A buried late MIS 3 shoreline in northern Norway — implications for ice extent and volume

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Buried beach gravel in northern Norway represents a late Middle Weichselian/Marine Isotope Stage (MIS) 3 shoreline and indicates a significant late MIS 3 ice retreat. An age of c. 50–31 cal ka BP, or most likely c. 35–33 cal ka BP, obtained on shells, stratigraphical evidence and comparisons between local and global sea-level data, indicate a local/regional glacioisostatic depression which was about 50–70% of that of the Younger Dryas interval. This suggests a late MIS 3 ice thickness/volume similar to or less than during the last part of the Preboreal, during which only minor or isolated remnants of the inland ice remained.

Keywords: northern Norway, MIS 3, Scandinavian ice sheet, glacioisostacy

Introduction

The extension of the glaciers in the western part of the Scandinavian Ice Sheet during the Marine Isotope Stage (MIS) 3 ice advance at c. 45 cal ka BP reached beyond the coastline in SW Norway (e.g., Larsen et al. 1987). The subsequent ice retreat, prior to the Last Glacial Maximum (LGM), has been discussed based on the distribution of sites which indicate ice-free conditions of this age. For example, the sites representing the Ålesund Interstadial (Mangerud et al. 1981), with an age now redated to 34–28 ^{14}C ka BP (Mangerud et al., in print), indicate an ice-free coast in SW Norway and retreat of the ice margin almost to the position of the late-glacial, Younger Dryas, maximum ice margin (Figure 1). Additional data, including sedimentary stratigraphy and dates from both coastal and inland locations, indicate a much more extensive late MIS 3 ice retreat in most parts of Norway (e.g., Olsen et al. 2001a, b). However, the stratigraphic correlations between sites and between regions are often hampered by dates of low precision and accuracy, which imply an uncertain location of the ice margin at each step in time and therefore also an uncertain minimum ice extension.

In this paper I try to reach beyond this problem by using data with implications particularly for ice volume, which generally changes at a slower rate and also has a wider regional effect than ice extension. To do this I have used traces of late MIS 3 raised shorelines and other sea-level data from two previously

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Figure 1. Key map of Scandinavia showing the study areas (grey squares), the position of the major ice margins during the late-glacial Younger Dryas interval (grey lines; dotted line = tentatively), and maximum extension of ice remnants during the last part of the Preboreal (stippled red). Ages are given in cal ka BP.

described localities, Leirhola on Arnøya (Andreassen et al. 1985) and Ytresjøen (Olsen 2002) (Figure 1). These localities have been revisited and are described here, with new field data included as reference sites for discussing the glacioisostatic conditions and implications for the size, and particularly the volume, of the ice sheet.

Methods

Standard methods for regional Quaternary geological mapping used by the Geological Survey of Norway (Bergstrøm et al. 2001) have been used also during the studies referred to here. These methods include, e.g., site observations with description of lithology and stratigraphy of sediments. The registrations include striations on bedrock and boulders (under tills) and various sediment data, e.g., grain-size distribution, colour, compactness, clast roundness, clast fabric and structures. Clast-fabric measurements have been carried out with similar but fewer measurements (n=20) than the standard method (n=33–50) used during regional Quaternary mapping (e.g., Olsen and Hamborg 1983). The reduced number of measured clast long axes, however, was considered high enough in view of the relatively strong, preferred orientation of the clasts (70% or more showing a main trend ±20° with n=20), and the fact that the settings are distinct fjord landscapes with high relief and with all known ice movements directed along the fjords.

Age estimations in this paper are mainly based on ^{14}C dating of marine shells (Tables 1 and 2). This was carried out at the dating laboratories at the Universities of Trondheim and Uppsala, and most of the dates have been published before (Andreassen et al. 1985, Olsen 2002). ^{14}C ages were calibrated to calendar years BP according to the calibration programme version 'Fairbanks0107' which is available on the Internet (Fairbanks et al. 2005). A reservoir age of 440 years, subtracted from each ^{14}C age, was used here. For high ages outside calculation range (>45 ka), I have simply added 4000 years to the ^{14}C age to obtain ages in calendar years (Olsen et al. 2001a, p. 75), and standard deviation is unchanged.

Leirhola

The stratigraphic sections at Leirhola are located c. 4–20 m a.s.l. (Figure 2a, b) (70°2.5' N, 20°30' E). Bedrock on Arnøya is dominated by mica schist, gneiss, metasandstone, dolomite,

Table 1. ^{14}C dates of shells from Arnøya and Ytresjøen, northern Norway. No. 1, 4–6: after Andreassen et al. (1985), no. 2–3: this paper; and no. 7–8: after Olsen (2002).

No	Site	Lab. Ref.	Unit	Material	Age ^{14}C yr BP	± 1 st.d.	Age cal yr BP	± 1 st.d.
1	Lauksundet	T-3507	Till "T1"	*Astarte sp. / Mya truncata*	27400	±1500 / 1200	32697	±1623 / 1277
2	Leirhola, site II	TUa-3624	Till T3	*Arctica isl. / Mya truncata*	44755	±1745 / 1435	48755*	±1745 / 1435*
3	Leirhola, site I	TUa-3626	Till T3	*Arctica isl. / Mya truncata*	48635	±2595 / 1960	52635*	±2595 / 1960*
4	Leirhola site I	T-4020	I	*Chlamys* and *Portl. arctica / lenticula*	29000	±4200 / 2700	34190	±4442 / 2705
5	Leirhola site I	T-4021	I	Div. shells	30200	±4100 / 2700	35448	±4229 / 2657
6	Leirhola site I	T-3509	I	*Mya/Astarte / Arctica isl.*	c. 40500 (>37500)	±3000**	c. 44500**	±3000**
7	Ytresjøen	UtC-8315	B/C	*Balanus bal.* (one fragm.)	28280	±240	33659	±292
8	Ytresjøen	UtC-8316	C/D	*Mya truncata* (one fragm.)	35060	±600	40395	±591

**) See description under* Methods *in the main text. **) Standard deviation for dating no. 6 is not reported, but is here simply set to 3000 yr, which also gives a fair calibrated age.*

Table 2. Sea-level data from Nordland (Olsen 2002) in northern Norway compared to sea-level data from coral terraces in New Guinea** (Shackleton 1987). A and B in the columns to the right refer to the m-values in columns A (Glacioisostacy, Younger Dryas) and B (Glacioisostacy, late Middle Weichselian (MW)).*

Sea-level data from*:	Y Dryas 11.5–12.7 ka m a.s.l.	Late Middle Weichselian m a.s.l.	Eustacy** YD m a.s.l.	Eustacy** late MW m a.s.l.	A. Glacio-isostacy, YD	B. Glacio-isostacy, late MW	B/A-ratio	% B of A
Åsmoen 1 age c. 34 ka	90	> 62	-45	-45	135 m	> 107 m	> 0.792	> 79.2
Åsmoen 2 age c. 33 ka	90	> 71	-45	-45	135 m	> 116 m	> 0.859	> 85.9
Ytresjøen age c. 33 ka	88	c. 23	-45	-45	133 m	c. 68 m	0.511	51.1
Oldra age c. 37 ka	90	> 23	-45	-55	135 m	> 78 m	> 0.578	> 57.8
Kjeldal age c. 38 ka	93	> 40	-45	-60	138 m	> 100 m	> 0.753	> 75.3

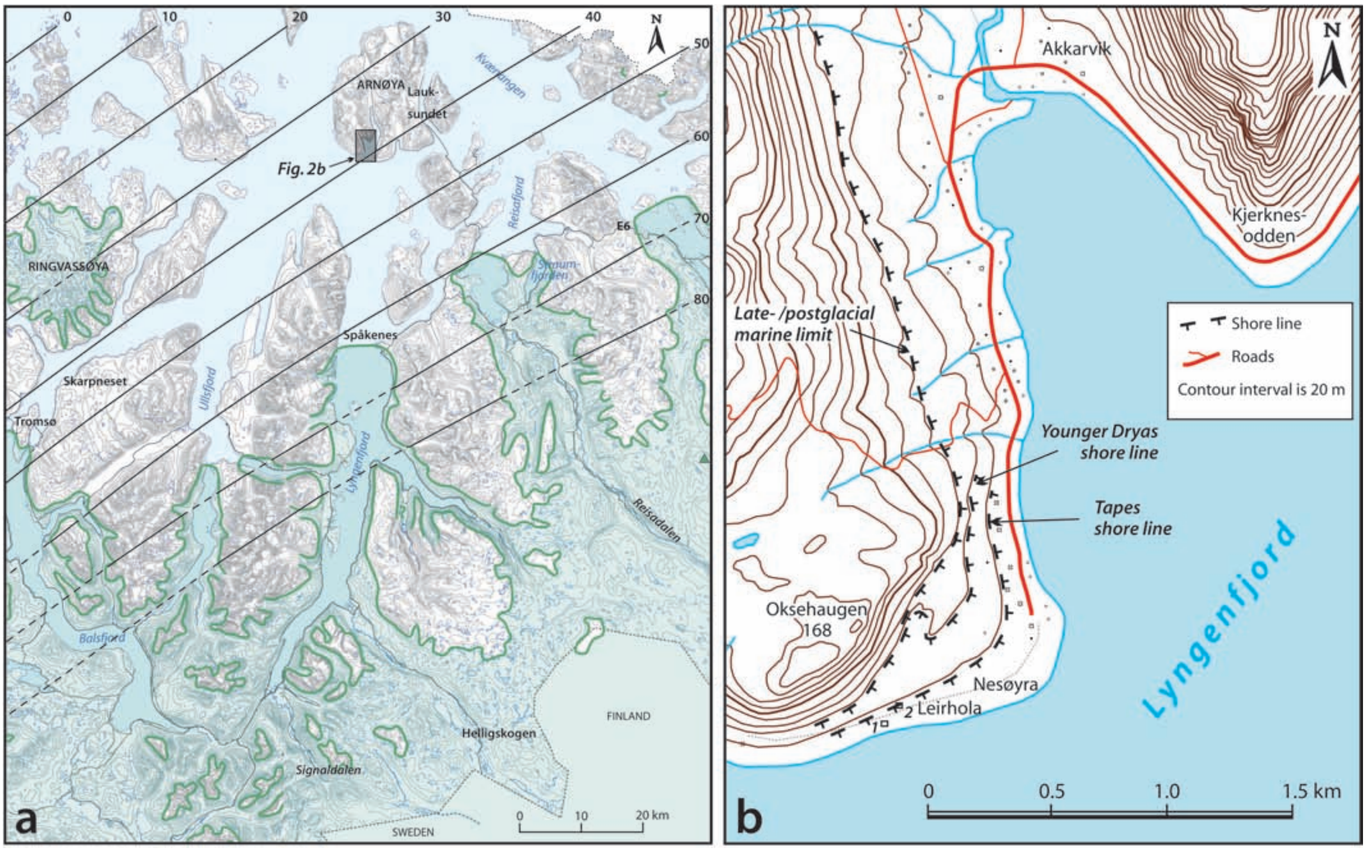


Figure 2. (a) Map of Troms and location of Arnøya. The Younger Dryas isobases (black lines, stippled on ice) and glacier extension (bluish transparent colour) are shown. (b) Close-up map showing the location of the Leirhola sites I (1) and II (2). Shorelines representing the late-/post-glacial marine limit, the YD and the Tapes intervals are also indicated.

greenstone and greenschist (Roberts 1974), and Quaternary sediments, which cover about 83% of the surface, are dominated by till, weathered material, scree and talus material, and marine shore deposits (Sveian et al. 2005). There are numerous cirque moraines on the island, most of which are supposedly of Younger Dryas (YD) age (Sveian and Bergstrøm 2004). The marine limit and the YD shoreline close to the Leirhola sites are located at c. 60 m a.s.l. and 38 m a.s.l., respectively (Figure 2b). The last deglaciation at Leirhola may have occurred as early as 15 cal ka BP (c. 13 ka ^{14}C BP), i.e. shortly after the D-event described from the outer fjord/inner shelf area farther south in Troms county (Vorren and Plassen 2002).

Leirhola site I

Three sections in the slope of a strand terrace at c. 10 m a.s.l. have earlier been described by Andreassen et al. (1985). These sections are here named Leirhola I (L I) (Figure 3) and include deformed glacimarine/marine sediments which are overlain by a diamicton interpreted as till. Another diamicton, also inferred to be a till, is resting on top.

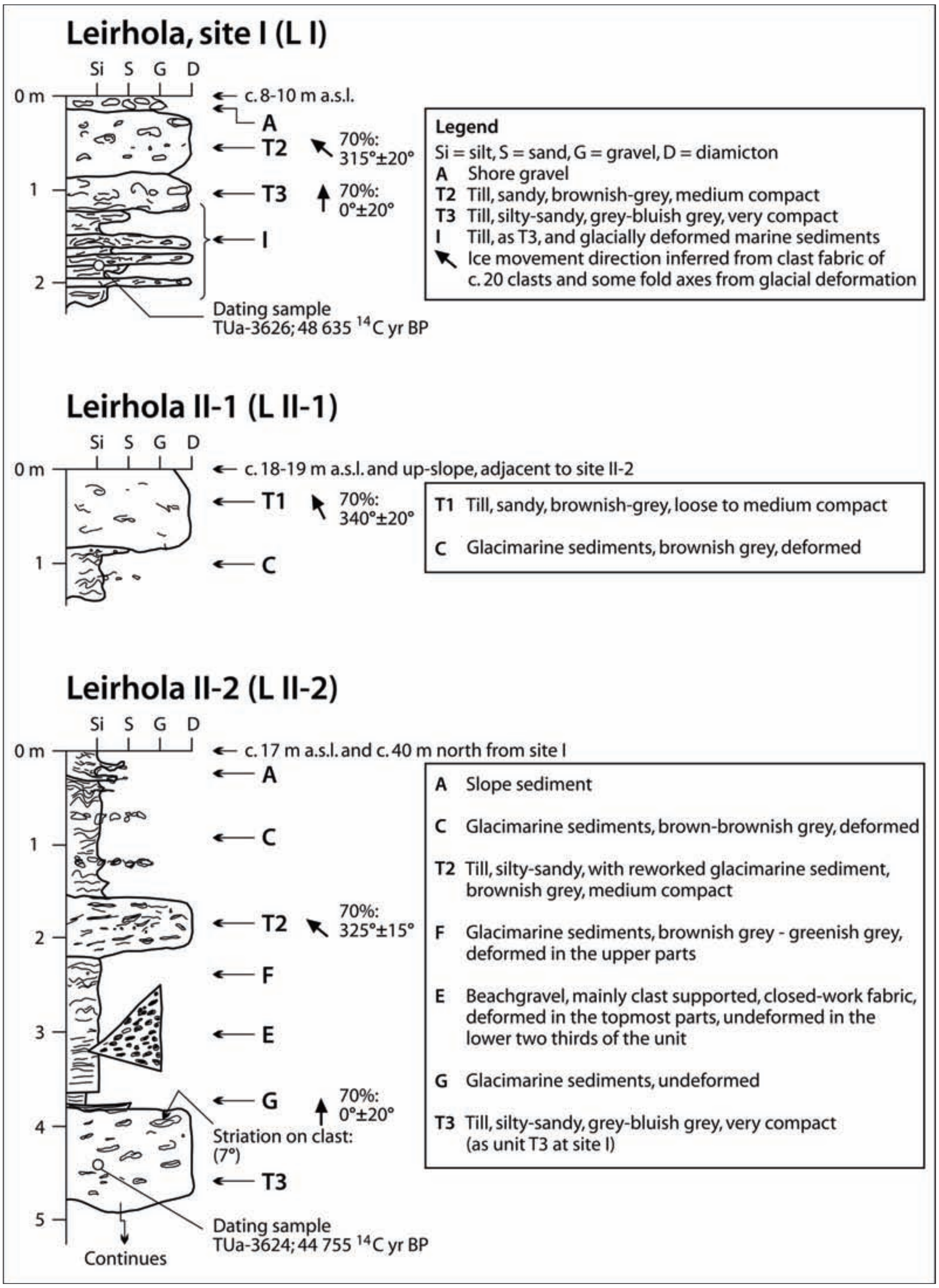
Both upper tills include deformed and probably partly dislocated glacimarine/marine sediments as well as diamict material with subangular to subrounded clasts, some of which show glacial striations. Marine shells from the lower till and from the subtill sediments date to 26.3–51.3 ^{14}C ka BP (within ±1 std and n=5) (Table 1). An age of c. 27.4 ^{14}C ka BP has been obtained from the dating of a shell in a surficial till at Lauksundet on the eastern side of the island (Andreassen et al. 1985). The till at Lauksundet is considered to be equivalent to the uppermost till at L II, based on a similarity of lithology and texture. Furthermore, regional mapping has shown that it is most likely that the uppermost tills at these sites and elsewhere on the island are of LGM and early late-glacial age (Sveian et al. 2005).

Leirhola site II

The new excavation (L II; a combination of L II–1 and L II–2; Figure 3) is located about 40 m from L I at the boundary between the Tapes shore terrace and the slope up to the YD shore terrace.

In the deepest part of the excavation (L II–2), till T3 from the upper part of L I is easily recognised by its fine-grained and compact character and its bluish-grey colour, under a thin cover of brownish-grey sandy and gravelly material. The pebbles in the sandy and gravelly top cover of till T3 are mainly subangular, and quite similar to the clasts in the till. The position at the top of the till with the overlying massive clay G (Figure 4), together with the subangular nature of the pebbles, suggest that this sub-

Figure 3. Stratigraphic logs from Leirhola sites I, II–1 and II–2. The log from Leirhola I is simplified and combines several sections described by Andreassen et al. (1985). The term Leirhola site II is used in the main text for a combination of sites II–1 and II–2. For details of dates, see Table 1. A suggested correlation between these sections is shown in Figure 5.



unit is a product of ice-rafting or possibly glacifluvial outwash rather than having originated by wave washing in shallow water (e.g., a shore deposit). Small fragments of marine shells are found in the till. Above till T3 follows an undisturbed, bluish-grey, massive clay that changes upwards into laminated clayey silt and sand (G), which are inferred to be glacimarine. Sediment unit F then follows (Figure 3). It is a faintly laminated, almost massive bedded, pale brownish-grey to greenish-grey sandy silt, which is undisturbed in its lower part, but deformed by slumping and subsequent glacial deformation in its upper part. These sediments are also interpreted as being of glacimarine origin. Gravel unit E, inferred to be a shore gravel, cuts into glacimarine units F and G (Figures 3 and 4) and wedges out in F. The excavation also revealed a cross-section through a beach ridge developed in shore gravel unit E. The buried erosional top of the ridge reached up to c. 1.5 m above the surrounding, subhorizontal, shore gravel horizon (E). The upper one-third of unit E (in the ridge cross section) shows deformational structures which indicate glacial thrusting and folding. This process may have resulted in the increased height of the ridge as compared to the

Figure 4. Photograph of the sandy gravelly top cover of till unit T3 (H on the photo) overlain by undeformed glacimarine sediments (unit G) and the lower part of shore gravel unit E.

original beach ridge. The lower two-thirds of unit E (i.e., about 1 m in thickness) show normal beach ridge structures, including pebble imbrication (Figure 4), and no signs of deformation. This would indicate that the original height of the beach ridge may have been around 1 m. Glacimarine unit F contains structures in its upper parts that point to slumping and sliding towards the upper part of the beach ridge, followed by glacial thrusting and overriding. These structures, however, were not observed in the sediments of unit F below the shore gravel E.

Till T2 overlies glacimarine unit F and is moderately compact, greenish-grey to brownish-grey and relatively fine grained with a silty and sandy matrix. The glacimarine sediments (unit C), which overlie till T2, are deformed, silty and sandy, faintly laminated and have a brownish-grey colour and are again overlain by till T1. This till is apparently more coarse grained, lithologically and texturally more variable, and generally has a less compact character than the underlying tills. The colour of till T1 varies between greenish-grey and brownish-grey, and this till, partly combined or intermixed with till T2, is considered to be the dominant surficial till on Arnøya. Till T1 is capped by sandy, slope-gravitational sediments (A). The youngest unit A also includes wave-washed material (sand, gravel, and some stones and boulders) on the Tapes and younger postglacial shore terraces.

The ice movement direction during the deposition of tills T3 and T2 is inferred from measurements of moderate precision (±10°) of deformation structures (fold axes, thrust planes) in unit I (at L I) and unit F, respectively, and from some clast fabric measurements from each till. From these data, it seems that tills T3 and T2 were deposited during ice flow towards the N and NW, respectively (Figure 3), which is also supported by striations on the tops of clasts under each till. Deformation structures (mainly fold axes) in unit C, striations on exposed bedrock and clast fabrics in the surficial till at L II–1 and elsewhere on Arnøya suggest that the uppermost till T1 was deposited during ice movement towards the N–NW. The observations of ice-flow directions are in full agreement with ice growth in the south and ice flow into the Lyngenfjord system (Figure 2), which probably occurred in this region during all major glaciations of the Quaternary, including the LGM. The records from L I and L II (L II–1 and L II–2) are combined in a schematic figure (Figure 5), which also includes inferred (eroded) parts of units T2 and E (stippled).

Ytresjøen

Ytresjøen is also located distally to the YD ice margin. It is located in a road cut at c. 21–27 m a.s.l. (Figure 6) (66°48.24' N, 13°34.8' E). Bedrock is dominated by mica schist, mica gneiss and granites (Gjelle et al. 1995). Quaternary sediments and the occurrences of YD cirque moraines are similar to those on Arnøya (Olsen 2002, Olsen and Bergstrøm 2003). The marine limit and the YD shoreline close to the site are located at c. 100 m a.s.l. and 90 m a.s.l., respectively. The last deglaciation at Ytresjøen is dated to c. 13.8 cal ka BP (c. 12 ^{14}C ka BP; Olsen 2002).

A sediment succession (Figure 6) from Ytresjøen has been described briefly by Olsen (2002). It includes from bottom to top: a sublittoral, gravelly sand with shells, mainly of *Mya truncata* (unit D); a lower till (unit C) containing a large boulder (1.5x3x>3 m) in the uppermost zone, with a horizontal belt of *Balanus sp*. on the exposed seaward side and glacial striae on top. The belt with *Balanus* shells may indicate the mean sea level of a former ice-free interval, in this case c. 23 m above the present sea level. Overlying the lower till is an upper till (unit B), with a shore deposit on top (unit A). Clast fabrics in the upper till show features similar to the striations on the large boulder and on exposed bedrock in the area, indicating ice movement towards the W–NW (Olsen 2002, Olsen and Bergstrøm 2003). ^{14}C dates from this site have given ages of c. 28.3 ^{14}C ka BP for a shell from the *Balanus* belt on the boulder, and c. 35 ^{14}C ka BP from a shell in the contact zone between the lower till and the subjacent sediments (unit D) (Table 1).

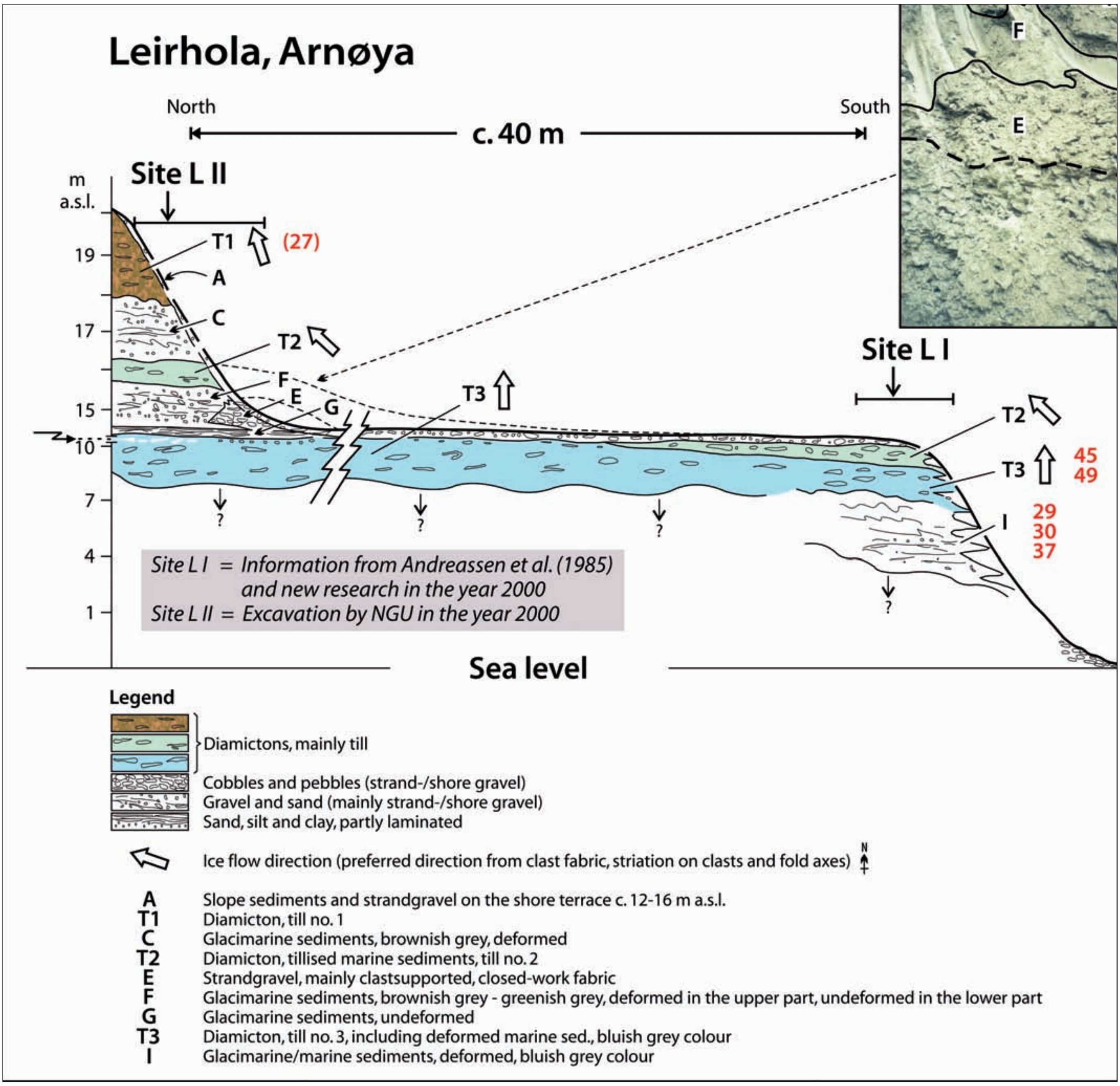


Figure 5. Simplified sketch of a N–S profile through Leirhola II and I. NGU=Geological Survey of Norway. Note the change in scale just above 10 m (a.s.l.) and the compression of the horizontal scale indicated by parallel 'zigzag' lines through units A and T3. The inset photograph represents a c. 2 m vertical section in L II and includes the basal part of till unit T2, the deformed upper part of glacimarine unit F, the topmost eroded and deformed part of the shore gravel unit E, and the lower undeformed part (below stippled line) of the shore gravel in the cross section through the inferred beach ridge. Dates in ^{14}C ka BP (red numbers) are indicated stratigraphically, except those from unit I, which are plotted in chronological order with respect to age. The ^{14}C date indicated as (27) from till T1 is from the adjacent site Lauksundet (after Andreassen et al. 1985).

Reliability of the ^{14}C dates

Radiocarbon dates of 30–40 ka-old shell samples are very sensitive to contamination with young C, and small samples are more sensitive than larger samples. All the shell dates from Leirhola and from a neighbouring area on Arnøya (Lauksundet; Figure 2) were performed on small samples taken mainly from fragments of shells and from shallow depths, and only a minor outer part was removed in each case before dating (Andreassen et al. 1985, and this paper). Resedimentation of shells from older units occurs frequently in coastal settings (e.g., Olsen 2002), and is a complicating factor for sediment age estimations. Together, these factors indicate that the dates from Arnøya, which all have high standard deviations (Table 1), should be considered with great caution. However, the fine-grained bluish-grey sediment in the oldest unit I (glacimarine deposit) at site L I, where the present groundwater level is well below the recorded sections, indicates anoxic conditions with only a very small amount of percolation

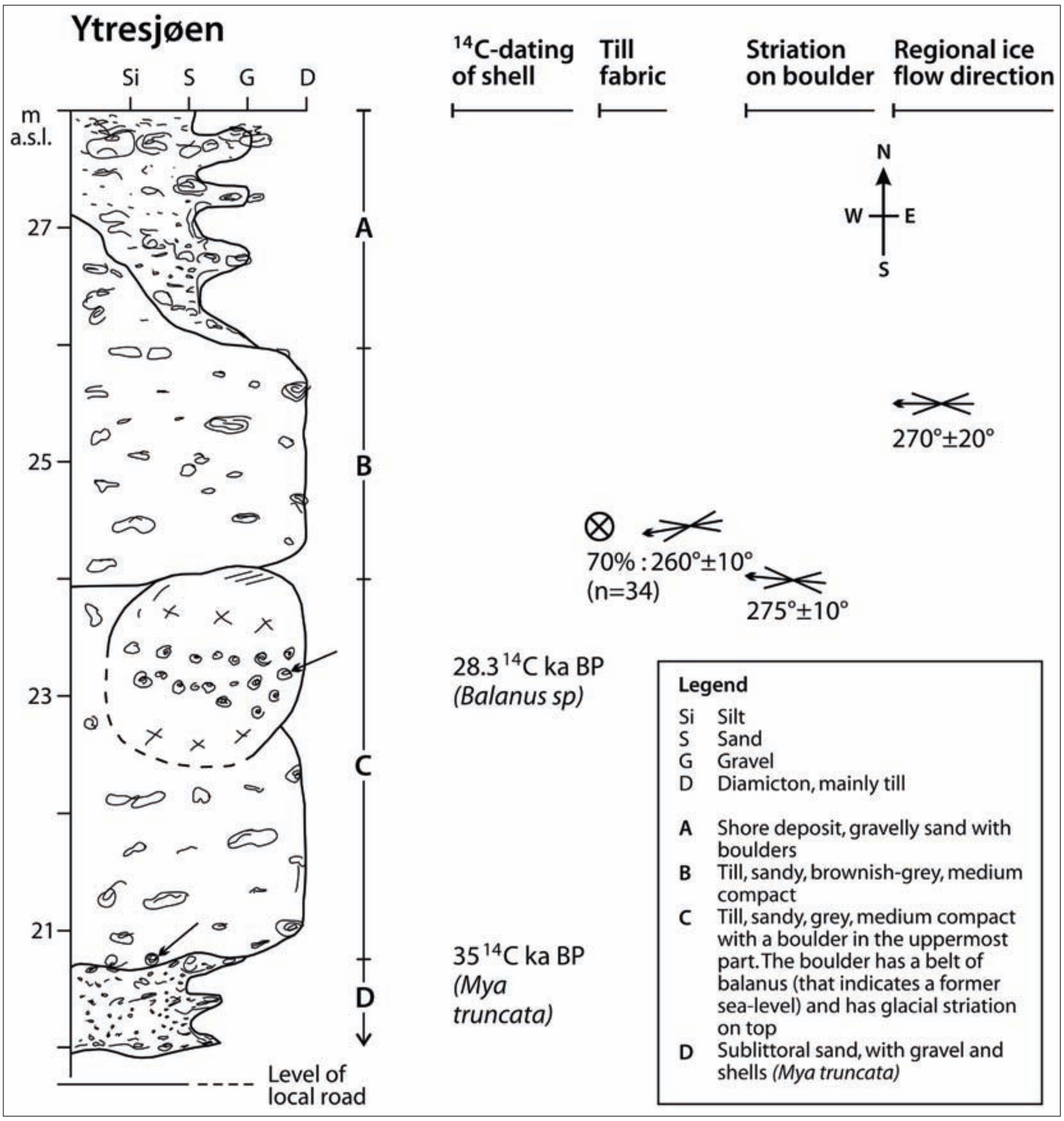


Figure 6. Stratigraphic log from Ytresjøen, Nordland, modified from Olsen (2002). The positions of the dated samples (shells) are shown with arrows on the log. See Table 1 for details of the dates.

of fresh groundwater. The input of young C may therefore have been low, and since there is no positive indication of contamination, but signs of resedimentation of older shells in overlying units, I conclude that the age range of 31–55 cal ka BP, including ±1 std for dates from this unit (Table 1), is reliable and that the age of unit I is around 35–50 cal ka BP.

The two dates from Ytresjøen (Table 1) are both ^{14}C-AMS dates of single fragments of well preserved shells. Both samples were taken from newly exposed sections at a sediment depth of more than 2–4 m. The dates at c. 33.6 cal ka BP (c. 28.3 ^{14}C ka BP) and c. 40 cal ka BP (c. 35 ^{14}C ka BP), which have low standard deviations, are both considered reliable.

Sea-level history inferred from Leirhola I and II

Eight relative sea levels of different age have been recorded at and around Leirhola (L I and L II) on Arnøya (Figure 7). The oldest of these is the 35–50 cal ka BP sea level at more than 10 m a.s.l., possibly 15 m a.s.l. or more, represented by glacimarine sediment unit I (site L I; Figure 3). The subsequent recorded sea-level phase, after an intervening glacial advance and retreat (represented by till unit T3 and its sandy and gravelly top cover), is represented by the glacimarine sediments of units G and F with a sea level reaching at least to 18–19 m a.s.l. The latter was followed by a regression phase reaching a minimum sea level at least as low as 14 m a.s.l. as represented by strand gravel of unit E. After another glacial advance (represented by till unit T2), the sea level rose to at least 20–21 m a.s.l. as indicated by the glacimarine sediments in unit C. The last glacial advance (till T1) was followed by two late-glacial phases with maximum sea levels of 60 m a.s.l. (marine limit) and 38 m a.s.l. (YD), an early postglacial phase with a weakly developed shoreline (step in the slope) at c. 25–27 m a.s.l. (Preboreal), and another postglacial phase with a maximum transgressional sea level at c. 16–18 m a.s.l. (Tapes).

Figure 7 compares the sea-level history from Leirhola (upper panel) to the global eustatic history inferred from coral terrace levels in New Guinea and the age model proposed by Shackleton (1987) (lower panel). These data sets are based on different

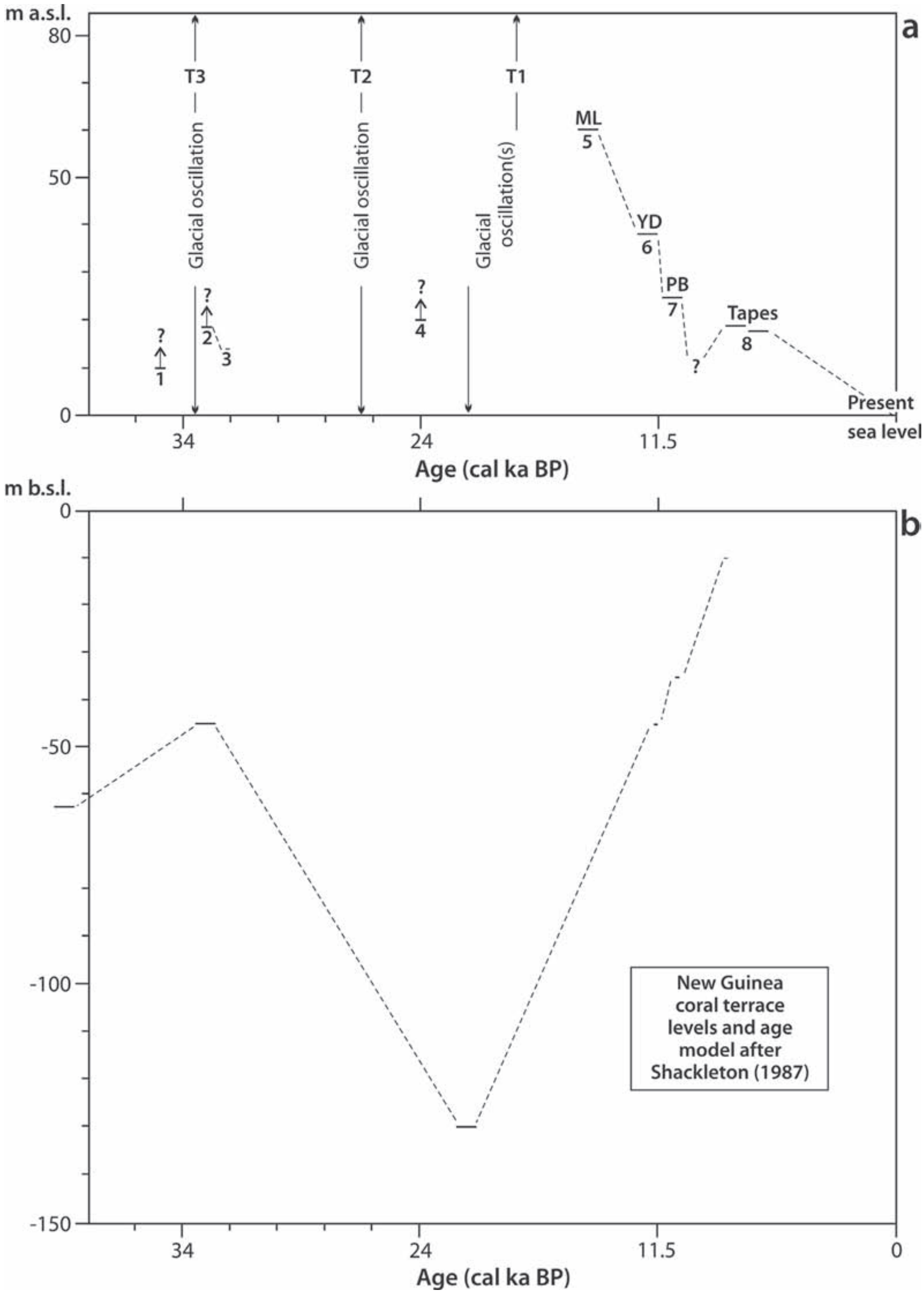


Figure 7. (a) Sea levels numbered 1–8 derived from Leirhola I and II are shown. T1, T2 and T3 refer to till units, and ML, YD, PB and Tapes refer to shorelines at the late-/post-glacial marine limit, during Younger Dryas, Preboreal and the Tapes intervals, respectively. Note that the ages for till T1, sea level 4 and till T2 are tentative. Note also that all pre-T1 sea levels are minimum estimates only, except for no. 3, which represents a more accurately estimated sea level (14 m a.s.l.). (b) Global eustatic data shown in the lower panel are modified from Shackleton (1987).

dating materials, different age models and derive from different regions, and the ages are therefore expected to be slightly out of phase. However, even with a possible small discrepancy in ages, it seems that the Arnøya sea-level history matches fairly well with the eustatic history at around c. 33–35 cal ka BP, which is considered to be the most likely minimum age of shore gravel unit E (discussed below).

Discussion

The shore gravel of unit E (Figures 3, 4 and 5) may represent a regression minimum to 14 m a.s.l. after a phase with a relative sea level that was several metres higher (Figure 7). The position of the Leirhola sites on the southern shore of the island indicates that the ice sheet did not reach Arnøya during the time of formation of the 14 m shore deposit. Therefore, the extension of the glacier towards the north must have been no more than during the late-glacial Skarpnes Substage (c. 13.9 cal ka BP) (Andersen 1968, Vorren and Plassen 2002) or slightly less (e.g., as that during the Tromsø-Lyngen (Spåkenes)/YD Substage, Figure 2a). A further discussion of the size of the ice sheet during the 14 m sea-level phase is difficult without consideration of the glacioisostatic conditions. I surmise that the New Guinea coral terrace levels may be a fairly good direct indicator of global sea levels during MIS 3 (Chappell 1983, 2002, Ota et al. 1993), and I therefore use these data here with the age model of Shackleton (1987) as the eustatic data source (e.g., Figure 7).

The 14 m sea level (Figure 5) predates the tills T1 and T2, which are considered to be of LGM and early late-glacial age. The best age estimate for the 14 m sea level is, therefore, that it is younger than unit I (35–50 cal ka BP) and the subsequent intervals represented by till T3 and glacimarine units G and F (Figures 3 and 5), and older than the LGM. Considering the global eustacy for this age interval (Shackleton 1987), the location of the Leirhola sites compared to the YD ice margin (Figure 2a), and the associated glacioisostatic conditions, any age between 50 and 33 cal ka BP for this sea level seems possible (Table 3). However, the age intervals with ice cover (further discussed below), e.g., shortly after 45 and 34 cal ka BP, may be excluded. An age older than 45 cal ka BP is possible, but only if the ^{14}C dates (from unit I) are severely contaminated with young C (see above). Even a slightly younger age is possible, but perhaps less likely since it is closer in time to the ice growth leading to the first LGM advance, prior to 25–26 cal ka BP (e.g., Vorren et al. 1988, Møller et al. 1992, Alm 1993, Olsen et al. 2001b).

I have estimated the relative glacioisostatic conditions of Arnøya (Table 3). The pre-LGM 14 m (a.s.l.) sea level on Arnøya is combined with the global eustacy at different ages and compared with the relative glacioisostatic conditions during the YD. For example, given an age of 33 cal ka BP for the 14 m sea level on Arnøya, the relative glacioisostatic depression would be c. 70% of that during the YD. However, it is not straightforward to use this as a direct estimate of the size of the 33 cal ka BP ice sheet as 70% of the YD ice sheet, because the glacioisostatic conditions depend on the memory of ice load in the crust. The following question should therefore be addressed. Was the crust loaded by a large ice sheet or a smaller one a short time before the 14 m sea-level event on Arnøya? I will consider this problem later.

Glacioisostacy, i.e., the response of the Earth's crust to loading and unloading of an ice body, can be described geophysically (e.g., Lambeck et al. 1998) or in a much more simple manner by using only empirical data. In this paper I use a simple 'model' where only the vertical movement of the Earth's crust is considered.

Based on a comparison with shoreline displacement and eustatic sea-level data, it seems that most of the recovery of the Earth's crust after the last glaciation in Scandinavia occurred within a few thousand years. Therefore, I use tentatively the 'half-life' of rebound, which I set at, e.g., 3000 yr, to represent the average postglacial rebound rate after release of the ice load. This

Table 3. Sea-level data from Arnøya, northern Norway (various sources), and from coral terraces in New Guinea (after Shackleton 1987). Ages are in cal ka BP. The Andøya-Trofors interstadials (A.-T. interst.) have a proposed age of 17–21 ^{14}C ka BP (20–25 cal ka BP), after Olsen et al. (2001b).

Sea-level data from:	Post-Tapes c. 5 ka m a.s.l.	Tapes 6.5–8 ka m a.s.l.	Preboreal 10.1–10.2 ka m a.s.l.	YD 11.5–12.7 ka m a.s.l.	A.-T. interst. m a.s.l.	Pre-LGM c. 33 ka m a.s.l.	MIS 3 c. 35 ka m a.s.l.	MIS 3 c. 40 ka m a.s.l.	MIS 3 c. 52 ka m a.s.l.	Comments
Buried shore deposit, Arnøya					14	14	14	14	14	Data from site L II
Eustacy; New Guinea terraces	0	-10	-35	-45	-130	-45	-50	-63	-30	Data from Shackleton (1987)
Y Dryas shore (11.5–12.7 ka)				38						Various sources (from NGU, and others)
Preboreal (10.1–10.2 ka)			27							
Tapes shore (6.5–8 ka)		16								
Post-Tapes, max. (c. 5 ka)	14									
Isostatic depression in metres	14	26	62	83	144	59	64	77	44	*) Ages > 45 ka BP less likely, based on C14-dates of subjacent unit I
Isostatic depr. vs YD isostatic depression	17 %	31 %	75 %	100 %	173 %	71 %	77 %	93 %	53 %	
Favourable (+)/unfavourable (–) result of isostatic conditions and age versus (vs) location of site vs YD ice margin					–	+	+	+	*	

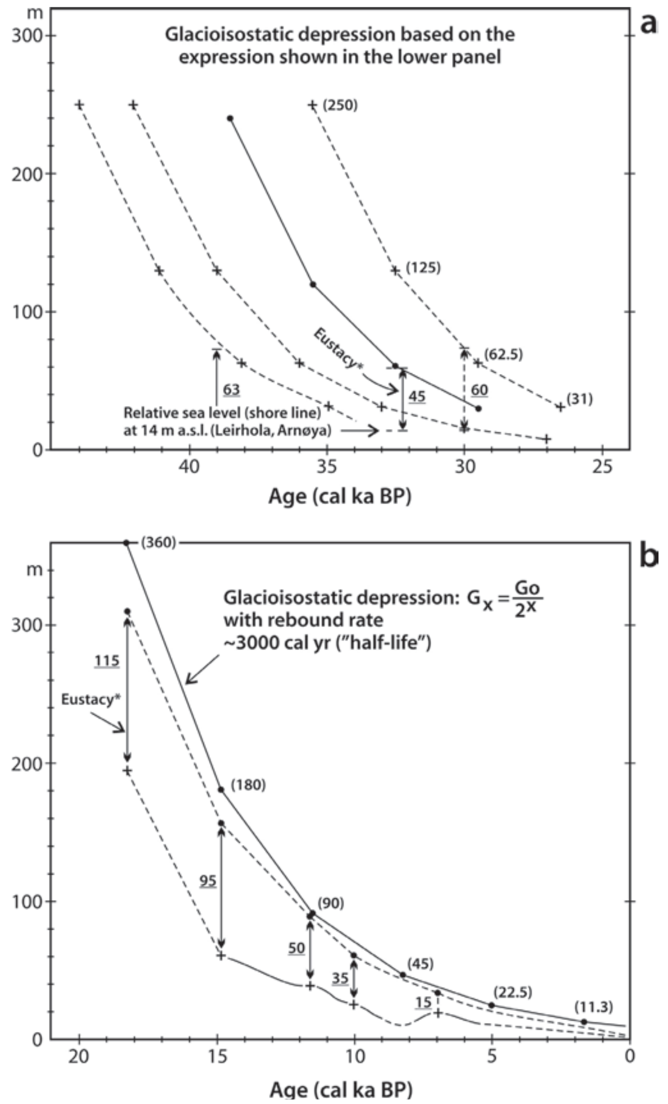


*Figure 8. Comparison between glacioisostatic depression after the equation $G_x=G_o/2^x$, assuming an initial depression (G_o) of the crust of 250 m (a, upper panel) and 360 m (b, lower panel) at selected start times for the rebound, and from relative sea level + absolute value of 'global' eustatic sea level in metres. The relative/eustatic sea-level curve between 18 and 15 cal ka BP in the lower panel is tentative (estimated from the glacioisostacy equation for comparison). The middle curve (full line) in the upper panel is based on the observed late Middle Weichselian 14 m (a.s.l.) shoreline with its possible age at 33 cal ka BP at Leirhola + global eustacy data, and rebound corresponding to these data and the given equation. *) Eustatic data are after Shackleton (1987) (upper panel) and Bard et al. (1990) and Fairbanks (1989) (lower panel).*

may be valid for the marginal zones of the former ice sheet, such as at the outer coastal parts of northern Norway where Arnøya is located. The rebound rate in the inner fjord regions has been much higher, as indicated by steep, postglacial, shoreline displacement curves, e.g., from the Oslofjord, the Trondheimsfjord and the Varangerfjord areas (Figure 1) (Hafsten 1956, Kjemperud 1986, Fletcher et al. 1993). The half-life of rebound is therefore a value that is specific for each area. The postglacial rebound in this model can be calculated from the equation: $G_x=G_o/2^x$, where G_o is the glacioisostatic depression at a given time and G_x is the glacioisostatic depression at x half-lives after this time. This gives a theoretical rebound as an exponentially declining curve during the entire postglacial period, which may be a fair and useful approximation to the real glacial rebound, at least for the marginal zones of the ice sheet.

Precise data, e.g., for the position of and distance to the central ice dome, and the age of initial ice growth are needed for advanced modelling of ice thickness and ice-sheet rebound (e.g., Lambeck et al. 2006). These data are not known in detail for the MIS 3 Scandinavian ice sheet. Therefore, I use here a simple 'model' where an ice load is considered to depress the Earth's crust by approximately one-third of the ice thickness (Paterson 1994). By assuming a very small *average* lowering of the bedrock surface due to erosion over the last 50 ka and with an assumed G_o=360 m, which therefore implies an ice-load effect of at least a 1000 m-thick ice sheet at 18 cal ka BP, I have shown in Figure 8 that there is a fairly good match between the calculated and the empirical data (relative sea-level/shoreline displacement and global eustacy) in the interval 15 cal ka BP to the present. The hypothetical Gx curve is supposed to reflect the recovery of the crust due to additional loading from ice, i.e., the total loading from ice minus eustatic water lowering (Figure 8, lower panel).

It is also shown that the glacioisostacy equation used together with the 14 m sea level from Leirhola at its possible age of 33 cal ka BP and the eustacy of that time is compatible with rebound after deglaciation of a c. 720 m-thick ice sheet (=240 m glacioisostatic depression) at c. 39 cal ka BP (Figure 8, upper panel).

From the published record it is known that there was a major ice advance in different parts of Norway at c. 45 cal ka BP which reached even beyond the coastline in SW Norway (Larsen et al. 1987, Mangerud et al. 2003) and northern Norway (Vorren et al. 1981, Olsen et al. 2001b, Olsen 2002). It is also known that significant ice growth, also reaching beyond the coastline, occurred at around 33–34 cal ka BP, i.e., after the Ålesund interstadial (Mangerud et al. 1981, Andreassen et al. 1985, Larsen et al. 1987, Olsen et al. 2001b). The redefined age range of the Ålesund interstadial is now 34–28 ^{14}C ka BP (c. 39–33 cal ka BP) (Mangerud et al. 1981, 2003, in print, Larsen et al. 1987). Different scenarios for the ice thickness (based on glacioisostatic depression) and age of the 14 m shoreline can be considered from Figure 8 (upper panel) and the regional record. If the duration of the deglaciation of the 45 ka ice sheet was short and most of the ice had melted before 41–42 cal ka BP, then a considerable ice growth just before or during (preferably towards the end of) the 39–33 ka interval would appear to be required to fit with the Leirhola shore line at 14 m a.s.l. and 33–35 cal ka BP (Figure 8). If, on the other hand, this deglaciation took a long time, then no ice growth or only a moderate ice growth towards the end of the 39–33 ka BP age interval would seem to be required to match the Leirhola data. Furthermore, an age closer to 40 cal ka BP for the shore line would require either a very rapid deglaciation after the 45 cal ka BP ice sheet or, alternatively, an ice sheet that was considerably thinner (<750 m) than I have postulated based on the regional data (e.g., Olsen et al. 2001b).

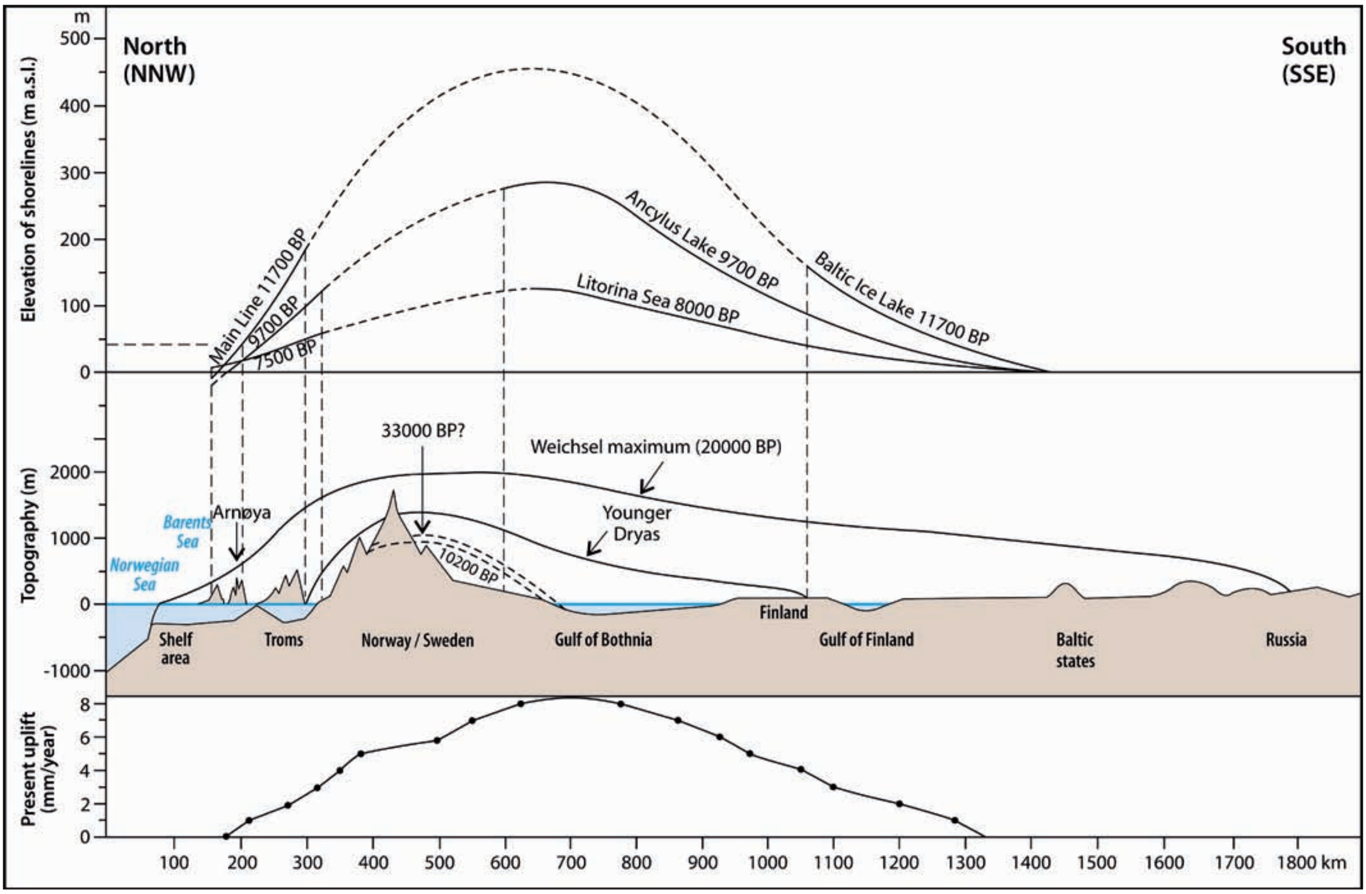


Figure 9. Sea levels, ice surfaces and present uplift data plotted in profiles along a NNW–SSE transect (location indicated in Figure 1). The conceptual idea, the sea levels (upper panel) and the ice surfaces (middle panel) are modified from Svendsen and Mangerud (1987). The sea levels *are adjusted in the northernmost part based on regional Quaternary mapping during the 1990s. The* ice surfaces *are based on a model with reduced ice thickness and a profile levelling out in the lowland and basin areas as well as on the shelves. The ice-surface profile at c. 35–33 cal ka BP (33000 BP) is based on the estimates in Tables 2 and 3 with a 50–70% isostatic depression as compared to that of the YD interval.* The recent uplift data *(lower panel) are from Dehls et al. (2000).*

There are few indications for accurate estimates of late Middle Weichselian relative sea levels in Norway. Most of the sea-level indicators are based on reworked marine shells, many of which are resedimented in tills and other sediments (e.g., Mangerud et al. 1981) and are therefore of limited value as sea-level indicators. However, some of the finds represent marine shells in sedimentary units in subtill positions and are therefore conceivably more accurate indicators of sea level. Five of these, all from Nordland, northern Norway, are listed in Table 2, and their glacioisostatic conditions indicate a 51–>85% depression of the crust as compared with that of the YD. I consider the most precise and accurate of these sea-level data to be those from the Ytresjøen locality (Table 2). The ^{14}C dating of one of these *Balanus* shells at c. 33.6 cal ka BP suggests an age close to that for the proposed most likely age of the shore deposit at 14 m a.s.l. at Leirhola, Arnøya. The similarity between the Ytresjøen and Leirhola data is even more intriguing if considered that, also at Ytresjøen, the preceding considerable ice advance, as represented by a till, occurred just before the discussed sea-level event. At Ytresjøen, this ice advance is constrained between c. 40 and 33.6 cal ka BP (Table 1) (Olsen 2002).

The glacioisostatic conditions during the Ytresjøen sea-level event indicate a 51% depression of the crust compared to that of the YD. With the preceding large ice load in mind, this signifies an even smaller ice remnant during the discussed sea-level event than is implied from the Leirhola data.

Conclusions

From the record of a late Middle Weichselian sub-till shore deposit at 14 m a.s.l. at Leirhola, Arnøya, northern Norway, it may be concluded that:

1) The ice extension during the formation of the shore deposit may have reached a maximum extent slightly greater than during the late-glacial Younger Dryas interval.
2) An age at c. 33 cal ka BP for the 14 m shoreline is in accord with the published record, with a large ice sheet at c. 45 cal ka BP that retreated rapidly (e.g., Olsen et al. 2001b), and with new ice growth at c. 34–33 cal ka BP (Larsen et al. 1987), which was followed by a rapid and significant ice retreat shortly after that time (Olsen et al. 2001b). An age

for the shoreline at 35–34 cal ka BP may also match with the regional record if the ice retreat after the 45 cal ka BP glaciation was slower, and if the 34–33 cal ka BP ice growth occurred mainly after the 14 m sea-level phase. Even older age alternatives may be possible, but these suggest a very rapid deglaciation after the 45 cal ka BP glaciation and/or a much thinner (<750 m) ice sheet than expected.

3) The relative glacioisostatic depression during formation of the shore deposit at 14 m a.s.l. on Arnøya was only c. 70–80% of that of the YD interval (Table 3). This result, combined with the published record of large ice growths/advances in Norway at c. 45 and 33–34 cal ka BP, implies that the volume (thickness) of the ice sheet during the shore deposit formation was *much less* than during the YD, and was probably more like the size attained during a late part of the Preboreal (Figure 1).
4) Corresponding sea-level data from Ytresjøen and other sites in northern Norway indicate a lesser relative glacioisostatic depression, almost as low as 50% of that of YD (Table 2), and therefore also imply a much smaller ice remnant during the discussed sea-level event.

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