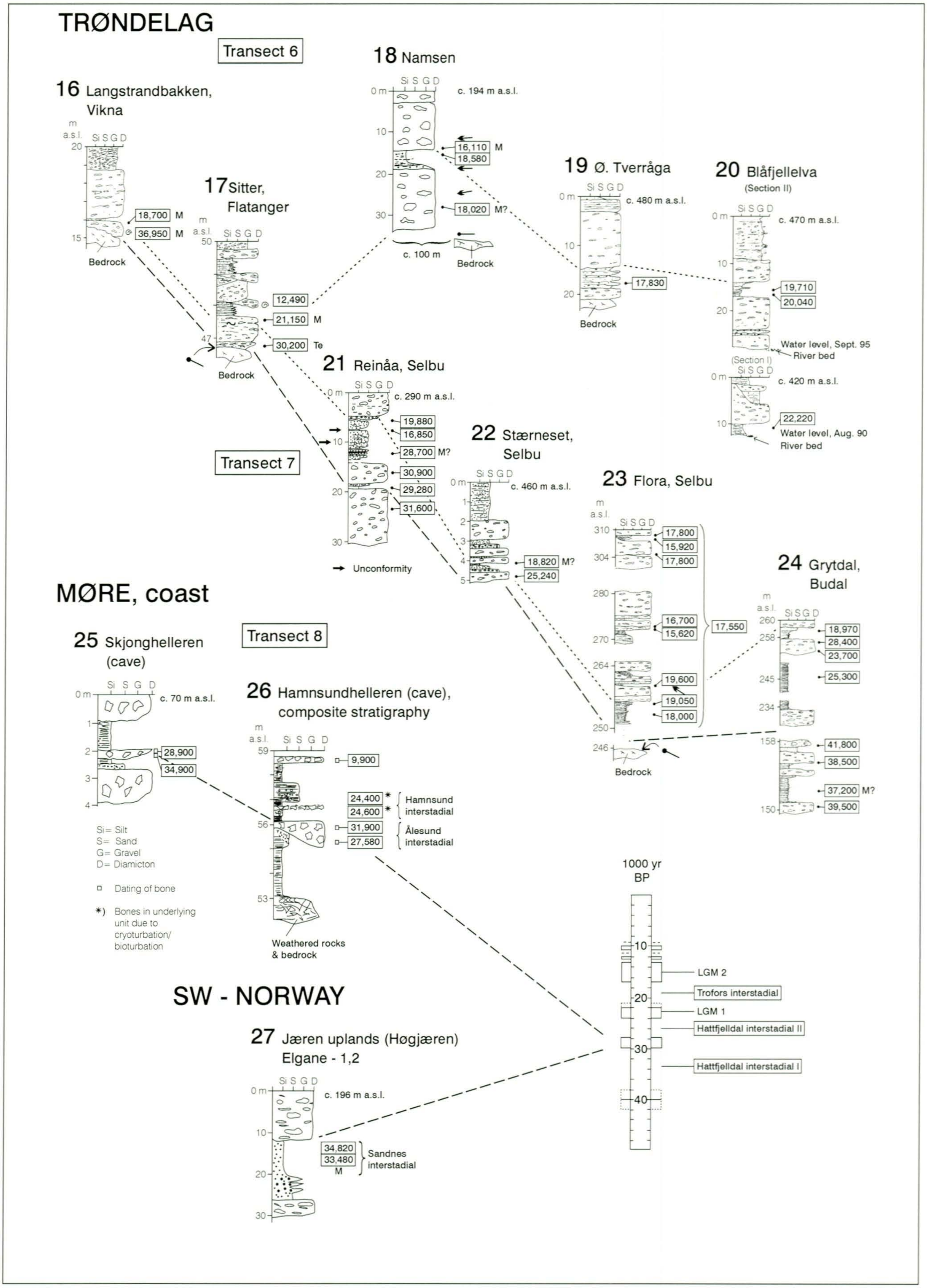
Meløya.* – A c. 1.5 m-deep and 2.5 m-wide trench on the western part of the island Meløya, at c. 66° 49′ N and 13° 30′ E, map refr. 1928 IV, 282122, is located 4-5 km distally from the oldest reconstructed, lateglacial, ice-marginal position (c. 12,300 yr BP, Andersen et al. 1981, Gjelle et al. 1995). The stratigraphy at this site, reaching up to 15-18 m a.s.l., comprises a fine-grained, compact, bluish-grey lodgement till, including shell fragments and redeposited marine sediments (with algae), and with littoral sand on top. An AMS dating of the insoluble fraction of a bulk-organic sediment of marine origin and redeposited in the till, indicates ice retreat from the shelf to the fjord area prior to 17,700 yr BP, and subsequent readvance to the shelf.

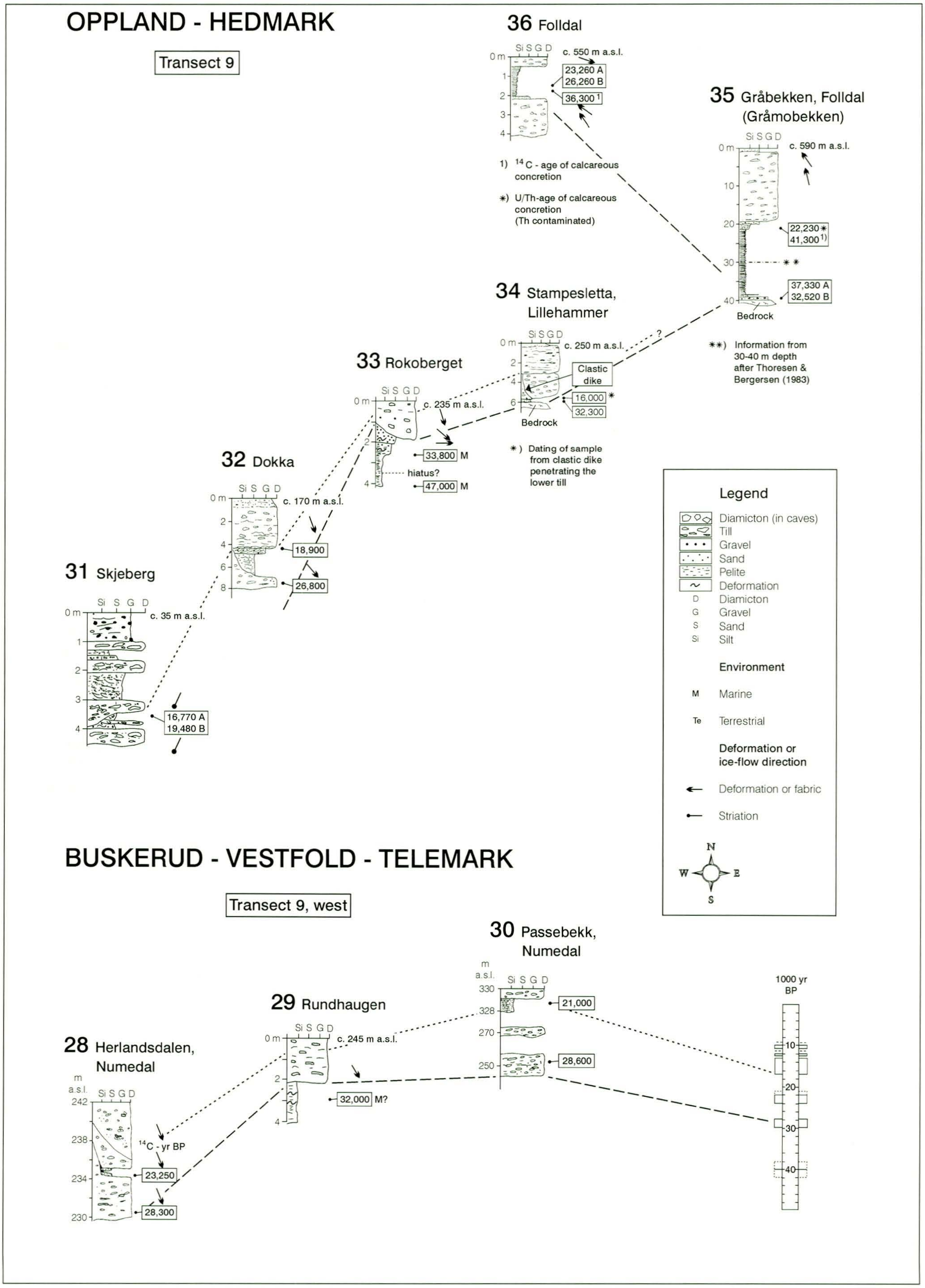
Bolden.* – This site, also called Skogreina, is a gravel pit with its sections all well below the lateglacial marine limit, in a complex ice-marginal deposit at c. 66° 58′ N and 13° 37′ E, map refr. 1928 IV, 382261. Coarse-grained beach and sublittoral deposits cover the surface of the formation, which include deltaic foreset beds overlain by a moraine complex comprising m-thick tills alternating with sandy gravel beds. In the northeastern part of the gravel pit the moraine is cut by a channel and a younger deltaic formation has replaced

Fig. 11. Examples of simplified logs from sites located along all nine transects indicated on the map, Fig. 1, and in Fig. 10. The logs are arranged from distal (left) to proximal (right) position and from north to south. Note that dates are shown as ka BP (i.e., time-scale in ^{14}C-yr, except those indicated as TL/OSL dates which are shown in cal yr) along transects 1 and 2, and as ^{14}C-yr BP along all other transects.



FINNMARK, east
TROMS - FINNMARK, west
Transect 1
Transect 2
1 Leirelva
2 Komagelva
3 Skjellbekken, Pasvik
4 Leirhola/ Lauksundet*
5 Sargejohka
c. 120 m a.s.l.
c. 55 m a.s.l.
c.125 m a.s.l.
c. 290 m a.s.l.
>15 ka
*26 ka
17.2 ka M?
*370 ka
*) TL- /OSL- dates
16.4
*17
*123
River bed
26
34
27*
30
37
35, >45
1000 yr BP
TROMS - NORDLAND
Transect 3
6 Øvre Æråsvatn (composite; coring)
(outlet of lake, c. 44 m a.s.l.)
10,430 A
Gyttja Te
Soluble fraction
21,800 A
21,500 B
Insoluble fraction
Gravel & stones
7 Storelva
c. 140 m a.s.l.
41,000 M
aIle/Ile=0.08
River
8 Mågelva II
c. 162 m a.s.l.
46,000 M
9 Urdalen
c. 360 m a.s.l.
27,580
20,470
NORDLAND
Transect 4
10 Bogneset
c.12,400* M
LGM 2
17,700*
LGM 1
40,025
32,100
38,090 **
28,355
35,940 **
Boulder horizon
Mollusc shell, mainly fragments
11 Åsmoen
12,500
28,000
29,000
*) Dating from correlative till at neighbouring site
**) Arctica islandica, fragments
Kjelddal (composite)
Unit A
18,880
35,360
24,858
33,260
12 Grytåga, Valnesfjord
9,670 M
41,460 M
35,400
River bed, water level
Bedrock
Marine mollusc shell
13 Risvasselva, Sulitjelma
c. 515 m a.s.l.
36,800
River bed, water level
14 Fiskelauselva
c. 486 m a.s.l.
19,500
28,000
29,400
Bedrock
15 Hattfjelldal
c. 270 m a.s.l.
LGM 2
LGM 1
14C - yr BP
25,700
30,500
28,060
27,300
26,720
25,980 A
25,370
25,780 A
23,500
HI = Hattfjelldal interstadial I
HII = Hattfjelldal interstadial II
T = Trofors interstadial
LGM = Last Glacial Maximum (extension)
Transect 5


TRØNDELAG
Transect 6
16 Langstrandbakken, Vikna
17 Sitter, Flatanger
18 Namsen
c. 194 m a.s.l.
19 Ø. Tverråga
c. 480 m a.s.l.
20 Blåfjellelva
(Section II)
c. 470 m a.s.l.
(Section I)
c. 420 m a.s.l.
Water level, Sept. 95
River bed
Water level, Aug. 90
21 Reinåa, Selbu
c. 290 m a.s.l.
Transect 7
22 Stærneset, Selbu
c. 460 m a.s.l.
23 Flora, Selbu
24 Grytdal, Budal
Unconformity
Bedrock
MØRE, coast
25 Skjonghelleren (cave)
c. 70 m a.s.l.
Transect 8
26 Hamnsundhelleren (cave), composite stratigraphy
Hamnsund interstadial
Ålesund interstadial
Weathered rocks & bedrock
Si = Silt
S = Sand
G = Gravel
D = Diamicton
Dating of bone
*) Bones in underlying unit due to cryoturbation/ bioturbation
SW - NORWAY
27 Jæren uplands (Høgjæren) Elgane - 1,2
c. 196 m a.s.l.
Sandnes interstadial
1000 yr BP
LGM 2
Trofors interstadial
LGM 1
Hattfjelldal interstadial II
Hattfjelldal interstadial I


OPPLAND - HEDMARK
Transect 9
36 Folldal
c. 550 m a.s.l.
23,260 A
26,260 B
36,300 1)
1) 14C - age of calcareous concretion
*) U/Th-age of calcareous concretion (Th contaminated)
35 Gråbekken, Folldal (Gråmobekken)
c. 590 m a.s.l.
22,230*
41,300 1)
37,330 A
32,520 B
Bedrock
**) Information from 30-40 m depth after Thoresen & Bergersen (1983)
34 Stampesletta, Lillehammer
c. 250 m a.s.l.
Clastic dike
16,000 *
32,300
Bedrock
*) Dating of sample from clastic dike penetrating the lower till
33 Rokoberget
c. 235 m a.s.l.
33,800 M
hiatus?
47,000 M
32 Dokka
c. 170 m a.s.l.
18,900
26,800
31 Skjeberg
c. 35 m a.s.l.
16,770 A
19,480 B
Legend
Diamicton (in caves)
Till
Gravel
Sand
Pelite
Deformation
D Diamicton
G Gravel
S Sand
Si Silt
Environment
M Marine
Te Terrestrial
Deformation or ice-flow direction
Deformation or fabric
Striation
N
W
E
S
BUSKERUD - VESTFOLD - TELEMARK
Transect 9, west
30 Passebekk, Numedal
21,000
28,600
29 Rundhaugen
c. 245 m a.s.l.
32,000 M?
28 Herlandsdalen, Numedal
14C - yr BP
23,250
28,300
1000 yr BP

the moraine complex. According to Andersen et al. (1981) and Rasmussen (1984), the ice margin at c. 12,300 yr BP was situated at Bolden. The moraine complex, including the upper deltaic formation, may belong to this lateglacial substage. Fragments of shells from the lower deltaic formation and from the moraine complex yielded ^{14}C-ages at 37-38 ka BP (Skogreina TUa-743, TUa-946, TUa-1092; Table 3, Olsen et al. 2001a). The lower deltaic formation may therefore represent a pre-lateglacial, ice-marginal deposit, possibly of late Mid Weichselian age.

Bogneset. – This site comprises the sections of a small gravel pit with adjacent road sections. It is located on the island Åmøya at c. 66° 46′ N and 13° 28′ E, map refr. 1928 IV, 328076, and c. 2 km proximally from the ice margin at c. 12,300 yr BP. The gravel pit includes a boulder horizon c. 4 m a.s.l., overlain by shell-bearing glaciomarine – marine sediments and tills (Fig. 11). The stratigraphy with radiocarbon dates indicates ice-free conditions in the interval 28.4 – 40 ka BP, followed by at least three ice advances which were separated by ice-retreat intervals between 28,355 and 12,300 yr BP.

Åsmoen. - This site is located on the mainland at c. 66° 53' N and 13° 43' E, map refr. 1928 I, 439190, and c. 6-8 km distally from the Younger Dryas ice-margin position. The site comprises two 6 m-high river sections, some 200 m apart, and reaching up to 75 m a.s.l. which is c. 15 m below the lateglacial marine limit. The stratigraphy includes a glaciofluvial – fluvial, sandy gravel overlain by till and fluvial gravel and sand on top (Fig. 11). AMS radiocarbon dating of shell fragments from the sub-till sediments and the till indicate a considerable age difference from late Mid Weichselian (28-29 ka BP) to lateglacial between the units.

Kjelddal. - This site, comprising two exposed river sections some 100 m apart, is located at c. 66° 46' N and 13° 43' E, map refr. 1928 IV, 414064 - 415065. The sections reach an altitude up to c. 50 - 55 m a.s.l. and the location is less than 1 km distally from an ice-marginal delta which was deposited in front of a local cirque-glacier that existed during the Younger Dryas Chronozone. The stratigraphy at Kjelddal reveals redeposited shallow-marine sediments and at least two tills, both several metres thick and containing deformed sediments. The uppermost part of the sections consist of 5-20 m-thick gravelly and stony sand (A) of glaciofluvial - fluvial origin. A combined stratigraphy from Kjelddal comprises a grey, sandy, compact, lower till C of at least 3 m thickness. It contains deformed sediments of gravelly silty sand with small, thin, shell fragments of unknown type (and too fragile to be sampled during the initial study). The overlying till (B) is subdivided into four different facies (B1 - B4), all compact and of bluish-grey colour. The lower facies (B4) is sandy, and the lower middle facies (B3) is silty, darker in colour and contains foraminifera and shell fragments (*Macoma calcarea*). The upper middle facies (B2) is sandy with more boulders and cobbles than in the other facies. The uppermost facies (B1) is again more silty and with fewer cobbles and boulders, and includes shells of *Macoma calcarea*, *Nuculana pernule*, a.o., and a relatively rich assemblage of foraminifera (Olsen, in prep.). AMS dating of shell fragments from facies B3 and B1 yielded ages of 33 and 35 ka BP, which indicate that the bluish-grey till belongs to the late Mid and Late Weichselian. AMS radiocarbon dating of the insoluble fraction of bulk-organic sediments of marine origin from the same facies of the upper till gave ages of c. 24,860 and 18,880 yr BP, respectively (Olsen, in prep.). Therefore, we think that the Kjelddal stratigraphy represents an ice advance (lower till) possibly older than 33 - 35 ka BP, a subsequent interstadial followed by a readvance of the ice after 33 ka BP (upper till, facies B4), a new interstadial at c. 25 ka BP (upper till, facies B3), another ice advance (LGM 1; facies B2) and then another interstadial at c. 19 ka BP (intercalated waterlain sediments in facies B1), followed by the last ice advance (LGM 2) which is represented by the uppermost part of the upper till. In our reconstruction, the Kjelddal stratigraphy seems to comprise all the major glacial fluctuations during the LGM interval 15 - 30 (40?) ka BP.

Grytåga. - This site is represented by an exposed c. 10 m-high river section reaching up to 75 m a.s.l. The position is at c. 67° 20' N and 15° 12' E, map refr. 2029 I, 088700. The stratigraphy comprises two tills, both compact, bluish-grey, lodgement tills. The lower till includes deformed sediments of supposed marine origin. The clast fabric in this till indicates an ice movement towards the shelf in the west, similar to that indicated by striations on the surface of the underlying bedrock. AMS radiocarbon dating of the insoluble fraction of bulk-organic sediment redeposited in the lower till (Fig. 11) indicates that the ice flow towards the shelf occurred after 35 ka BP. Clast fabrics in the upper till indicate a northerly directed ice flow, which is likely to represent an ice-flow direction during a deglaciation period. The upper till, which contains redeposited shells of Middle Weichselian age (Fig. 11), may therefore belong to the last deglaciation, e.g., the late part of the Younger Dryas Chronozone during which the ice flow was northerly in this area (Olsen, in prep.), or it may belong to a previous deglaciation period. The stratigraphy at Grytåga ends with a shell-bearing, silty sand of shallow-marine origin from the last deglaciation on top.

Risvasselva. - This site is represented by a river section with location at c. 67° 02' N and 15° 59' E, map refr. 2129 II, 434369. The 6-15 m-high section reaching up to c. 515 m a.s.l. exposes a stratigraphy which includes laminated, ice-dammed, silty sediments overlain by two tills (Fig. 11). The lower till is of a fine-grained, compact, bluish-grey, regional lodgement type of till, similar to, e.g., the Jørstad Till from the Lillehammer area (Olsen 1985b), and the upper till is silty sand with a brownish-grey colour and is also a lodgement till. Attempts to find geomagnetic excursions in the sub-till sediments were negative (R. Løvlie, pers. comm. 1997), whereas an AMS radiocarbon dating of the insoluble fraction of bulk-organic sediments from the silt yielded an age of c. 36.8 ka BP. The ice-dammed sediments require an ice body situated in the north, probably arising during an ice-advance phase, and this corresponds with the oldest striations in the area which indicate an ice movement during advance phases towards the SSW from the mountain area in the N and NE where two ice caps exist today. It is likely that the ice-damming phase and the lower till belong to an ice advance well after the expected occurrence of the Laschamp geomagnetic excursion. This excursion is recognised, e.g., in cave sediments in western Norway, and occurred slightly before 40 ka BP (Larsen et al. 1987, Valen et al. 1995, 1996). We consider the organics in the silt to be resedimented from older deposits, which give a possible age of the ice-damming phase closer to 30 ka BP than indicated by the ^{14}C-dating, but prior to the Lake Mungo geomagnetic excursion at c. 28 ka BP.

Sites along transect 5

Hundkjerka.* – This site is represented by sediments in a karst cave at the coast, at c. 65° 26' N and 12° 33' E, map refr. 1825 IV, 862576. The cave is developed in marble and the sediments were studied in sections exposed during activity in a marble quarry. The sediments, reaching up to c. 40 m a.s.l. (before further quarrying), were situated in the main entrance of the cave and in a cave shaft 4-7 m from the cave mouth. The total sediment column was c. 10 m high and the stratigraphy comprised, from base to top, a 2 m-thick diamicton with a dominance of local rocks, an overlying 1 m-thick marine regression sequence followed by a 4.5 m-thick, bouldery, stony diamicton of varied lithology, a thin gravelly diamicton, a 0.5 m-thick till and a 1.5 m-thick marine regression sequence on top (Olsen, in prep.). A ^{14}C-dating of a shell fragment from the lower marine sediments yielded an age of c. 46 ka BP (TUa-1093, Table 3, Olsen et al. 2001a), whereas dates of shells from the upper marine sediments yielded only early Holocene ages (Olsen, in prep.). The till may represent a LGM advance, either LGM 1 or 2, or it may represent a Middle Weichselian stadial. We consider a LGM 2 age to be most likely because deposition of tills probably occurred during each stadial and silty clay overlies the present upper till; which is not straightforward to combine with erosion of subjacent, probably coarse-grained materials (e.g., tills).

Fiskelauselva. – A c. 5 m-high river section reaching up to 486 m a.s.l. represents this site and is located at c. 65° 40' N and 13° 40' E, map refr. 1926 III, 342819. The stratigraphy, comprising three tills with intercalated sediments, belongs to the Weichselian after c. 30 ka BP (Fig. 11). All tills at this site are of the compact, bluish-grey, fine-grained regional type, but the middle and upper tills include more resedimented silty and sandy sediments. AMS dating of the insoluble fraction of bulk-organic sediments from the waterlain units and the lowermost till indicate the occurrence of three ice-retreat intervals /interstadials at c. 29.4, 28 and 19.5 ka BP (Fig. 11) and ice advances between 29.4 and 28, 28 and 19.5 (LGM 1), and after 19.5 ka BP (LGM 2). The representation of a disturbed magnetic signal of a possible palaeomagnetic excursion in the lower intercalated silt (Løvlie 1994) may correspond to the Lake Mungo excursion, in accordance with the ^{14}C-age of c. 28 ka BP. This excursion is also thought to be represented in cave sediments some 15-20 km southwest of this site (Valen et al. 1997). The upper intercalated sediments at Fiskelauselva represent the Trofors interstadial (Olsen 1997a).

Hattfjelldal. – A 10 m-high machine-excavated section along a road adjacent to a creek at c. 65° 36' N and 13° 57' E, map refr. 1926 II, 518765, represents this site. The section, reaching up to 270 m a.s.l., comprises a stratigraphy with several metres of glaciofluvial gravel, capped by a 1-3 cm-thick layer of silty sand and overlain by three lodgement tills and intercalated glaciotectonised silt and sand (Fig. 11). The lowermost till is c. 0.5 m thick and folded over and into the basal part of the overlying laminated silt and sand. This may have happened during the subsequent ice advance. The consequent reversed age of the sequence of dates through the lower intercalated sediments, including the overfolded part, may be explained either by overfolding of the entire waterlain sequence or by overfolding of the lowermost part combined with input of organics from erosion in gradually older strata. We think that the erosion hypothesis fits best with the observed structures and that the oldest organics with ^{14}C-ages of 30.5 and 34.9 ka BP (the latter from an adjacent section) are redeposited in the basal part of the overlying till. In contrast to the two lower tills, which are of a fine-grained, compact, bluish-grey regional type (e.g. Olsen 1985a, b), the uppermost till is more sandy, with a grey to brownish-grey colour. The upper, intercalated sediments are composed of a more homogeneous sand than the lower, intercalated, waterlain sediments, which include layers of both gravelly sand, sand and laminated silt. The pollen and macrofossil content of the lowermost sand layer, which is capping the gravel, and of the lower, intercalated, waterlain sediments at Hattfjelldal indicate two assemblages of vegetation, thought to represent two interstadials (Hattfjelldal I and II), which are separated by an intervening stadial (Olsen 1997a, Olsen & Selvik, in prep.). The ice advance between Hattfjelldal I and II is represented by the thin, glaciotectonised, lowermost till (Fig. 11), which in our reconstruction has an age slightly older than 28,060 yr BP and corresponds to the ice advance between 29.4 and 28 ka BP recorded at Fiskelauselva. However, the oldest stadial represented at Hattfjelldal is represented by its final phase of deglaciation prior to 34.9 ka BP with deposition of the thick glaciofluvial gravel represented in the lowermost part of the section (Fig. 11). The ice advances during the LGM interval, first LGM 1 and then LGM 2, are probably represented by the middle and upper tills. The ice-retreat interval separating these phases is represented by the upper intercalated waterlain sand and corresponds with the Trofors interstadial at Fiskelauselva (Olsen 1997a).

Sites along transect 6

Langstrandbakken. – A c. 5 m-high machine-excavated section reaching up to 20 m a.s.l. along a road at c. 64° 54' N and 10° 50' E, map refr. 1624 I, 868001, represents this site. The stratigraphy includes two tills, both younger than 37 ka BP and the youngest probably representing LGM 2 after 18.7 ka BP (Fig. 11). The latter is indicated by an AMS radiocarbon dating of bulk organics from waterlain sediments which are partially intercalated between the tills and partially glaciotectonised into the uppermost part of the lower till.

Sitter. – This site is represented by the sections of four machine-excavated trenches of 1.5 m width, 2.5 - 3.5 m depth and 5-10 m length, with location at c. 64° 31' N and 10° 58' E, map refr. 1624 II, 947572. The sections, reaching up to c. 50 m a.s.l., comprise a combined stratigraphy which includes six thin tills with reworked and/or intercalated waterlain sediments. The surface is covered with beach gravels. The three lower tills are all very compact, but different in composition. The lowermost till is a c. 0.3 m-thick, mainly compacted and glaciotectonised sandy silt, with a more diamictic character including clasts in its upper part. An AMS radiocarbon dating of bulk organics from this unit, which contains only terrestrial organic material, yielded an age of c. 30 ka BP (Fig. 11). The organic content in the overlying till seems to be close to zero, whereas the subsequent thin till is mainly reworked and tillised marine sediments with microfossils such as dinoflagellates and foraminifera (Olsen & Grøsfjeld 1999). A dating of bulk organics from these sediments gave an age of c. 21 ka BP, indicating that the reworking and compaction probably occurred during the LGM 2 ice advance and that the underlying till belongs to LGM 1. All the units which overlie the lower three tills represent lateglacial depositional events, c. 12.5 ka BP or younger.

Namsen. – This site is represented by a 30 m-high river section, mainly in till deposits, but also including one intercalated waterlain sediment unit of up to at least 4.5 m thickness (Fig. 11). The waterlain sediments represent the infilling of a more than 15-20 m-wide channel which has been incised into the lower till. The location of the site is at c. 64° 45' N and 12° 51' E, map refr. 1824 I, 982838. The waterlain sediments include organic material of terrestrial and marine origin and are situated at c. 174.5-179 m a.s.l. (Olsen & Grøsfjeld 1999), which is up to 37 m higher than the lateglacial marine limit. AMS radiocarbon dating of the insoluble and hexane extracted fractions of bulk-organic sediments indicates that the high sea-level conditions occurred c. 16-18.5 ka BP. This corresponds with the regional ice-retreat interval between LGM 1 and 2, during which time the glacial isostatic depression of the land surface must have been considerable over such a long distance from the LGM position and the coast (Fig. 10) and in so short a time after LGM 1.

Østre Tverråga. – A machine-excavated section of c. 8 m height, combined with percussion drilling and coring through the remaining 12 m of overburden above the bedrock, represents this site. The site is located at c. 64° 28' N and 13° 12' E, map refr. 1823 I, 141519, and the stratigraphy includes tills, mainly of fine-grained, compact, bluish-grey type, and reworked intercalated, waterlain sediments. The overall stratigraphy and AMS radiocarbon dating of the insoluble fraction of bulk organics from the intercalated sediments indicate ice-free conditions at c. 17.8 ka BP (Fig. 11), and subsequent ice advance during the LGM 2 interval.

Blåfjellelva. - This site is represented by two river sections of 12 and 27 m height (Fig. 11). The stratigraphy comprises tills, mainly of the regional, fine-grained, compact, bluish-grey type, intercalated lake sediments, glaciofluvial outwash sediments and ice-dammed lake sediments on top. The position is at c. 64° 10' N and 13° 38' E, map refr. 1923 III, 338181 (section I). The overall stratigraphy and AMS radiocarbon dating of the insoluble fraction of bulk organics from the intercalated sediments indicate that both LGM 1 and 2 with the intervening ice-retreat interval may be represented here (Fig. 11).

Sites along transect 7

Reinåa (Renåa). – This site is situated some 20-30 km proximal from the Younger Dryas ice-marginal position (Fig. 10), map refr. 1621 II, 882138, and is represented by two adjacent road sections which include a combined stratigraphy of c. 30 m thickness (Fig. 11). The stratigraphy comprises a more than 15 m-thick lower till of fine-grained, compact, bluish-grey type, with an intervening unit of c. 0.3 m-thick silt and sand some 5 m from the upper boundary of the till. Laminated silt and sand, overlain by sand and gravelly sand, are deposited in a glaciofluvial channel which is incised some 10-15 m deep into the lower till. Two erosional unconformities are recognised in the sediment sequence of the channel. A thick, sandy and silty till of grey to brownish-grey colour overlies the channel sediments. AMS radiocarbon dating of the insoluble fraction of bulk organics from reworked sediments in the tills and from intercalated sediments (including the sediments in the channel) indicate ice advances between 31.6 and 29.2 ka BP, between 29.2 and 28.7 ka BP and after 16.9 – 19.9 ka BP (Fig. 11). It is possible that the regional major LGM ice advance (LGM 1) may correspond with one or both of the unconformities in the channel sediments between 28.7 and 19.9 ka BP (Fig. 11).

Stærneset (Sterneset). – This site is represented by a 5 m-high section reaching up to c. 460 m a.s.l. along a road at c. 63° 11' N and 11° 16' E, map refr. 1721 III, 141078. The stratigraphy includes three tills with intercalated and overlying waterlain sediments. The sediments are of glaciofluvial and glaciolacustrine origin. AMS-^{14}C dating of the insoluble fraction of bulk organics from reworked sediments in the lower till and from the sediments in the boundary zone to the overlying till (Fig. 11), indicates that the stratigraphy comprises ice-free intervals at c. 25.2 and 18.8 ka BP and ice advances during the LGM stadials (LGM 1 and 2). The upper part of the stratigraphy also includes two tills which indicate one or more oscillations of the ice sheet during the last deglaciation period.

Flora. – This site is represented by three sections along a steep creek (or small river) at c. 63° 06' N and 11° 18' E, map refr. 1721 III, 163006 – 164003. The sections, reaching up to c. 264, 280 and 310 m a.s.l., respectively, include a combined stratigraphy which comprises several tills and units of intercalated waterlain sediments. Based on 8 AMS-^{14}C dates, with an average age of c. 17.6 ka BP, of the insoluble fraction of bulk organics from sediments reworked in the tills or from intercalated sediments, it follows that the recorded stratigraphy indicates ice-free conditions followed by ice-front oscillations and a final ice advance after c. 17.6 ka BP during the LGM 2 stadial (Fig. 11).

Grytdal. – This site is represented by four sections along a steep local road at c. 62° 58' N and 10° 34' E, map refr. 1620 IV, 797825 – 798826 – 799826 – 800827. The sections, reaching up to c. 158, 235, 247 and 260 m a.s.l., respectively, comprise a combined stratigraphy with at least six tills, and intercalated and underlying sediments. The overall stratigraphy and radiocarbon dates indicate that ice-free intervals occurred at c. 39.5 – > 41.8, 37.2 – 38.5, 23.7 – 28.4 and c. 19 ka BP, and ice advances occurred between these intervals and after 19 ka BP (Fig. 11). The dates are all of the insoluble fraction of bulk organics from sediments, and all of terrestrial origin, except for those of age 37-39 ka BP where a Ce-deficiency and badly preserved, possible dinoflagellates indicate a probable marine input (e.g. Table 4).

Sites along transect 8

Skjonghelleren. - The 20 m-thick sediments in this cave (Skjonghelleren) have been studied and described by Larsen et al. (1987), and the location of the cave is at c. 62° 32' N and 6° 08' E, map refr. 1120 II, 510353. The sediments, reaching up to c. 63 m a.s.l., comprise diamictons in the upper 4 m, indicating three ice-free intervals separated by periods of ice-cover represented by laminated glaciolacustrine silt (Fig. 11). Bones and speleothems from the middle diamicton are ^{14}C- and U/Th-dated and yield ages between c. 28.9 and 34.9 ka BP, thus representing the Ålesund interstadial (Mangerud et al. 1981, Valen et al. 1996). A palaeomagnetic excursion correlated with the Lake Mungo excursion (c. 28 ka BP) is recorded in the upper laminated silt sequence (Løvlie & Sandnes 1987), thus indicating that the last ice advance represented in the Skjonghelleren stratigraphy started shortly before 28 ka BP.

Hamnsundhelleren. - The cave Hamnsundhelleren is located at c. 62° 33' N and 6° 20' E, map refr. 1220 III, 600367, some 10 km east of the Skjonghelleren cave, and the cave sediments have been studied and described by Valen et al. (1996). The sediments reach up to 59 m a.s.l. (65 m a.s.l. in the cave mouth) and comprise three cave-diamictons of similar character to those at Skjonghelleren, with underlying and intervening waterlain sediments (Fig. 11). Bones from the lower diamicton are ^{14}C-dated to c. 24.4, 24.6 and 27.6 - 31.9 ka BP, but the first two dates are of bones which are considered to have been reworked and dislocated by cryoturbation and/or glacial activity from the middle diamicton. These two dates are considered to date the Hamnsund interstadial (Valen et al. 1996), but this has been ignored (!) by Sejrup et al. (2000) who correlated the Hamnsund interstadial with the regional ice-retreat interval at c. 20 ka BP.

A palaeomagnetic excursion recorded in the middle sequence of waterlain subglacial sediments is correlated with the Lake Mungo excursion (Valen et al. 1996), whereas an older excursion in the lowermost laminated silt has been correlated with the Laschamp excursion, at c. 42 ka BP (Løvlie & Sandnes 1987, Valen et al. 1995). The composite stratigraphy and dates at Hamnsundhelleren indicate ice-free intervals during the Ålesund interstadial and the Hamnsund interstadial, as well as during the Holocene; and also ice-covered conditions at c. 40 ka BP, between the two interstadials (c. 25-28 ka BP) and after c. 24.4 ka BP (LGM 1?). The upper intercalated sediments have a complex composition with laminated clay in the lower part, coarser sand-dominated, debris-flow sediments in the middle and till mixed with other diamict sediments in the uppermost part close to the cave entrance. Valen et al. (1996) considered this unit to represent a continuous ice-covered interval from the Hamnsund interstadial to the Holocene, but we suggest that the complexity in composition of the unit may hide traces of an ice-free interval at c. 20 ka BP, i.e. younger than the Hamnsund interstadial. With this interpretation, the LGM 2 stadial, corresponding to the Tampen formation in the North Sea (Sejrup et al. 1994), may also be represented in the upper part of the same complex unit.

Additional sites* along transect 8, at Gamlemsveten, Kortgarden and Skorgenes, all located distally from the Younger Dryas ice-marginal position, and at Kollsete which is located in the inner Sognefjord region and 90-100 km proximal from the Younger Dryas ice-marginal position (Fig. 1), are included in Table 6.

In the overview shown in Fig. 11 we have included a site from Elgane, Høgjæren, in southwestern Norway. This site is located less than 10 km from the coast, more than 50 km distally to the Younger Dryas ice-marginal position, and midway between transects 8 and 9, i.e. a long distance from both transects. Nevertheless, the site is included due to its important stratigraphy with *in situ* Middle Weichselian marine sediments (overlain by till) situated at an altitude 170-180 m higher than the lateglacial marine limit of c. 15-25 m a.s.l. in this area (Janocko et al. 1998). Middle Weichselian marine sediments at Høgjæren have been known for a long time and a number of sites with similar information such as that of the Elgane site have been reported from this area (see review in Stalsberg et al. 1999).

Sites along transect 9, western region, middle zone

Relevant information from sites farther inland are not available from this region.

Herlandsdalen. - This site is represented by a 12 m-high river section reaching up to c. 242 m a.s.l. and is located at c. 59° 28' N and 9° 50' E, map refr. 1713 I, 470923. The stratigraphy includes three tills, the two lower of fine-grained, compact, bluish-grey regional type with intercalated silt and sand, and the upper till of more sandy, coarse-grained character with grey to brownish-grey colour. Clast fabrics indicate a generally southeastward ice-flow direction (Fig. 11). The stratigraphy and AMS radiocarbon dating of the insoluble fraction of bulk organics from the lowermost till and from intercalated sediments indicate ice-free conditions at c. 28.3 and 23.3 ka BP, and ice advances between these ages and after 23.3 ka BP.

Rundhaugen. - This site has previously been described by Roaldset (1980), and reinvestigated and dated by the Geological Survey of Norway (Olsen & Grøsfjeld 1999). The site is represented by a 4 m-high section along a local road at c. 59° 28' N and 9° 49' E, map refr. 1713 I, 467927. The section reaches up to c. 245 m a.s.l. and the stratigraphy comprises deformed silt overlain by a till, which varies in composition and colour from fine-grained bluish-grey and greenish-grey in lower parts to coarse-grained brownish-grey in its upper part. The clast fabric in the till and deformation structures in the sub-till sediments with small-scale folding and shearing indicate an ice-flow direction towards the SE (note that the arrow head is pointing in the opposite/wrong direction in Fig. 3: Olsen & Grøsfjeld 1999, due to a printing error). This indicates open-sea conditions during deposition, which implies that the silt may have a marine origin as also indicated by a strong Ce depletion (see above, and Roaldset 1980). Some algae-like microfossils of possible marine origin occur in the silt, but have not been properly identified (due to bad preservation) and must therefore be considered as unknown. Dating of bulk organics from the silt (Fig. 11) supports a correlation with the Sandnes interstadial (c. 30-40 ka BP), as suggested by Roaldset (1980).

Passebekk. - This site is represented by three sections along a road located at c. 59° 31' N and 9° 45' E, map refr. 1714 II, 457963 – 1713 I, 457956. The sections, reaching up to 251, 270 and 330 m a.s.l., comprise a stratigraphy with three tills and reworked and intercalated sediments (Fig. 11). The lowermost till is of fine-grained, compact, bluish-grey regional type, whereas the younger tills are more sandy and with brownish-grey colour. The stratigraphy at this and the neighbouring sites west of Oslofjorden, and the AMS radiocarbon dating of the insoluble fraction of bulk organics from reworked and intercalated sediments (between tills), indicate ice-free conditions at c. 28-32, 23.3 and 21 ka BP, and ice advances with deposition of tills between these ages, as well as after 21 ka BP.

Sites along transect 9, eastern region, from coast to inland

Skjeberg. - This locality is represented by the 4 m-high sections of a garage site located at c. 59° 10' N and 10° 04' E, map refr. 1913 II, 280605. The sections, reaching up to c. 35 m a.s.l., comprise a stratigraphy including four tills with intercalated and overlying sand and gravel. Striations on bedrock in the neighbourhood and on stones in the tills indicate an ice-flow direction generally towards the SSW. AMS radiocarbon dating of the soluble and the insoluble fractions of bulk organics from a silt layer in the lowermost, intervening, waterlain sediments yielded ages of c. 16.8 and 19.5 ka BP (Fig. 11). This indicates that the underlying and overlying tills may represent LGM 1 and 2, respectively. The site is located within the wide and complex zone of the Onsøy - Borge moraines (c. 11,300 yr BP; R. Sørensen 1983, Olsen & Sørensen 1993), and the two upper tills may therefore represent ice-front oscillations during this substage. The gravel on top is beach gravel of Mid Holocene age (Olsen & Sørensen 1993).

Dokka. - This site is represented by a 8 m-high section adjacent to a creek and along a road at c. 60° 49' N and 10° 04' E, map refr. 1816 IV, 584435. The section reaches up to 170 m a.s.l. and comprises a stratigraphy with two tills and intercalated sand and gravel. The lower till is of a fine-grained, compact, bluish-grey regional type (Olsen 1979, 1985a, b), whereas the upper till is silty to sandy, grey and also relatively compact. Clast fabrics indicate ice-flow directions towards the SE and SSE (Fig. 11). The stratigraphy and AMS radiocarbon dating of the insoluble fraction of bulk organics from lenses of redeposited sediment in the lower till, and from clasts and veins of silt in the boundary zone between the intercalated sediments and the overlying till, indicate ice-free conditions at c. 27 and 19 ka BP (Fig. 11). The tills indicate ice advances between these ages and after 19 ka BP, probably corresponding to LGM 1 and 2, respectively.

Rokoberget. - This site is represented by a 4 m-high section along a local road at c. 60° 47' N and 11° 28' E, map refr. 2016 IV, 348412. The Rokoberget site was first reported by Rokoengen et al. (1993), and then further described by Olsen & Grøsfjeld (1999). The stratigraphy comprises a till which overlies glaciotectonically deformed silt, with pollen and marine microfossils (dinocysts) recorded at two levels, c. 47 and 34 ka BP. A hiatus is believed to occur between the dated levels (Fig. 11; Olsen & Grøsfjeld 1999). The silt reaches up to c. 233 m a.s.l., which is well above the lateglacial marine limit (190 m a.s.l.) in this area. The high altitude of the corresponding sea levels is explained by glacial isostasy (Olsen & Grøsfjeld 1999). Deformation structures in the sub-till sediments, clast fabrics in the till and flutings on the adjacent surface indicate an ice-flow pattern which corresponds to the late Middle and Late Weichselian glacial ice-flow development in the Mjøsa region (Olsen 1985a, b).

Stampesletta. - This locality is represented by the 6 m-high sections on the site of one of the sports buildings (Håkonshallen) used during the Olympic Winter Games at Lillehammer, 1994, and the location is at c. 61° 07' N and 10° 28' E, map refr. 1817 II, 794776. The sections, reaching up to c. 250 m a.s.l., comprise a stratigraphy with 10-15 cm of silt overlain by two tills, the lower one corresponding to the fine-grained, compact, bluish-grey Jørstad till (Olsen 1985b), and the upper till of more coarse-grained character and with a grey to brownish-grey colour. AMS-^{14}C dating of the insoluble fraction of bulk organics from the sub-till silt indicates an age corresponding to the Middle Weichselian waterlain sediments overlain by the Jørstad till and younger tills at the neighbouring Mesna site (Olsen 1985b, 1995, 1998). Bulk organics from a clastic dyke which penetrates the lower till, starting from the boundary zone to the overlying till, have been ^{14}C-dated and yielded an age of c. 16 ka BP (Fig. 11). Dating of bulk organics from a similar dyke which penetrates the Jørstad till at the Mesna site also yielded an age of c. 16 ka BP (UtC 6041, Table 2, Olsen et al. 2001a). Clastic dykes of this kind have been described by, e.g., Larsen & Mangerud (1992), and are typically thought to have been injected into subjacent materials from the sole of an overriding glacier. In the examples from Stampesletta and Mesna, such injections may thus have occurred during the last major ice advance (LGM 2).

Gråbekken. - This site, named Gråmobekken and first described by Garnes (1978), was further studied by Thoresen & Bergersen (1983), and then by Olsen (1997b; and unpublished material) who also renamed the site in accordance with the name Gråbekken used on the 1:50,000 map-sheet. The location is at c. 62° 11' N and 10° 26' E, map refr. 1619 III, 749959. The stratigraphy comprises gravel and sand with a thick intervening sequence of laminated clayey silt, and an overlying thick till. The till is of fine-grained, compact, bluish-grey type, similar to the Jørstad till (Olsen 1985b). Radiocarbon dating of the insoluble and soluble fractions of bulk organics from the lowermost gravels, close to the bedrock surface, yielded ages of 32-37 ka BP (Thoresen & Bergersen 1983). U/Th and ^{14}C dating of a calcareous concretion from the upper part of the sub-till sediments gave significantly different ages, c. 19 (i.e. 22,230 cal yr) and 41 ka BP (Fig. 11). We consider the ^{14}C-age to be too old due to old carbonate circulating in the groundwater, and the U/Th age to be too young due to a low ^{230}Th/ ^{232}Th ratio (< 20) which indicates contamination by detrital thorium, and which generally gives too young ages.

The stadial repesented by the till is probably younger than 32 ka BP, in accordance with the ^{14}C dates from the underlying sediments, but an age as young as 19 ka BP, as indicated by the minimum age of the calcareous concretion, seems less likely.

Folldal. - This site is represented by a section along the main road in Folldal and located at c. 62° 11' N and 10° 27' E, map refr. 1619 III, 756965. The section is located c. 550 m from the Djupdalsbekken site which has been described, e.g., by Thoresen & Bergersen (1983) and more recently studied by the Geological Survey of Norway (Olsen, unpublished material). The upper 4 m of the Folldal section, which reaches up to 550 m a.s.l. and some 20 m lower than the sub-till sediments at Gråbekken, is shown in Fig. 11. The stratigraphy comprises a more than 5 m-thick lower till overlain by 1.5 m of sand and laminated silt, followed by the erosional remnants of a fine-grained, compact, bluish-grey till, which at Djupdalsbekken exceeds 10 m thickness and underlies at least one younger, more coarse-grained till. AMS radiocarbon dating of the soluble (A) and insoluble (B) fractions of bulk organics from the silt indicates ice-free conditions at c. 23.3 - 26.3 ka BP (Fig. 11). We consider an average of c. 25 ka BP, or closer to the age of the insoluble fraction (26.3), to be the most likely age of the sediments, and a correlation with the Gråbekken sub-till laminated silt seems reasonable. The overlying, fine-grained, bluish-grey tills at the nearby Folldal, Djupdalsbekken and Gråbekken sites are considered to represent a correlative till unit, and this till may represent an ice advance during the LGM interval. The ice flow was first directed down-valley to the E-ESE, as indicated by clast fabric and deformation structures in the lowermost part of the till, but then turned to a more northerly direction, and even to the NNW and NW in the upper parts, also in accordance with clast fabrics in the till. In this reconstruction there are no indications of ice-free conditions between LGM 1 and 2 in the Folldal area.

Discussion

The methods used for palaeoclimatic and palaeoenvironmental interpretations, and the presented examples of Middle to Late Weichselian stratigraphic successions along nine transects from inland to coast in different parts of Norway, are all important elements in the reconstruction of the glacial history presented in this paper. The high regional consistency of the general stratigraphy, as indicated in Figs. 9-11 & Table 6, is the major basis for the glaciation model which is presented in a linked paper (Olsen et al. 2001b).

It is possible that the examples of glaciomarine facies C (Table 5), although sparsely represented in Table 6, represent the most qualitatively important sediment facies for the reconstruction of the regional glacial history. The significance of this facies is that it reflects very high relative sea-level conditions, thus probably implying a considerable glacial loading on the land surface. Such conditions also indicate extremely unstable glacial conditions, which is an important element of our glacial model (Olsen et al. 2001b).

Theoretically, some of the uplift reflected by these marine sediments could be of tectonic origin. However, it is difficult to understand how generally irregular tectonic movements could explain the finds of marine sediments of widely different ages at nearly the same altitudes and locations (e.g., Mågelva II, Storelva, Rokoberget; Table 6). Although glacial transportation cannot be rejected in all such known cases (e.g., Slettaelva; Vorren et al. 1981, and Mågelva I; Olsen et al. 2001b), it has been claimed that repeated, vertical, glacial isostatic movements caused by the loading - unloading of major ice sheets explains most of the very high, uplifted, marine sediments (Olsen & Grøsfjeld 1999).

There is a noticeable scarcity of radiocarbon dates of shells with ages between 27 and 17 ka BP in our data base, which may reflect a general scarcity of shells in this age range on the Norwegian mainland. This is discussed by Olsen et al. (2001a, b), and needs to be studied more thoroughly in the future.

AMS radiocarbon dating of sediments with low organic content is another important method for the reconstruction of the glacial history. We have tried to overcome the disadvantage with regard to sensitivity to contamination of sediments with small organic content, by careful sampling and storing, and by using several dates from each set of closely spaced and genetically and chronologically connected units (Olsen et al. 2001a).

It has been shown by a few examples with 'control' dates based on different dating methods, that the accuracy of the sediment dates (mainly the INS fraction) is relatively high, e.g. less than 10-15 % deviation between (test-) dates and control dates, and by using replicates we have also shown that the precision is fairly high (Olsen et al. 2001a). However, it is evident that the strongest argument for an overall reliability of the method and approach we have used is the apparently high regional consistency, which we also have postulated based on general considerations of the timing of the stratigraphy and geological events in our model (Olsen et al. 2001a, b).

Based on various dating methods (Olsen et al. 2001a), the geochronological range of the regional stratigraphic record presented here seems fairly accurately determined to the 40-15 ka (^{14}C) BP interval. The four major ice advances which are thought to be represented along most of the transects (Figs. 1 & 9) may not have been synchronous, but the time needed for repeated cycles of build-up of extensive glaciers followed by major ice retreat during the 40-15 ka BP interval constrains the non-synchroneity to a few thousand years in each case. Therefore, even if the major stadial and interstadial events are not synchronous regionally, these events cannot in any case be more than 2000-3000 years outside the estimated (regional) age–range (Fig. 9).

The overall pattern of glacial variation during the 40-15 ka BP interval shows rapid shifts between alternating ice cover and ice-free conditions, even with a much lower dating accuracy and precision than we have found (Olsen et al. 2001a). Hence, most of the western parts of the Scandinavian ice sheet must have been warm-based, except for some high mountain areas with possible cold-based ice, during the Middle and Late Weichselian stadials. This is different from the central parts of Fennoscandia where extensive cold-based ice is suggested to have occurred and prevailed during a considerable part of the Late Weichselian (e.g., Lagerbäck 1988, Olsen 1988, Sollid & Sørbel 1988, Kleman 1992).

Rapid shifts between glacial and interstadial conditions also include intervals of rapid ice growth. So far, no accurate calculations have been made on precipitation necessary for such fast ice growth. However, we suggest that a precipitation with a net accumulation on the same scale as the average for the Holocene in Greenland (c. 0.1 m per year; Dansgaard et al. 1993) may be enough to produce such high ice-growth rates which are required in our model.

An attempt has been made to use magnetic susceptibility (MS) as a tool for correlation between soils from the last interglacial in northern and southern Norway (Olsen 1998), and this possibility is further emphasised for Weichselian interstadial soils (Fig. 5; Olsen 1997b). Olsen (1997b) also carried out a preliminary study with reconstruction of palaeorainfall using tentative numbers obtained directly from MS measurements of well-drained Norwegian soils and paleosols. This is based on the assumptions that (i) the pedogenic magnetic susceptibility of soils is a rapidly formed soil property which is preserved after burial in an almost steady-state condition, and (ii) a proportional relationship exists between rainfall and the MS pattern of well-drained soils. Such a proportional relationship between modern rainfall and the pedogenic MS of young soils from different parts of the world, mainly China, has been reported by Maher & Thompson (1995).

The inferred palaeorainfall based on the paleosol MS data shown in Table 1 indicates that the climate may have been generally drier than today during the Middle and Late Weichselian interstadials, with the long and complex Sargejohka interstadial (Olsen et al. 1996) as a possible exception to this trend.

The sparse pollen data that we have acquired from Middle and Late Weichselian interstadials from inland areas of Norway are too skeletal to support, as well as to challenge, the climatic interpretation based on the MS data (i.e., relatively dry conditions). However, the climate and vegetation tentatively inferred from the pollen data and plant remains are thought to have been colder and poorer than the present, possibly similar to low arctic to subarctic tundra areas today (Table 2).

Tentative sea-surface temperature (SST) may be inferred from mollusc shells and some dinoflagellates, but precise estimates are not available and the SST values may therefore range from arctic to boreal temperatures (e.g., Fig. 6, and Tables 3 & 4). Pollen from coastal sites provides proxy data for summer air temperatures, which also have a wide range even for the short time interval 21-16 ka BP (e.g., Vorren et al. 1988, Alm 1993).

Summary and conclusions

In this contribution we have reviewed the comprehensive stratigraphic database and indicators for palaeoclimatic and palaeoenvironmental interpretations during the Mid to Late Weichselian time interval based on nine transects from inland to coast in Norway. The constructed glacial curves for these transects and their geochronologic basis are presented in two companion papers (Olsen et al. 2001a, b).

The generalised stratigraphy and regional stratigraphic consistency show clearly a similar and therefore regional trend, with large ice-sheet fluctuations in all regions during the period 40-15 ka BP. The overall pattern of glacial variations shows rapid shifts between alternating ice cover and ice-free conditions. Marine sediments in sub-till positions at high altitudes above lateglacial marine levels are recorded in many areas and regions of Norway (Andersen et al. 1991, Olsen 1997a). These uplifted sediments could theoretically be explained by tectonics, but as they occur in many areas and at high altitudes in several ice-free periods, the most likely explanation must be strong glacial isostasy (Olsen & Grøsfjeld 1999). This must have included an element of rapid ice retreat, e.g., comparable to the last deglaciation, or even faster than that. With a stable ice sheet and phases of slow ice retreat, combined with insignificant tectonic movements, there would be no *in situ* marine sediments at high altitudes. Consequently, the occurrences of regionally high relative sea levels imply an unstable ice sheet and rapid ice retreat, which is not compatible with a thick ice sheet and a large ice volume included in the classical Scandinavian ice-sheet model (Vorren 1977, Andersen 1981, Mangerud 1991).

The reported and reviewed palaeoclimatic evidence (e.g., biological data: Tables 2-4 and Fig. 6; other data: Table 1 and Figs. 4 & 5) may be taken as a tentative indication of relatively dry, low arctic to subarctic conditions during most of the phases of reduced ice extension during the period 40-15 ka BP. This implies that, to reach the high ice-growth rates needed to explain all the recorded glacier fluctuations, there must have been abrupt changes to high-precipitation conditions during the transitions from interstadials to stadials.

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