Postglacial sea-level history of Edgeøya and Barentsøya, eastern Svalbard

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Four relative sea-level curves from Edgeøya and Barentsøya are constructed based on 81 radiocarbon age determinations on carefully selected and levelled samples in raised beaches, mostly driftwood embedded in beach gravel. All the dates, covering the period from the deglaciation to the present, are calibrated to calendar years, and the sea-level curves are defined by fitting the data with a least square regression curve. The dates are internally very consistent, and the results are some of the most precise sea-level curves from the Arctic.

The four curves are quite similar, and from the marine limit at 85–90 m a.s.l. they show a rapid emergence (ca 40 mm/year), formed about 11,000 cal yrs BP (≈10,000^{14}C yrs BP). A minimum rate of emergence close to 8000 cal years ago is explained by a decreased rate in isostatic uplift parallel with a sustained rate of eustatic sea-level rise. During the last 7000 cal years, the emergence rate has decreased linearly. The uplift rates have been slightly higher on southern Edgeøya than further north during the last 7000 years. By comparing the sea-level curves from Storøya (ca 270 km to the north) and Hopen (ca 150 km to the south), we suggest that a memory of an earlier and larger glacio-isostatic downwarping in the southern Barents Sea is detected in the sea-level curves from Hopen and southern Edgeøya.

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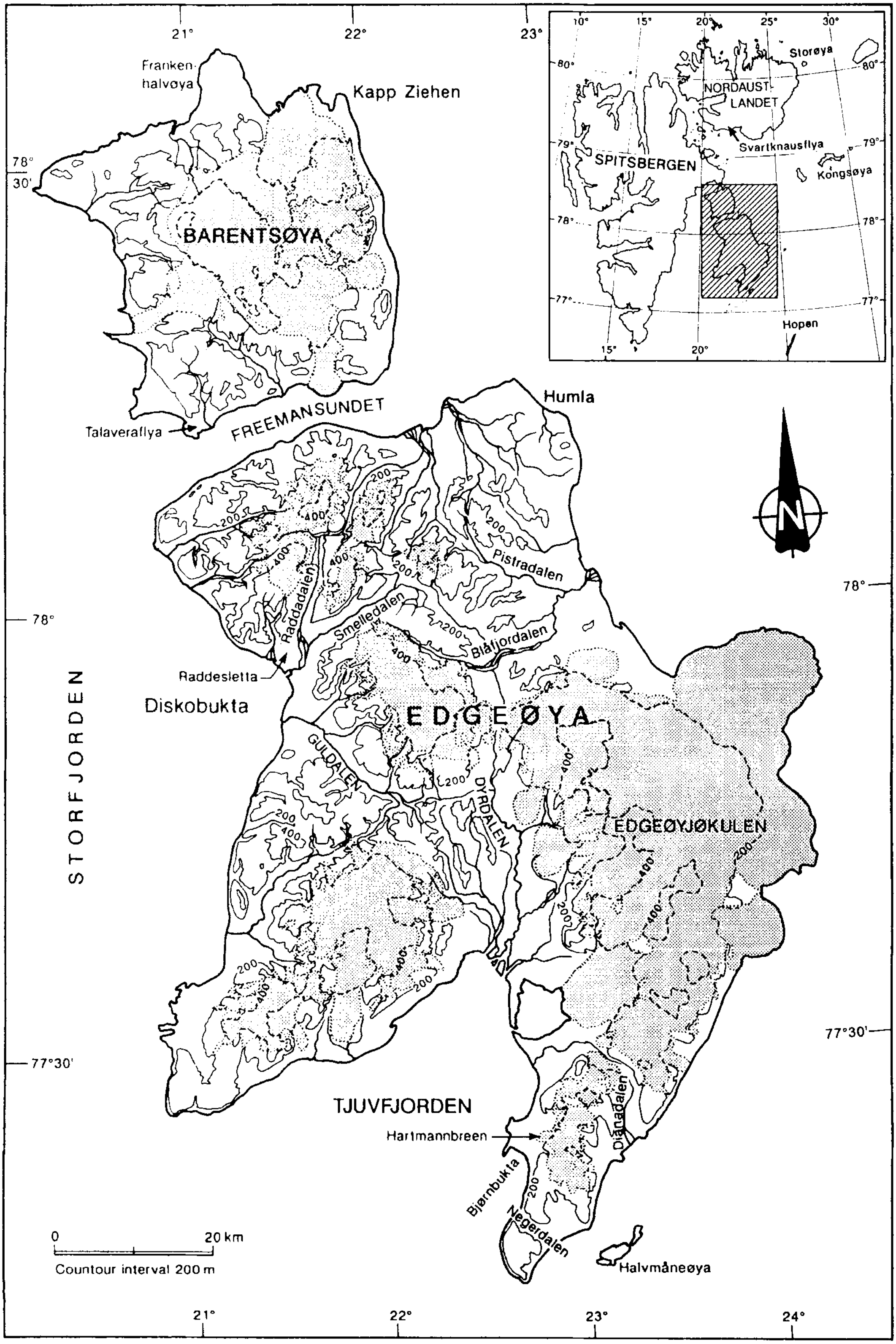
Introduction

The pattern of glacio-isostatic uplift has been a classical tool for reconstructing the last glacial maximum ice sheets in the Arctic of both North America (e.g. Andrews 1970; Blake 1970) and Europe (e.g. Schytt et al. 1968). In recent years a more sophisticated geophysical modelling has been applied to sea-level data, both to reveal the glacial history and to study the structure of the earth's interior. For the Svalbard and Barents Sea areas, this was recently done by Elverhøi et al. (1993), Breuer & Wolf (1995) and Lambeck (1995). Thus the importance of the geological work has moved more to primary observational data and the geological interpretation of the field relationships. Accordingly the aim of this study is to determine as accurately as possible the elevation and age for the relative sea level by means of extensive and careful field work and sample treatment. Edgeøya and Barentsøya represented a lacune in our previous knowledge of the uplift of Svalbard (see compilation in Forman 1990). It was therefore important to cover this area with reliable sea-level data. The sea-level curves constructed are some of the most accurate sea-level curves available from the Arctic.

Driftwood is frequent on and within the raised beaches in eastern Svalbard (Salvigsen 1978, 1981) and is extremely well preserved due to the dry, cold climate. On Edgeøya and Barentsøya raised beaches are common in a number of forelands and outer valley mouths up to 90 m a.s.l. These provide a high resolution record for the construction of sea-level curves.

Wood, fed by the large rivers of Siberia into the Arctic Ocean, is caught in drifting ice and transported towards Svalbard at an average speed of 600 km/year (Häggblom 1982; Eggertsson 1994). To cover a distance of 3000 km, a driftwood log needs more than three years for the passage from Siberia to Svalbard. Because wood absorbs water, logs can float in the ocean at maximum 1–1.5 years and therefore no driftwood would reach Svalbard from Siberia drifting on an ice-free Arctic Ocean (Häggblom 1982). Also some wood probably originated from European Russia, which is closer. The stranding of driftwood on the shores in eastern Svalbard takes place mainly during the summer period when the coastal waters are ice free.

Emergence of land relative to the sea is a process measured in mm/year. Since a ^{14}C year has varied in length through the Holocene, rates given


21°
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Storøya
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Svartknausflya
SPITSBERGEN
Kongsøya
Hopen
Frankenhalvøya
Kapp Ziehen
78° 30'
BARENTSØYA
Talaveraflya
FREEMANSUNDET
Humla
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Pistradalen
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Blåfjordalen
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Raddesletta
Diskobukta
STORFJORDEN
EDGEØYA
GULDALEN
DYRDALEN
EDGEØYJØKULEN
77°30'
TJUVFJORDEN
Hartmannbreen
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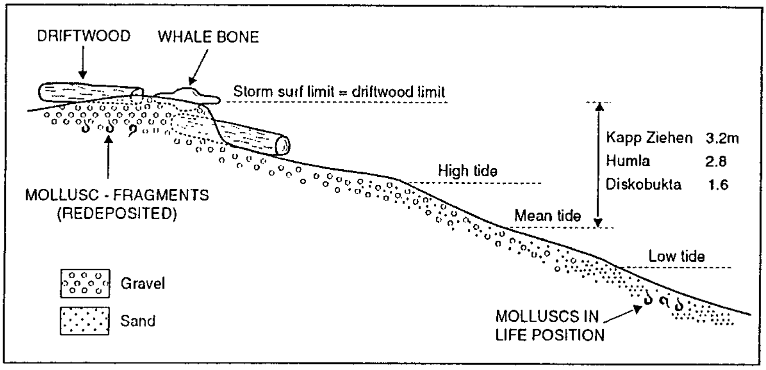

Fig. 2. Relation between sea level (mean tide) and sea level indicators (driftwood, whalebone and molluscs).

in ^{14}C years will be imprecise. We have therefore calibrated the ^{14}C dates to calendar years by using the calibration program of Stuiver & Reimer (1993). This calibration program, based on dendrochronology, will probably not change much in the future for the time period considered here (the last 10,000 ^{14}C years). Both ^{14}C years and calibrated years are given in the tables (Tables 1–4).

Samples for radiocarbon dating three complete sea-level curves were collected at Kapp Ziehen on Barentsøya and Humla and Diskobukta on Edgeøya (Fig. 1). In addition we collected some samples from higher elevations to complete a well-dated sea-level curve for the last 9000 ^{14}C years from the southern part of Edgeøya (Knape 1971).

A preliminary sea-level curve from Humla has been published (Mangerud et al. 1992b), and a more detailed description of both dated and undated samples from Humla and Diskobukta is given in Bondevik (1993). In this paper we present four complete sea-level curves from the area, based on more than 80 radiocarbon age determinations.

Methods

Fieldwork

All sample and paleoshoreline (terraces, beach ridges) altitudes were determined by precise levelling, except for the samples collected in Dianadalen on southern Edgeøya (Fig. 1), which were determined with an altimeter. In the field we used the local driftwood limit as reference point. This was determined to be 3.2, 2.8 and 1.6 m above mean tide level at Kapp Ziehen, Humla and Diskobukta, respectively (Fig. 2). All altitudes of samples and shorelines are corrected and refer to mean-tide level. The locations of samples are shown on aerial photographs (Figs. 7–10).

Wood and bones partly or totally embedded in beach gravel were preferred instead of samples resting on the surface. In intervals where embedded samples were not found, we preferred to sample large logs and bones (2–5 m length) located on wide terraces as these were unlikely to have been moved after primary deposition. However, most of the dated samples were anchored in beach gravel and often covered with a silt-rich surface soil. (Fig. 4, Tables 1–4).

An effort was made to date only the outer wood from driftwood logs. For most logs we sampled the whole cross section in the field and then prepared a piece of the outer wood for dating in the laboratory. The densest part of the bone was collected, and in the laboratory it was cut into cubes in order to examine any porous bone for extraneous matter, as recommended by Dyke et al. (1991). Most of the dated bones were completely dense with a greasy lustre on the sawed surface.

Radiocarbon dates and age calibration

The radiocarbon dates are reported as recommended by Stuiver & Polach (1977) and include a correction for isotopic fractionation to

Fig. 1. Key map of the investigated areas on Barentsøya and Edgeøya. Glaciers are shaded. Inset map of Svalbard.

Fig. 3. Driftwood logs embedded in beach gravel 31.9 m a.s.l. in Humla. Another log having similar stratigraphic position found close to these (1–2 m) was dated to 7220–7090 cal yrs BP (sample 88-508, Table 2, Fig. 8). The boundary between beach gravel and the silt-rich surface soil lies just above the log to the left of the trowel. The trowel is ca 25 cm long.

$-25‰$ $\delta^{13}C$ on the PDB scale. A reservoir age of 440 years has been subtracted in the reported ^{14}C ages (Tables 1–4) for all samples that have obtained their carbon from sea water (shells and whale bones) (Mangerud & Gulliksen 1975). The samples have been dated at the laboratory in Trondheim (prefix T-, on samples), and at the laboratory in Lund (prefix Lu-). Samples with prefix TUa- are accelerator mass spectrometry (AMS) datings. The target was prepared in Trondheim, and the AMS measurements performed in Uppsala.

The samples cited from Knape (1971) were dated at the laboratory in Stockholm (prefix St-). Initially, these dates were not corrected for isotopic fractionation (Magnus Hedberg, oral comm. 1994). We have corrected the dates on whale bones to $-25‰$ $\delta^{13}C$ by assuming a value of $-16.4‰$ for the bones, which is a mean value for Arctic whale bones dated at the laboratory in Trondheim (Gulliksen 1980). The Stockholm dates on driftwood are not corrected for fractionation, but any errors for this reason would be negligible.

A mean value of $-24.5 \pm 0.8‰$ $\delta^{13}C$ was obtained from 28 driftwood samples from Humla and Diskobukta and used for the age calculations (S. Gulliksen, Laboratory for Radiological Dating in Trondheim, written comm. 1994). The laboratory in Lund assumes a value of $-27.2‰$ $\delta^{13}C$ for all wood samples before correction. To make them comparable to the driftwood samples of $-24.5‰$ $\delta^{13}C$, we have added 45 years.

All dates were calibrated to calendar years by using the calibration program CALIB ver 3.0.3 (Stuiver & Reimer 1993) and denoted as cal yrs BP in the text. The datings are cited in the text and figures as the interval between the maximum age and the minimum age (one σ) in calibrated years before present (1950), given as column A and D in Tables 1–4.

Determination of wood species

Nearly all the dated driftwood samples were identified to genus or species level (Tables 1, 2 and 3) under the microscope by Leif M. Paulssen at the University in Oslo (Kapp Ziehen) and Olafur Eggertsson at the University of Lund (Humla and Diskobukta). In addition, Paulssen studied the wood after carbonisation. We are aware that identification of *Picea* and *Larix* is problematic and sometimes controversial. Here we simply cite the results reported to us.

Amino acid measurements

Six shell fragments from the assumed marine limit terrace in Humla were analysed at the Bergen laboratory (prefix BAL-). In this paper we report the epimerisation of isoleucine to alloisoleucine for the total fraction, expressed as D/L ratios (by some labelled AIle/Ile) and the D/L ratios measured for the free fraction. All fragments are *Mya truncata* or *Hiatella arctica*, which have approximately similar epimerisation rates (Miller 1982).

Relation between the mean tide level and sea-level indicators

Our aim was to construct precise and well-documented sea-level curves. A pre-requisite for this is to understand the relationship between the present sea level and indicators of paleo-sea-levels such as shore sediments and the datable material within or on top of shore sediments.

On the present shore a gravel beach ridge is formed during heavy surf and storms. The crest of the ridge is found 1 to 2 m above high-tide level; its altitude is determined by wave height during storms. Wave energy reaching the shore is the major factor controlling the development of the beach (Reineck & Singh 1980). On gently sloping shores, as are found on Edgeøya and Barentsøya, the waves break a considerable distance offshore producing a beach ridge having a low relief. Driftwood and other flotsam are commonly found on top of the ridge (Figs. 2 and 3).

A beach ridge formed during an extreme storm will destroy lower ridges on the shore. This probably means that the elevated beach ridges were formed during the largest storm within a time period of 20–50 years for the oldest beaches (rapid regression, 20–40 mm/year) and 500–1000 years for the youngest (slow regression, 0.5–2 mm/year), and this is the reason why the shorelines often depict a staircase from the present shore and upward (e.g. Fig. 7) (Fletcher III et al. 1993).

Driftwood is the most reliable indicator for paleo-sea-level in arctic areas (Blake 1975; Dyke et al. 1991) because it floats ashore and becomes stranded at the high tide level. Subsequently, storm-waves may throw the wood further up and either bury it in the beach ridge or leave it on the surface on or behind the ridge (Fig. 2). This level is the so-called driftwood limit where recent driftwood appears as a marked line in the landscape (Fig. 3). The local altitude variation of fresh driftwood on the present day shore is within ±0.5 metre at the three investigated locations. Due to the low gradient from the marine limit to the present shore, wave energy reaching the shore has not changed much because of emergence. Thus, the driftwood limit is believed to be constant throughout postglacial time.

Whales usually float after they die and while they decompose. Their cadaver may float ashore and become stranded (Dyke et al. 1991). Also old, injured or disoriented whales may beach themselves in the near-shore zone. Individual bones or the entire carcass will normally be reworked by waves and thrown up to the driftwood limit. Thus, bones from one whale may be spread over a larger area. However, Blake (1975) argued that because of their weight and size, whales would more likely be deposited in shallow water than thrown up onto the beach ridge by storm waves. In Smelledalen (Figs. 1 and 9), we found three bone heaps on the surface 25 m a.s.l., each containing most of the bones of an individual whale; at another site we found nearly a whole row of a dorsal vertebra embedded in beach gravel (Fig. 5). These bones cannot have been significantly reworked, which implies that the whole carcass was deposited close to the driftwood limit.

Sea-level curves from the Arctic are based mainly on age determinations on both whalebone (Forman 1990; Dyke et al. 1991) and driftwood (Salvigsen 1978, 1981). It has been assumed that whalebone curves and driftwood curves are directly comparable because ages from both type of material plots on a smooth sea-level curve (Salvigsen 1978; Forman et al. 1987). However this has never been rigorously tested.

At five locations we collected whalebones and driftwood from the same shoreline. In addition, Knape (1971) reported three pairs of such samples from southern Edgeøya. Fig. 6 shows that the

Fig. 4. Recent driftwood appears as a marked line, called the driftwood limit, on the present beach ridge in Humla (Fig. 1). Photograph towards northeast. Barentsøya seen in the background.

Table 1. Conventional and calibrated ^{14}C ages from Kapp Zichen.

Field number[1]	Laboratory number	^{14}C age[2] $\pm 1\sigma$	Calibrated ^{14}C ages BP[3] A	B	C	D	$\delta^{13}C$ ‰[4]	Material	m a.s.l.	Description/species
87-812	T-9913	9585 ± 65	10930		10875	10785	−20.6	whalebone	88.5	Jaw bone, 130 cm long, max. diam. 20 cm. Well preserved. Found near the river cutting through the 88.5 m marine limit terrace.
87-812	T-99131	9470 ± 60	10835		10595	10475	−22.9	whalebone	88.5	Same sample as above. Redated because of unexpected young age.
88-260	T-10256	9595 ± 70	10925	10865	10615	10485	−24.5*	wood	80.2	Log identified to *Picea mariana*, 1.20 m long, diam. 20 cm. Embedded in beach gravel. Exposed in small gully.
87-815	Lu-3382	9615 ± 110	10960	10880	10670	10480	−24.5*	wood	79.8	Log of *Larix gmelinii*, 1.8 m long, max. diam. 15 cm. Embedded in sediments. Exposed in river side.
87-813	Lu-3381	9445 ± 110	10800		10420	10300	−24.5*	wood	70.8	Log 1.15 m long, diam. 8.5 cm (*Picea abies*). Found 0.5 m below terrace surface in the sediments.
86-507	T-9914	9105 ± 55	10075		10035	9990	−23.5	wood	63.5	Log (*Salix sp.*) at least 2.0 m long, diam. 10 cm. Found in the river bed below the 63.5 m terrace.
86-508	T-10978	9135 ± 45	10265		10150	10050	−19.8	whalebone	63.5	Two big jaw bones that seem to be in correct position to each other. About 6 and 4 m of the bones are exposed in a gully 1.4 m below the terrace surface. The rest are incorporated in gravel.
86-510	TUa-689	9205 ± 85	10360		10270	10115	1.0*	shell	63.5	Piece of *Hiatella arctica* found close to 86-508 in the same stratigraphic position as the two samples above.
86-505	T-9915	8870 ± 55	9955		9895	9860	−24.5*	wood	56.7	Log, *Larix laricina*, at least 90 cm long covered by 20 cm sediments. Frostwedged.
86-528	T-10257	8855 ± 160	10010		9890	9675	−16.4	whalebone	50.1	Part of a rib-bone, 55 cm long. Well preserved.
86-524	T-9916	7905 ± 110	8955	8645	8615	8510	−24.5*	wood	42.9	Log (*Pinus cembra*) at least 1.6 m long, max diam. 20 cm. Covered with 20–40 cm sand and gravel in a well-pronounced terrace.
86-531	T-10255	7880 ± 115	8950		8580	8495	−24.5*	wood	39.2	Log, *Larix gmelinii*, at least 1.6 m long, diam. 24 cm. Embedded in distinct beach ridge.
86-512	T-10980	6945 ± 50	7780		7710	7660	−25.6	wood	36.6	Small log, 30 cm long, diam. 6 cm buried in beach gravel 1 m below terrace surface.

86-513	T-10981	6950 ± 40	7770		7715	7670	−27.3	wood	36.6	Piece of transition between root and trunk. Found in same stratigraphic position as sample 86-512 (above).
86-516	TUa-690	6995 ± 60	7860		7775	7700	1.0*	shell	36.6	Paired *Hiatella arctica* found in the same stratigraphic position as sample 86-512, -513.
86-529	T-10254	7220 ± 110	8120		7965	7910	−24.5*	wood	34	Lower part of log (*Pinus cembra*), trunk with roots, 1.6 m long, diam. 35 cm. Found in an area with marked shorelines.
86-501	T-9917	6170 ± 85	7175	7140	7020	6905	−24.5*	wood	30	At least 1.8 m long log (*Larix sp.*) in beach sand and gravel 30 cm below the terrace surface.
87-818	Lu-3383	5355 ± 80	6275	6175	6115	5995	−24.5*	wood	22.8	Log of *Picea sp.* 2.4 m long, diam. 25 cm. Partly embedded in beach ridge. Frostwedged.
88-264	T-10253	4680 ± 75	5570	5445	5330	5310	−24.5*	wood	20.5	Part of a root (*Picea sp.*) with 0.8 m long trunk and a 0.35 m root-branch situated in beach sediments.
86-502	T-9918	4475 ± 95	5295	5205	5050	4875	−24.5*	wood	17.2	Log of *Picea mariana*, 1.3 m long, diam. 13 cm. Covered with 10 cm sand and gravel 0.5 m below terrace surface.
88-265	T-10252	3640 ± 90	4085	3960	3925	3835	−24.5*	wood	13.5	Log (*Picea sp.*) 2.8 m long, diam. 18 cm resting on shore gravel.
86-504	Lu-3543	3605 ± 70	3983		3890	3780	−24.5*	wood	12	Log (*Picea abies*) 1.3 m long, diam. 5–6 cm. In slope material from the 12 m terrace.
86-522	T-10251	2835 ± 50	2980	2940	2895	2860	−24.5*	wood	8.9	Log (*Pinus cembra*) 1.6 m long, diam. 17 cm found on terrace.
87-819	Lu-3384	975 ± 60	940	900	920	790	−24.5*	wood	4.8	Log 4.0 m long, diam. 25 cm. Found on the surface.
87-820	Lu-3542	655 ± 50	660		645	555	−24.5*	wood	3.8	Log (*Larix gmelinii*) 2.1 m long, near the roots 45 cm diam. Partly buried in sediments.

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1) PONAM number.

2) A reservoir age of 440 years have been subtracted for all marine samples (whalebones and shells).

3) Calibrated ages according to method A in CALIB Rev 3.0.3 (Stuiver & Reimer 1993) using the bidecadal atmospheric/inferred atmospheric curve for driftwood samples. A ΔR value of 70 ± 25 yr has been used for the marine samples.

A: Maximum calibrated age range (one sigma)

B: Oldest calibrated age when two or more intercepts are given.

C: Calibrated age (when only one is given, youngest when two or more intercepts are given).

D: Minimum calibrated age range (one sigma).

4) Values marked with * are assumed values (not measured) used for correction to −25‰ $\delta^{13}C$.

Samples with lab. number T- are dated at the laboratory in Trondheim.

Samples with lab. number TUa- are accelerator mass spectrometry (AMS) dating.

Samples with lab. number L- are dated at the laboratory in Lund.

Table 2. Conventional and calibrated ^{14}C ages from Humla.

Field number[1]	Laboratory number	^{14}C age[2] ± 1σ	Calibrated ^{14}C ages BP[3] A	B	C	D	$\delta^{13}C$ ‰[4]	Material	m a.s.l.	Description/species
88-516	TUa-271	>54,800					1.0*	shell	86.8	Shell fragment from section in the marine limit terrace.
88-525A	TUa-400	9885 ± 130	11500	1.0*	11190	10980	1.0*	shell	76	Shell fragment found on the surface.
88-504	T-9882	9485 ± 80	10850	10530	10475	10370	−27.3	wood	75.6	Wood-fragment, *Populus sp.* (15–20 cm) on the surface of gravel sloping from the 75.6 m terrace.
88-527	T-10133	9620 ± 130	10970	10880	10685	10475	−23.6	wood	75.6	Trunk, 75 cm long and 5 cm diameter. Close to sample 88-504.
87-664	T-9877	9310 ± 80	10520		10365	10280	−15.6	whalebone	73.9	Big jaw bone stuck in permafrost. (65 cm × 45 cm above permafrost). The bone is well preserved.
88-533	T-9881	9385 ± 90	10535		10365	10220	−25.4	wood	70	Piece of wood (*Larix sp.*) partly anchored in sediments, just below a minor beach ridge.
88-529A	T-9888	9240 ± 55	10295	10280	10165	10045	−25.7	wood	65	Log (*Picea*/*Larix*), 26 cm in diam. in silty cryoturbation diamicton, 0.5 m below terrace surface. In permafrost.
88-531	T-10803	9125 ± 130	10325		10135	9985	−16.9	whalebone	65	In a small gully 6 m from the wood sample 88-529, whalebones are frequent. The sample is taken from a 130 cm long rib-bone.
88-535	T-9889	9310 ± 70	10370	10295	10225	10155	−23.9	wood	61.6	Log 2.8 m long resting on the surface. The wood (*Larix sp.*) is perforated by worm borings.
87-668	T-9878	8940 ± 100	10030		9955	9875	−17.5	whalebone	58.8	Two big whalebones (jaws?) in silty cryoturbation diamicton on terrace surface.
87-659B	T-9896	8720 ± 65	9855	9794	9651	9535	−25.2	wood	55.1	More than 3.2 m long log of *Larix sp.* embedded in beach gravel. Exposed in small gully.
87-661	T-10804	8750 ± 90	9890		9820	9640	−16.6	whalebone	55.1	A 2 m long jawbone found on the surface 10 m from the wood sample 87-659B.
87-669	T-9895	8725 ± 70	9860	9800	9650	9535	−23.5	wood	51.4	At least 4 m long log of *Larix sp.* with max. diameter 45 cm. Partly anchored in sediment. The log is frostwedged.

88-514	T-9884	8200 ± 65	9250	9195	9050	8995	−24.2	wood	47.5	Nearly vertical log (*Larix sp.*) in an ice-wedge on a terrace. One metre of the log is visible. Diameter 28 cm.
87-671	T-9894	7850 ± 85	8710		8560	8495	−25.5	wood	43.8	Small log 0.9 m long, 23 cm diam., frozen up in an ice-wedge.
87-676	T-9879	6670 ± 90	7550		7480	7390	−18.2	whalebone	35.5	Two big jaw bones that seem to be in correct position to each other. 2.5 m of the bones are visible above the ground; maximum diameter 50 cm.
88-508	T-9883	6275 ± 65	7220		7185	7090	−23.1	wood	31.9	Log of *Picea/Larix* 3–4 m long, diam. 60 cm. Partly incorporated in beach gravel.
88-538	T-9890	6180 ± 55	7170	7145	7025	7000	−23.9	wood	30.2	In a small ravine a 4 m long log (*Pinus silvestris*), 36 cm in diam., is partly anchored in the sediments. The log rests on shore gravel.
87-684	T-9892	5830 ± 60	6730		6665	6555	−24.6	wood	27.9	Log (*Larix sp.*) 3.5 m long with max diam. 20 cm. Partly buried by sediments and vegetation.
87-678	T-9893	5130 ± 65	5935		5905	5760	−24.2	wood	23.4	Log of *Picea/Larix*, 4 m long, diam. 21 cm. Partly buried on terrace surface.
88-524	T-9887	4555 ± 65	5315		5290	5053	−25.7	wood	19.8	Small log (*Pinus silvestris*), 120 cm long, max. diam. 15 cm, partly anchored in the sediments on top of terrace.
88-521	T-9886	4460 ± 70	5280		5045	4875	−24.0	wood	17.2	Small log (*Larix sp.*), 1 m long, diam. 14 cm. Partly buried in the terrace surface.
87-677	T-9898	3765 ± 40	4220	4135	4095	4000	−24.7	wood	14.6	Log of *Larix sp.* (70 cm length, 16 cm diam. above the permafrost) frozen up along an ice wedge in shore gravel.
88-518A	T-9885	3105 ± 45	3365		3345	3260	−24.5	wood	11.2	Log 3.5 m long, max. diam. 22 cm, buried 20 cm below the surface, resting on beach gravel.
87-685	T-9880	2125 ± 65	2260		2125	2045	−16.1	whalebone	7.7	Part of a whale cranium, 1 m × 1 m, on terrace surface.
87-656	T-9897	1725 ± 45	1700	1680	1610	1550	−23.8	wood	5.6	More than 4.5 m long log (*Pinus cembra*) with diam. 45 cm.
88-546	T-9891	580 ± 50	640		550	535	−25.1	wood	3.6	More than 4 m long log (*Pinus silvstris*), partly anchored in the sediments.
88-544	T-10806	605 ± 55	615		545	510	−17.0	whalebone	3.2	Jaw bone 4.9 m long.

For explanation see Table 1.

Table 3. Conventional and calibrated ^{14}C ages from Diskobukta.

Field number[1]	Laboratory number	^{14}C age[2] ± 1σ	Calibrated ^{14}C ages BP[3] A	B	C	D	$\delta^{13}C$ ‰[4]	Material	m a.s.l.	Description/species
86-572A	TUa-338	10015 ± 75	11685		11470	11290	1.7	shell	77.6	Shell fragment from section near the marine limit.
86-572B	TUa-627	9565 ± 80	10930		10855	10610	1*	shell	77.6	Shell fragment from same section as 86-572A (above).
86-585	T-10045	9335 ± 105	10560		10395	10285	−20.3	whalebone	67.8	Big jaw bone, over 2 m long, found on the slope from the 67.8 m terrace. The bone, partly covered by slumped material is well preserved.
86-573	T-10043	9380 ± 45	10390		10360	10300	−24.6	wood	66	Log of *Larix sp.*, 3.1 m long, diam. 35 cm, embedded in beach gravel near top of terrace.
86-325	T-10134	9345 ± 130	10530	10345	10310	10140	−25.4	wood	48.9	Piece of wood (*Picea*), 25 cm long, from section in terrace 2.5 m below surface (Locality 2706 in Stubdrup 1992).
86-570	T-10044	8130 ± 70	9205		9055	8970	−17.6	whalebone	43.2	Rib-bone, 1.2 m long on the slope 2 m below the terrace surface (43.2 m a.s.l.).
86-707D	T-9919	8755 ± 125	9915		9820	9600	−0.2	shell	38	A bed with at least 20 paired *Mytilus edulis* found in section 3.5 m below the 38 m terrace.
86-554	TUa-691	8615 ± 60	9640		9525	9490	−24.5*	wood	38	Small stick from same bed as the paired *Mytilus* above.
86-569B	T-10138	7550 ± 115	8410		8335	8170	−25.2	wood	36.8	Short log (*Picea/Larix*) with parts of the root system intact. Found on the slope from terrace 36.8 m a.s.l.
86-580	T-10805	7050 ± 115	7935		7835	7700	−16	whalebone	35.9	Big whalebone on terrace surface. The bone is well preserved.
86-581	T-10807	7255 ± 65	8115	8055	7995	7945	−24.6	wood	35.4	At least 4 m long log, max. diam. 25 cm. Partly anchored in beach gravel on terrace surface.
87-703A	T-9922	7175 ± 110	8070		7940	7860	0.5	shell	35.4	A zone of paired *Mytilus edulis* in a 10 cm gravel bed, 2 m below terrace surface.
86-578	T-10140	6770 ± 60	7625		7560	7535	−23.5	wood	33.3	Log of *Larix sp.*, 2.66 m long and 25 cm diam. found on the slope 1 m below the terrace surface.
86-701A	T-9920	5835 ± 125	6775		6650	6480	0.5	shell	26.8	Two halves of *Mytilus edulis* found in a small gully starting from the 26.8 m terrace.
86-575	T-10139	5930 ± 55	6850		6750	6720	−24.9	wood	26.6	Log of *Picea/Larix*, 1.7 m long, diam. 22 cm, found on the surface. Frostwedged.
86-566	T-10137	6020 ± 60	6900		6870	6790	−25.5	wood	25.1	Log of *Larix sp.*, 3 m long, 30 cm diam. The log is frostwedged, so the outermost wood is probably missing.
86-582	T-10141	4130 ± 90	4830	4800	4575	4450	−24.2	wood	15.6	Small log (*Larix sp.*) on the surface at the end of the beach ridge towards the braided river system.
86-583	T-10142	3730 ± 90	4230	4085	4010	3930	−24.8	wood	12.6	Log, 2.1 m long, diam. 26 cm. Partly covered by beach gravel in beach ridge.
86-564	T-10136	1715 ± 75	1710	1605	1580	1530	−23.3	wood	4.6	Outer part of a 5 m long log identified to *Larix sp.* Found on the surface, partly covered by vegetation.
86-563	T-10135	1270 ± 75	1280	1220	1180	1070	−23.7	wood	3	Big log of *Larix sp.*, 11 m long, partly enclosed in sediments just inside a distinct beach ridge.

For explanation see Table 1.

Table 4. Conventional and calibrated ^{14}C ages from southern Edgeøya.

Field number[1]	Laboratory number	^{14}C age[2] ± 1σ	Calibrated ^{14}C ages BP[3]				δ^{13}C ‰[4]	Material	m a.s.l.	Description/species
			A	B	C	D				
86-705	T-9907	9595 ± 110	10955	10870	10615	10475	−24.5*	wood	75	Dianadalen. Big log found on the slope from the 75 m terrace. Altitude measured with barometric altimeter.
86-706	TUa-269	10200 ± 95	12130		11891	11630	1.0*	shell	75	Dianadalen. Shell fragment on the surface sloping from the 75 m terrace. Altitude measured by barometric altimeter.
88-462	T-9908	9520 ± 125	10925		10795	10470	−17.6	whalebone	72	Dianadalen. Big jaw bone partly enclosed in large terrace measured to 72 m a.s.l. with barometric altimeter.
N.dal-11	St-2520	9230 ± 110	10350	10280	10160	10035		wood	53	Negerdalen. Log 1.5 m exposed, diam. 20 cm, frostwedged. The rest of the log buried under 0.5 m of terrace-sediments. The terrace height was measured with a barometric altimeter to 53 m a.s.l.
N.dal-16	St-2485	7965 ± 100	8985	8945	8725	8565		wood	39.5	Negerdalen. Log 1 m exposed in steep slope, the rest covered with 0.5 m marine sediments. Diam. 20 cm.
N.dal-24	St-2590	7795 ± 110	8805		8565	8435	−16.4*	whalebone	39	Negerdalen. Unidentified part of a well preserved whalebone on a flat surface. Originally published age 8095 ± 110.
N.dal-25	St-2579	6630 ± 100	7530		7440	7365	−16.4*	whalebone	34.5	Negerdalen. Dorsal vertebra on flat surface, partly enclosed in sediments. Originally published age 6930 ± 100.
N.dal-26	St-2519	5300 ± 100	6260	6165	6035	5935		wood	24.5	Negerdalen. Log 2.5 m long, diam. 27 cm. One end enclosed 0.5 m below surface in beach ridge.
N.dal-17	St-2484	4760 ± 100	5595	5570	5480	5325		wood	20	Negerdalen. Log embedded in marine sediments, diam. 15 cm.
N.dal-21	St-2522	3955 ± 100	4525		4410	4250		wood	16.5	Negerdalen. Half of the 6.5 m long log is enclosed in beach shingle and sand. Diam. 25 cm.
N.dal-22	St-2521	3725 ± 100	4230	4080	4000	3920		wood	14	Negerdalen. Log diam. 30 cm partly enclosed in marine sediments in beach ridge. The heartwood was used for dating.
N.dal-19	St-2523	2015 ± 100	2105		1950	1835		wood	6	Negerdalen. Log 2.5 m long, diam. 20 cm. The log was found enclosed in gravel. Heartwood used for dating.
B.bukta-2	St-2660	1240 ± 100	1280		1170	1055		wood	3	Bjørnbukta. Log 7 m long, diam. 27 cm, found on the surface. The log rests on sand.
B.bukta-3	St-2698	1170 ± 100	1195		1070	955	−16.4*	whalebone	3	Bjørnbukta. Dorsal vertebra situated on top of St-2660. Well preserved. Originally published age 1470 ± 100.
B.bukta-4	St-2819	620 ± 100	670	645	575	540		wood	1.9	Bjørnbukta. Log 4.5 m long, diam. 30 cm; exposed part is 50 cm long, the rest enclosed in sand in beach ridge.
B.bukta-5	St-2873	620 ± 100	640		550	495	−16.4*	whalebone	1.9	Bjørnbukta. Rib-bone 21 m SE of St-2819. Found on the surface of a beach ridge. Originally published age 920 ± 100.

Lab. number St- are from Knape (1971), and the whale-bone dates are correct as described in the text. Originally, whalebones dated by Knape (St-) were not corrected for the reservoir effect or frationation.

For explanation see Table 1.

Fig. 5. In situ dorsal vertebra of a whale embedded in beach gravel in Smelledalen (Fig. 1). The trowel is ca 25 cm long.

calibrated ages plot on a straight 45° line, demonstrating that driftwood and whalebones found on the same shoreline yielded similar ages. Knape (1971) concluded that the whalebones yielded 125 to 420-year younger results than driftwood after substracting a reservoir correction of 400 years for the whalebones. However, as mentioned above, the ages were not corrected for isotopic fractionation and thus were reported 140 years too young.

In arctic areas where the shore is covered with sea ice most of the year, all molluscs live below the low-tide level (Fig. 2) (Aarefjord 1969; Blake 1975). Even the bivalve *Mytilus edulis*, which is known to inhabit intertidal waters, lived 10–20 m below the contemporaneous sea level on Edgeøya during the Holocene climatic optium (Hjort & Mangerud 1995). During emergence, shells from older sediments are commonly reworked by waves and redeposited together with younger beach sediments. Therefore, shells provide a minimum altitude of the sea level at the obtained ^{14}C age, but frequently the sea level was considerably higher. Evidently, shells are normally not suitable as sea-level indicators in these regions. Exceptions are shells found close to the marine limit where they cannot have been redeposited from much older sediments, simply because the area was covered by glaciers immediately before the marine limit shore line was formed.

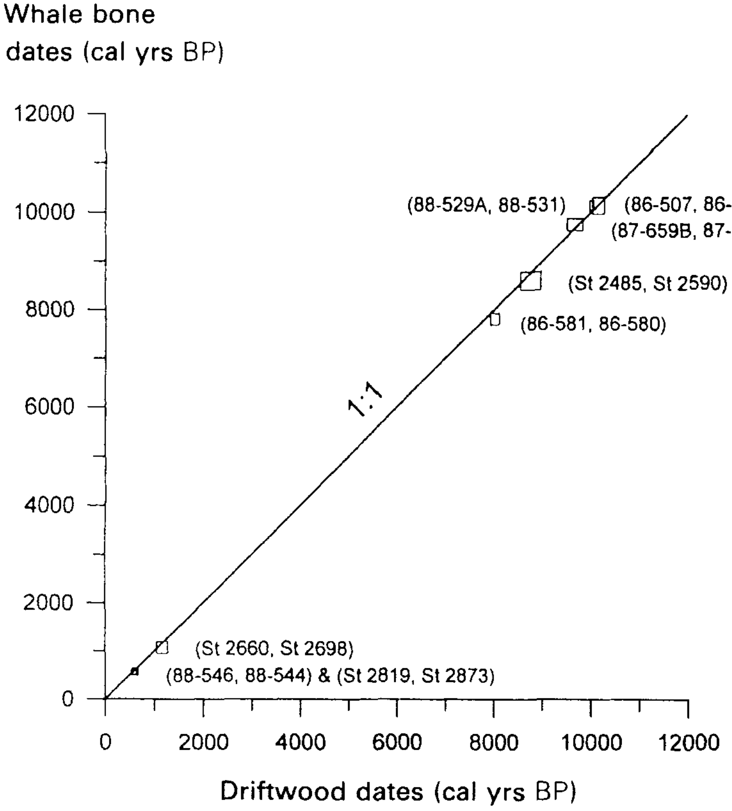

Fig. 6. Dates of whale bone and driftwood collected on the same shoreline. The error boxes show the maximum and the minimum calibrated age range (one sigma).

Results

Kapp Ziehen

The Kapp Ziehen area (Fig. 1) is characterised by morphologically well-developed strandlines (Fig. 7). The strandlines are cut by rivers originating from the glacier Augnebreen. In the northern part, Augnebreen overrode the Holocene shorelines during the Little Ice Age (probably during the 19th century) (Lefauconnier & Hagen 1991). The average thickness of the littoral sediments in the shorelines is estimated from rivercuts and

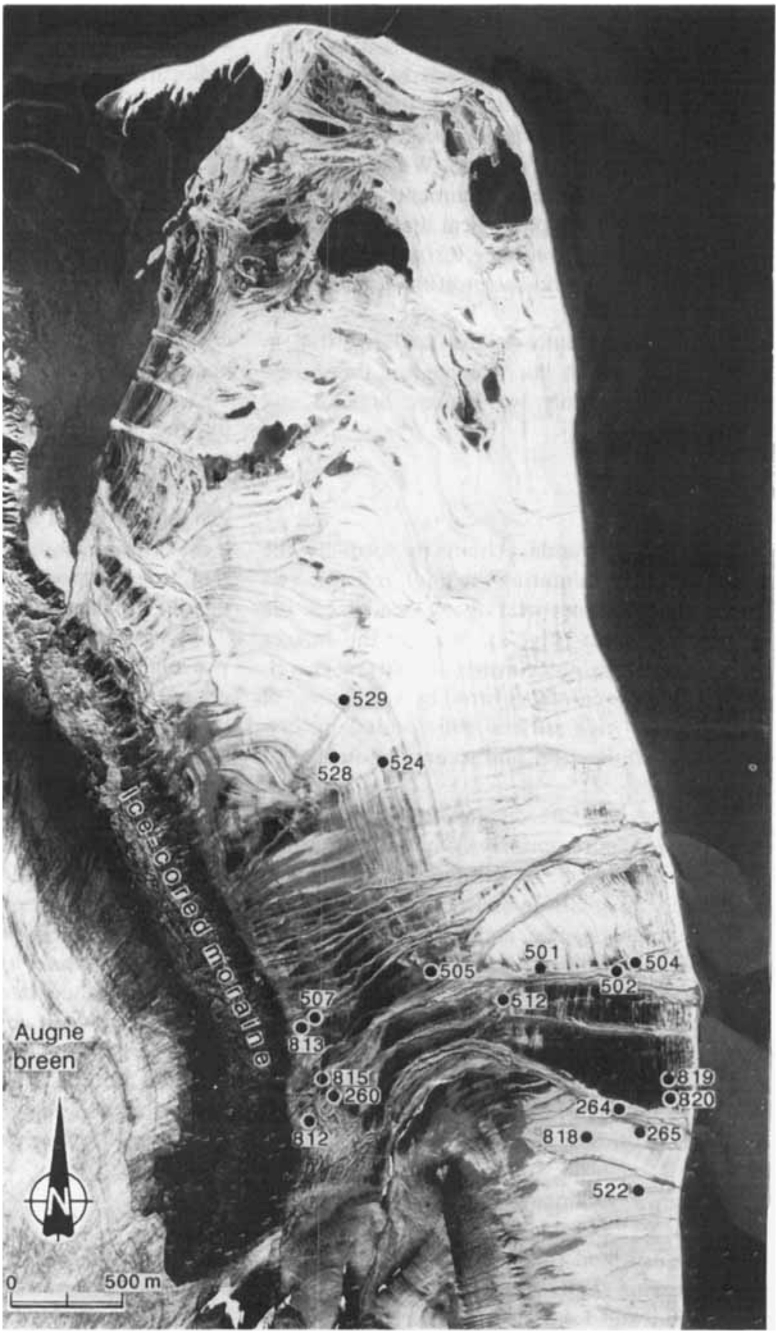

Fig. 7. Vertical aerial photograph of Kapp Ziehen (Fig. 1). Location of radiocarbon dated samples are marked, using the three last digits in the sample (field) number (Table 1). Photograph: Norsk Polarinstitutt S 90-6602.

outcrops of underlying bedrock to be less than 2 m.

The marine limit is marked by a large terrace 88.5 m a.s.l. (Fig. 7, sample 812). There is an increase in the surface slope from 78 m a.s.l. up to the nearly horizontal marine limit terrace. Sediment in the terrace consists of well-rounded and sorted gravel with foresets dipping up to 10° towards the sea.

Above the terrace, to the south, the rivers have locally eroded into (weathered) bedrock. The sediment on top of the bedrock is a diamicton with frequent, large dolerite boulders that are both bullet-shaped and striated. We interpret the diamicton as a glacigenic sediment, probably a till. The distinct morphological and sedimentological boundary between the terrace and the dissected diamicton marks the position of the marine limit.

Dated samples with description are listed in Table 1. A search for pumice on the raised beaches yielded only two pieces, at 34.3 and 42.2 m a.s.l.

Humla

The small bay Humla (Humla is formally the name of the river entering the bay), is located on the northeast corner of Edgeøya and faces the open Barents Sea (Fig. 1). Most of the surface below the marine limit consists of sand and gravel, although it is generally covered by a thin layer of peat or a silt-rich surface soil formed by cryoturbation, solifluction, and accumulation of wind blown silt (Fig. 4).

Raised beaches are distinct from the present shore up to approximately 35 m a.s.l. (samples 508 and 676, Fig. 8). At this level there is a 8 to 10 m high step or cliff in bedrock. Above the cliff the terrain rises gently, and only subdued beach forms can be identified. A series of distinct shorelines appear again from about 70 to 78.8 m a.s.l. (between sample 533 and 525, Fig. 8). Further up-valley on the east side of the river Humla, a small terrace with shell fragments occurs at 86.8 m a.s.l. (sample 516, Fig. 8). Age determinations with description of samples are listed in Table 2.

No marine sediments were found above the terrace at 86.8 m a.s.l. (Fig. 8), and during field work we assumed that it represented the postglacial marine limit. We made two small excavations (0.9 and 1.4 m deep) down to permafrost in the terrace slope. In both sections, mainly well-rounded, weakly stratified gravel with frequent shell fragments are present. The gravel is loose and many rounded cobbles and pebbles have been split by frost action. In one of the sections the gravel grades upwards into a silty diamicton on top of the section. A shell-fragment from the terrace was radiocarbon dated to >54,800 yrs BP (Table 2). Amino acids measurements on 6 shell fragments, including the one that was radiocarbon dated, yielded high D/L ratios (Table 5), supporting the infinite radiocarbon date. Compared to the D/L ratios from the Kapp Ekholm section at Spitsbergen (Mangerud & Svendsen 1992) and the sections on Kongsøya (Ingólfsson et al. 1995), the D/L ratios suggest an Early Weichselian, or older age, for the shell fragments.

In the field we interpreted the diamicton to be of the same origin as the silt-rich surface soil mentioned above, which covers most of the Holocene terraces. However, if the diamicton is a till, the terrace may be compared with the 87 m terrace in Linnédalen on the western coast of Spitsbergen (Mangerud et al. 1992a). In that case the terrace is not related to the post-glacial sea level (marine limit). If we had known that the shell fragments were "old", we would have investigated the diamicton more carefully.

Along the mountainside west of Humla, there is a small abrasion cliff in bedrock with its foot at approximately the same altitude as the 86.8 m a.s.l. terrace (arrow in Fig. 8). Above this small cliff, glacially striated and polished boulders are common in stream bottoms, indicating a till at the surface, which was not found in the upper 2 m of sediments below the cliff. This supports the interpretation that the 86.8 m terrace is related to the post glacial sea-level. Whether the terrace was formed by erosion in old sediments at the postglacial marine limit or the shell fragments were redeposited from higher elevations cannot be determined. In any case, we consider the terrace to represent the postglacial marine limit. Also the altitude correlates well with other observations of the postglacial marine limit on Barentsøya and Edgeøya (see below).

Diskobukta

Diskobukta, situated on the western side of Edgeøya, faces towards Storfjorden (Fig. 1). The two valleys Raddedalen and Smelledalen enter

Fig. 8. Vertical aerial photograph of Humla (Fig. 1). Location of radiocarbon dated samples are marked, using the three last digits in the sample (field) number (Table 2). Arrow (lower left side) points to the ablation cliff with the same altitude as the marine limit terrace. Photograph: Norsk Polarinstitutt S 90-2404.

Table 5. Amino acid D/L ratios from the 86.8 m a.s.l. terrace at Humla.

Field no.	Lab. no.	Species	D/L Total	D/L Free
88-516A	BAL 2709	Mya truncata	0.071 ± 0.003	0.395 ± 0.005
88-516B	BAL 2710	Hiatella arctica?	0.059 ± 0.005	0.357 ± 0.049
88-516C	BAL 2711	Hiatella arctica	0.077 ± 0.006	0.329 ± 0.006
88-517A	BAL 2712	Mya truncata	0.075	0.348
88-517B	BAL 2713	Hiatella arctica?	0.087 ± 0.003	0.496 ± 0.006
88-517C	BAL 2714	Mya truncata	0.120 ± 0.002	0.373 ± 0.046

Amino acid D/L (D-alloisoleucine/L-isoleucine) ratios in shell fragments found in the 86.8 m a.s.l. terrace at Humla. Samples 88-516A–C are fragments picked directly from the section, and 88-517A–C are fragments found on the surface of the terrace slope.

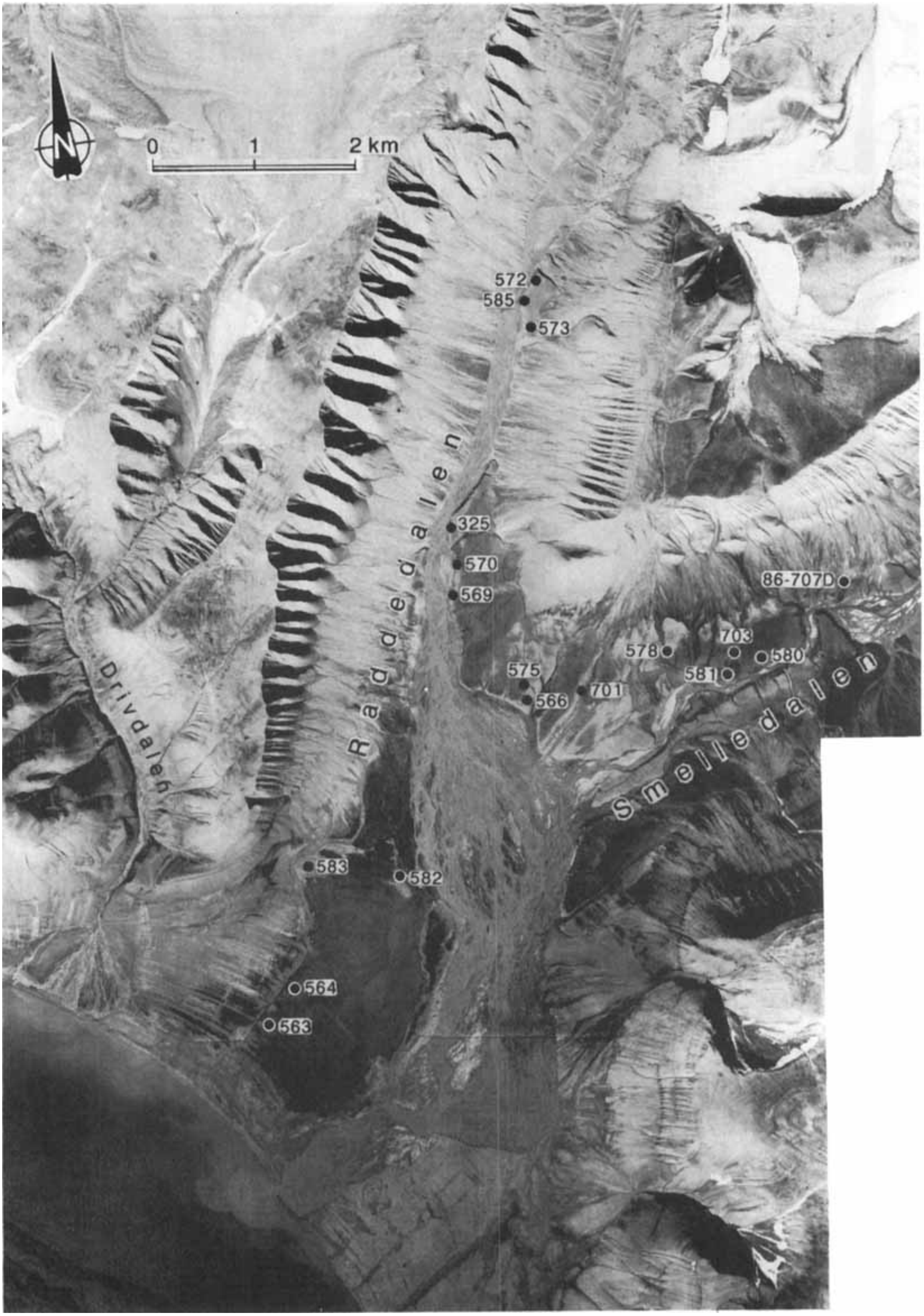

Fig. 9. Vertical aerial photograph of Diskobukta, Raddedalen and Smelledalen (Fig. 1). Location of radiocarbon dated samples are marked, using the three last digits in the sample (field) number (Table 3). Photograph: Norsk Polarinstitutt S 90-2649, S 90-2650 & S 90-6613.

Raddesletta (*sletta* in Norwegian means *plain*) about 5 km from the present shore (Fig. 1). Raddesletta is a coastal plain with a well-developed braided river system (Fig. 9). A continuous series of raised shorelines appears on Raddesletta from the shore to about 17 m a.s.l. (Fig. 9, sample 582). Terraces which consist of marine sediments occur on both sides of Raddedalen from 23 m (Fig. 9, sample 566) to the marine limit (Fig. 9, sample 572), except for the interval between 45 to 60 m (Fig. 9, between samples 325 and 573), where sediments have been removed by slope processes. Dated samples with descriptions are listed in Table 3.

On the eastern side of the river in Raddedalen, approximately 9 km from the present shore, there is a large terrace (Fig. 9, samples 585 and 572). Sections in the terrace show sand and gravel beds dipping both down and up valley. The deposit is inferred to be a large spit formed by longitudinal drift from the south. Shell fragments were found in gravel beds near the terrace surface. Two fragments were dated to 11,685–11,290 cal yrs BP (TUa-338) and 10,930–10,610 cal yrs BP (TUa-627), respectively. The highest point on the deposit is found near the valley slope, 85.1 m a.s.l. Here rounded pebbles occur frequently on the surface, and outcrops show sand and gravel beds dipping towards the valley side. From this we conclude that 85.1 m a.s.l. is a minimum value for the marine limit in Raddedalen. Marine sediments were not found at higher elevations in this valley.

Southern Edgeøya

The sea-level curve constructed by Knape (1971) for southern Edgeøya lacked ages above 53 m a.s.l. Knape collected the samples in Bjørnbukta and Negerdalen (Fig. 1) and levelled all altitudes except the uppermost sample of driftwood (53 m a.s.l.), which was measured with an altimeter.

In Dianadalen (Fig. 1) situated 15 km north of Negerdalen, we collected three samples close to the marine limit (Fig. 10; Table 4). Unfortunately, due to harsh weather conditions, these terraces and samples were not levelled, and the barometric readings were not rechecked. Because of the uncertainties in altitudes for the Dianadalen samples and a possible difference in emergence between Dianadalen and Negerdalen, we have not constructed a sea-level curve for the period prior to 7000 years BP for southern Edgeøya. However, these data are plotted together with Knape's data from Negerdalen, and the course of sea level is indicated by a stippled line (Fig. 14).

The marine limit on Edgeøya and Barentsøya

As a result of weathering and solifluction processes in the soft and schistose rocks, the marine limit is not morphologically well marked. Our best measurements of the marine limit are from Kapp Ziehen, Humla and Diskobukta and are between 85 and 89 m a.s.l. (described above; for other observations of marine limits on Edgeøya and Barentsøya, see Mangerud et al. 1992b).

Knape (1971) concluded that the marine limit on the western coast of Edgeøya was about 90 m a.s.l. and on the east coast 95 m a.s.l. This assumption was based on altimeter readings by himself and by Glaser (1968) on the western coast of Edgeøya, and by Büdel (1962, 1968) on the eastern and northern coasts of Edgeøya. However, our data do not show any significant difference in altitude of the marine limit between the western and eastern coasts of Edgeøya. Our observations also imply that Knape's altitudes are slightly overestimated. We are not confident that the measured differences obtained by us reflect real differences in elevation of the marine limit, and we therefore conservatively conclude that the marine limit is 85 to 90 m above sea level on Barentsøya and northern Edgeøya.

In southern Edgeøya the data are scarcer. Knape (1971) reported a beach ridge at 72 m a.s.l. overlain by an end moraine in front of Hartmannbreen just east of Bjørnbukta (Fig. 1). In Negerdalen the highest terrace is 75 m a.s.l. (Knape 1971). Both these elevations are minimum values and are based on barometric readings. The altitudes on the terrace in Dianadalen are even more uncertain because they were measured only once. In spite of the scarce data, it seems likely that the marine limit on the southern part of Edgeøya is between 75 and 80 m a.s.l., and is thus just a few metres lower than on the northern part of the island.

Construction of sea-level curves

Measurement errors on the samples are small both concerning altitude and age, and errors should be random on each side of the real value. Evidently, most samples should plot on or close

Fig. 10. Vertical aerial photograph of Dianadalen (Fig. 1). Location of radiocarbon dated samples are marked, using the three last digits in the sample (field) number (Table 4). Photograph: Norsk Polarinstitutt S 90-6634.

to the true sea-level curve. Therefore, we have defined the sea-level curves by fitting the driftwood and whale bone dates with a least square regression curve. The advantage of this approach is first of all that the curve represents an objective mean of the individual data points. Secondly, the sea-level curve is expressed by a mathematical equation that may be used to calculate the rate of change and quantify the differences in sea-level change between different areas. The weakness of this method is that the constructed sea-level curve is probably smoother than the real curve because short-lived variations in the rate of eustatic sea-level rise must have occurred. However, these variations could hardly have been detected with the available dating accuracy.

We have tested different functions (second-order function, exponential function, etc.) on the datasets. To obtain the best fit, the dataset from each locality had to be split into two groups: dates older and dates younger than 7000 years BP. We obtained a third-order function for the dates older than 7000 years BP and a second order function for the dates younger than 7000 years BP. The goodness of fit is between 0.97–0.99 for all curves. Sea-level curves for the four localities are shown in Figs. 11–14.

As pointed out by Andrews (1986) and Pirazzoli (1991), it is important not only to plot the sea-level index point but also to include the uncertainty associated with each point on the sea-level graph. On the sea-level curves (Figs. 11–14) the age range of one standard deviation of the calibrated radiocarbon ages is drawn. This calibrated age range varies from 100 to 500 years (Tables 1 to 4, columns A and D). At about 10,000 cal yrs BP, the emergence was about 20 mm/year (Fig. 15), and an age range of 300 years corresponds to an altitudinal range of ±6.0 m. In the lower part of the curve, at about 4000 cal yrs BP, the same age range would correspond to an altitudinal range of ±1.5 m.

The altitudinal uncertainty consists of errors in determining the driftwood limit, variation in the driftwood limit and errors in levelling of the samples. These errors sum up to about ±1 m. As illustrated, the main uncertainty prior to ca 5000 cal yrs BP is a result of the imprecision of the calibrated radiocarbon ages, whereas the altitudinal measurement errors, which are not more than ±1 m, become more important after 5000 cal yrs BP, due to lower emergence rates.

Relative sea-level history

The initial phase: stable or rapidly falling sea-level?

As constructed, the sea-level curves indicate a rapid fall from the marine limit immediately after deglaciation (Figs. 11–14). The sea-level curves also suggest that the marine limit on both Edgeøya and Barentsøya was formed almost simultaneously about 11,000 cal yrs BP (Figs. 11–14). However, some ages on shells in glaciomarine sediments indicate that the deglaciation occurred approximately 1000 cal years earlier (see below). If these results are correct, then sea level remained stable during this early phase.

On Frankenhalvøya (Fig. 1), 15 km west of Kapp Ziehen, Landvik et al. (1992) found the bivalve *Nuculana pernula* in glacio-marine sediments located about 3 m above the base of the sequence. A sample was dated to 10,265 ± 95 ^{14}C yrs BP (Ua-2536) (12,235–11.750 cal yrs BP). The last ice movement on Frankenhalvøya was from the west across the peninsula. It is therefore likely that Kapp Ziehen was deglaciated earlier than Frankenhalvøya (Landvik et al. 1992). However at Kapp Ziehen the large whale bone found in the marine limit terrace was dated to 10,930–10,785 cal yrs BP (Table 1, T-9913). Because of the old date from Frankenhalvøya, the Kapp Ziehen sample was redated, but with a similar result (10,835–10,475 cal yrs BP, T-9913I). Two ages on shell fragments from Blåfjorddalen and Dianadalen (Fig. 1) also tend to push the date of deglaciation 1000 cal years back in time (Landvik et al. 1992) compared to the sea-level curves.

On the western coast of Spitsbergen (Fig. 1) there are arguments for a nearly stable relative sea level between about 12,500 to 11,000 cal yrs BP (10,700 and 9700 ^{14}C yrs BP) (Landvik et al. 1987; Lehman & Forman 1992). The reason is postulated to be an ice growth during the Younger Dryas in eastern Svalbard, such that the rate of glacio-isostatic rebound was reduced or reversed. This implies a stillstand or reduced rate of uplift also beneath the ice sheet covering Edgeøya and Barentsøya. The subsequent deglaciation was rapid because of calving. It is therefore possible that the inception of rapid uplift was delayed until Edgeøya and Barentsøya were ice-free, and that the last phase of the abovementioned stillstand caused a stable sea level during the first period after the deglaciation.

There are several arguments against this interpretation:

(1) The timing is problematic. If the stillstand on the western coast was due to ice growth in the east, then Barentsøya and Edgeøya must have been ice-covered during most of the stillstand. However, the shell dates from Barentsøya and Edgeøya cover most of the stillstand period in western Spitsbergen.

(2) The shorelines formed during this period on the western coast of Spitsbergen are very distinct (large beach ridges and terraces) compared to younger shorelines. This morphological difference in shorelines has been used as an argument for a stable or transgressive sea level (Landvik et al. 1987; Forman et al. 1987). The shorelines from this period on Edgeøya and Barentsøya are similar to younger shorelines formed during rapid emergence.

(3) Also, if this interpretation is correct, we would expect a gradual increase in emergence rate after the stillstand, whereas the curves are steep from the outset (Figs. 11–14).

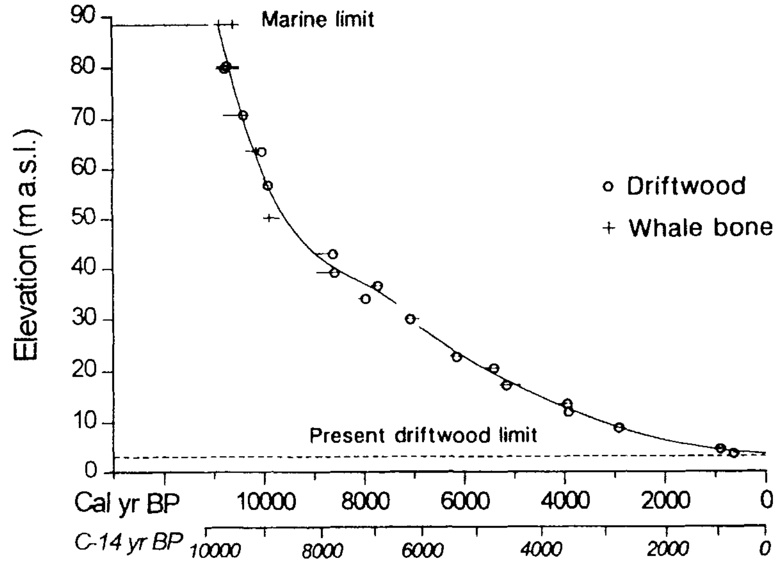

Fig. 11. Relative sea-level curve for Kapp Ziehen. The calculated regression equation prior to 7000 cal yrs BP is: y (m a.s.l.) = $1.80311 \cdot 10^{-9}x^3 - 4.40261 \cdot 10^{-5}x^2 + 0.363333x - 975.5$. After 7000 cal yrs BP: $y = 4.43627 \cdot 10^{-7}x^2 + 5.25669 \cdot 10^{-4}x + 3.68727$ (x = cal yrs BP).

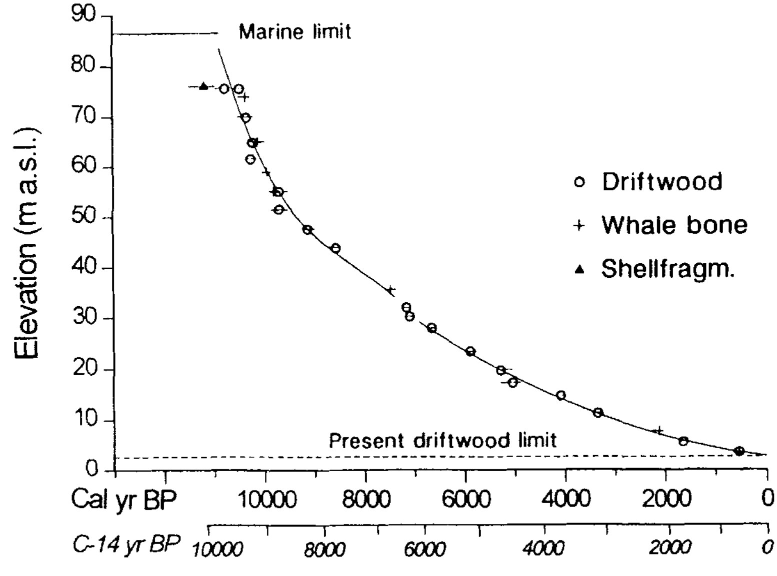

Fig. 12. Relative sea-level curve for Humla. The calculated regression equation prior to 7000 cal yrs BP is: y (m a.s.l.) = $1.26935 \cdot 10^{-9}x^3 - 3.11141 \cdot 10^{-5}x^2 + 0.261035x - 708.187$. After 7000 cal yrs BP: $y = 3.68251 \cdot 10^{-7}x^2 + 1.27263 \cdot 10^{-3}x + 2.73365$.

We have no ready explanation to this discrepancy between the ages on the three abovementioned shells and the sea-level curves. According to the sea-level data it seems most reasonable that the sea-level curves fell rapidly from the marine limit following deglaciation at about 11,000 cal yrs BP.

At about 9000 cal yrs BP, the relative sea level was as low as 40–45 m a.s.l. (Figs. 11–14). This means that half of the total postglacial emergence occurred within the first 2000 years after the deglaciation. A half-response time of 2000 years is common for emergence curves from deglaciated areas (Dyke et al. 1991).

Transgression between 9000–7000 cal yrs BP?

A transgression in Holocene time is reported from several sites in western Spitsbergen (Landvik et al. 1987; Forman et al. 1987; Salvigsen et al. 1990)

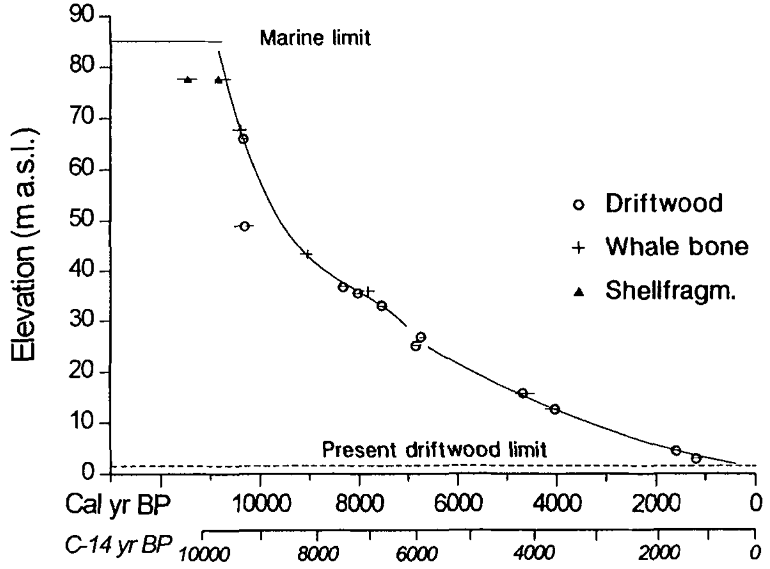

Fig. 13. Relative sea-level curve for Diskobukta. The calculated regression equation prior to 7000 cal yrs BP is: y (m a.s.l.) = $1.48743 \cdot 10^{-9}x^3 - 3.60474 \cdot 10^{-5}x^2 + 0.296724x - 792.632$. After 7000 cal yrs BP: $y = 2.93397 \cdot 10^{-7}x^2 + 1.62237 \cdot 10^{-3}x + 1.23663$.

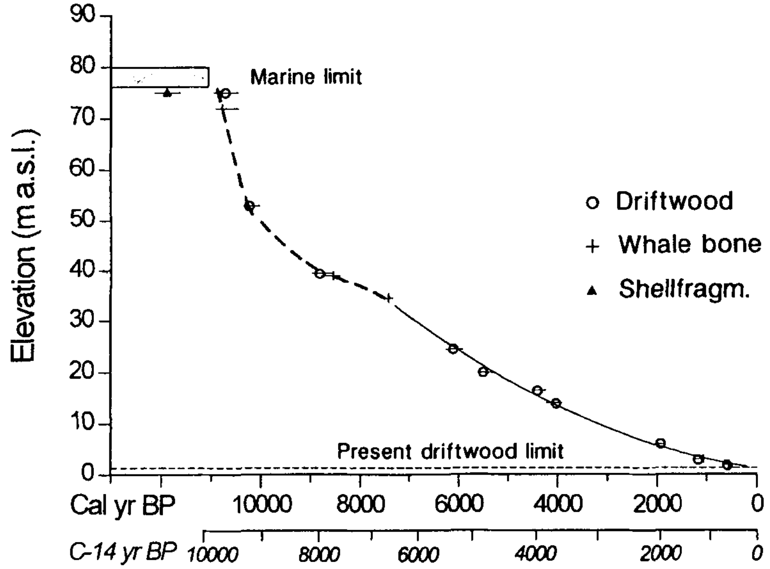

Fig. 14. Relative sea-level curve for Southern Edgeøya. Due to uncertainties with the data prior to 7000 cal yrs B.P. no sea level equation is calculated for this period. After 7000 cal yrs BP the calculated regression equation is: y (m a.s.l.) = $3.94446 \cdot 10^{-7}x^2 + 1.47441 \cdot 10^{-3}x + 1.20223$.

and from Nordaustlandet (Hyvärinen 1969). On Talaveraflya, southwestern Barentsøya (Fig. 1), Feyling-Hanssen (1965) described a 2 to 4 cm thick layer with terrestrial plant remains covered by marine sediments at 12.6 m a.s.l. The layer, interpreted by him to be a terrestrial peat, was dated at 7270–6360 cal yrs BP (6000 ± 400 ^{14}C yrs BP), and the overlying marine sediments were consequently interpreted as indicating a transgression. Talavera is later used as the name for the Holocene transgression on Svalbard (Landvik et al. 1987; Forman 1990). According to the curves (Figs. 11–14), sea level cannot possibly have been as low as 12.6 m a.s.l., 7000 to 6000 cal years ago. The terrestrial plant remains must have been redeposited in shallow sea water. The name Talavera Transgression should thus be abandoned.

Between 8500 and 8000 cal yrs BP the rate of emergence was less than 10 mm/year for all three

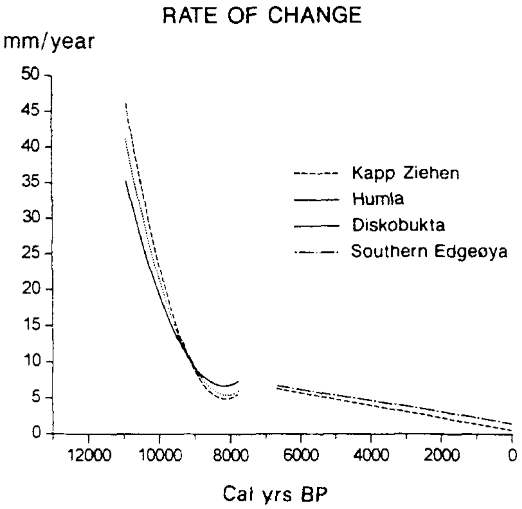

Fig. 15. Rate of change for the four localities obtained by differentiating the relative sea-level equations (Figs. 11, 12, 13 and 14). For the last 7000 cal years, the rates for Humla and Diskobukta lie between the curves shown for Southern Edgeøya and Kapp Ziehen.

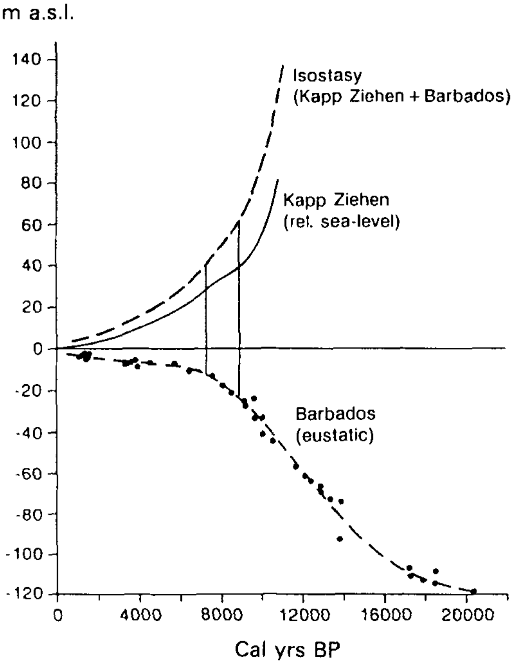

Fig. 16. Calibrated coral dates (= calendar years) from the Barbados sea-level curve (Fairbanks 1989) plotted together with the sea level curve from Kapp Ziehen. The isostasy curve drawn here is simply the Kapp Ziehen curve and the eustatic sea-level curve added together. The reduced rate of emergence observed between 9000 and 7000 cal yrs BP is caused by a sustained eustatic sea level rise parallel with a decreased rate of isostatic uplift.

curves (Fig. 15), considerably lower than during preceding and subsequent periods. A reduced rate of emergence is also shown by Landvik et al. (1987) for several curves on Svalbard. The emergence curve from Svartknausflya (Salvigsen 1978), on the southern part of Nordaustlandet (Fig. 1), shows the same pattern with a reduced rate of emergence in this period. On the northern part of Nordaustlandet, Blake (1961) described a well-developed beach, about 7300 cal years old, that is cut into bedrock in many places. This, he argued, indicates a balance between the isostatic uplift of the land and the eustatic rise of the sea. This cannot be seen on Barentsøya and Edgeøya.

In order to explain this reduced rate in emergence, we have compared the eustatic sea-level curve from Barbados (Fairbanks 1989) (calibrated to calendar years) with the sea-level curves from Edgeøya and Barentsøya. Sea-level changes are not globally uniform because of changes in the geoid (Fjeldskaar 1989). However, as the change in gravity between Barbados and Svalbard has probably been insignificant during the last 9000 years, the Barbados curve gives a good approximation for the eustatic sea-level changes on Svalbard (Fjeldskaar pers. comm. 1995). It is clear from Fig. 16 that the reason for the slower emergence is the result of a sustained eustatic rise together with a decreased isostatic uplift. The increased emergence rates after 8000 cal yrs BP are caused by the levelling out of the eustatic sea-level rise.

Regional implications

Isobase map 10,000 ^{14}C years BP ≈ 11,000 cal yrs BP

Deglaciation ages suggest an almost instantaneous and final withdrawal of the last ice-sheet on Svalbard at 10,000 ^{14}C yrs BP (Mangerud et al. 1992a). Subsequently the entire archipelago emerged extremely rapidly (Forman 1990). An isobase map showing the elevation of raised beaches just before this rapid uplift started would depict the load of the melted ice masses better than isobase maps for younger periods. Isobase maps for other periods have been presented

Table 6. Sea-level data for the 10,000 ^{14}C yrs BP isobase map.

Locality	Reference	Sea level	Comments
1) Mitrahalvøya	Forman 1990	15	Broad terrace at 15 m a.s.l. dated to 10,450 ± 330 yrs BP
2) Brøggerhalvøya	Forman et al. 1987	30	Large raised barrier beach present at 29 m a.s.l. Whale rib at 30 m a.s.l. dated to 9745 ± 135 yrs BP
3) P. Karls Forland	Forman 1990	30	Constructional beach ridge at 30 m a.s.l. Whalebones at 32 m dated to 10,610 ± 160 yrs BP and 28 m dated to 9700 ± 130 yrs BP
4) Daudmannsøyra	Forman 1990	42	Whalebone at 42 m a.s.l. dated to 10,080 ± 310 yrs BP
5) Bohemanflya	Salvigsen et al. 1990	55–57	Washing limit at 60 m a.s.l. Sea-level interpreted to be somewhat more than 55 m a.s.l.
6) Kapp Ekholm	Salvigsen 1984	65–84	Piece of wood at 65 m a.s.l. dated to 10,030 ± 140 yrs BP Marked terrace at 84 m a.s.l., possibly marine limit, but shell fragment yielded infinite ages (Mangerud & Salvigsen unpubl.).
7) Linnédalen	Sandahl 1986	38	Wood from terrace 37 m a.s.l. dated to 9980 ± 70 yrs BP Whalebone 39.5 m a.s.l. dated to 10,020 ± 140 yrs BP
8) Ytterdalen	Landvik et al. 1987	50	Beach level B parallel with Nordenskiöldkysten dated to 10,600 ± 130 yrs BP
9) NW W. J. berg land	Salvigsen et al. 1991	37/40	Beach level B. This beach rises slightly from west towards east.
10) NW Sørkappland	Salvigsen & Elgersma 1993	30	Beach level B.
11) Bjørnøya	Salvigsen & Slettemark 1995	<0	No elevated shorelines.
12) Agardhbukta	Salvigsen & Mangerud 1991	52–60	Terrace at 52 m a.s.l. dated to 9870 ± 140 yrs BP Possibly the marine limit. Altitude re-checked by Salvigsen & Mangerud 1991. Not >60 m a.s.l. Tectonic subsidence?
13) Diskobukta	This paper	85	
14) S. Edgeøya	This paper	80	
15) Hopen	Zale & Brydsten 1993	60	Driftwood at 58 m a.s.l. dated to 9800 ± 130 yrs BP Curve extrapolated back to 10,000 yrs BP from this date.
16) Humla	This paper	87	
17) Kapp Ziehen	This paper	89	
18) Wilhelmsøya	Knape 1971	75	Curve extrapolated back to 10,000 yrs BP from whalebone at 57 m a.s.l. dated to 9435 ± 155 yrs BP
19) Svartknausflya	Salvigsen 1978	75	Whalebone dated to 9630 ± 120 yrs BP at 70 m a.s.l. The 10,000 sea-level is probably a little higher.
20) Kongsøya	Salvigsen 1981	100	Samples at 100 m a.s.l. dated to 9850 ± 80 yrs BP The marine limit exceed the 100 m level slightly.
21) Storøya	Jonsson 1983	66	Extrapolation of curve to marine limit (66 m a.s.l.) suggests deglaciation at 10,000 yrs BP
22) P. Oscars Land	Österholm 1990		Deglaciation between 11,000 and 10,000 yrs BP
Kraemerbukta		57	Marine limit.
Zorgdragerfjorden		43	Marine limit.
23) Murchisonfjorden	Blake 1961	55	Curve extrapolated to 10,000 yrs BP from shell dated to 9640 ± 120 yrs BP at 44 m a.s.l.
24) Sjuøyane	Salvigsen unpubl.	20	Marine limit, area deglaciated around 10,000 yrs BP
25) Mosselbukta	Salvigsen & Österholm 1982	40	Area deglaciated approximately 11,000 yrs BP Elevation read off from curve.
26) Gråhuken	Salvigsen & Österholm 1982	17	Area deglaciated approximately 11,000 yrs BP Elevation read off from curve.
27) W of Reinsdyrflya	Lehman & Forman 1987	0	0-isobase marks the boundary for elevated shorelines.

The altitude/age is supported by a sea-level curve based on several ^{14}C dates except 11) Bjønøya and 26) W of Reinsdyrflya. All dates in ^{14}C years BP.

before (Schytt et al. 1968; Boulton et al. 1982; Forman 1990 and Forman et al. 1995). Table 6 shows the sea-level data used to construct the 10,000 ^{14}C yrs BP isobase map. In western Spitsbergen the emergence was slow at that time, and thus an error in dating would not result in a large

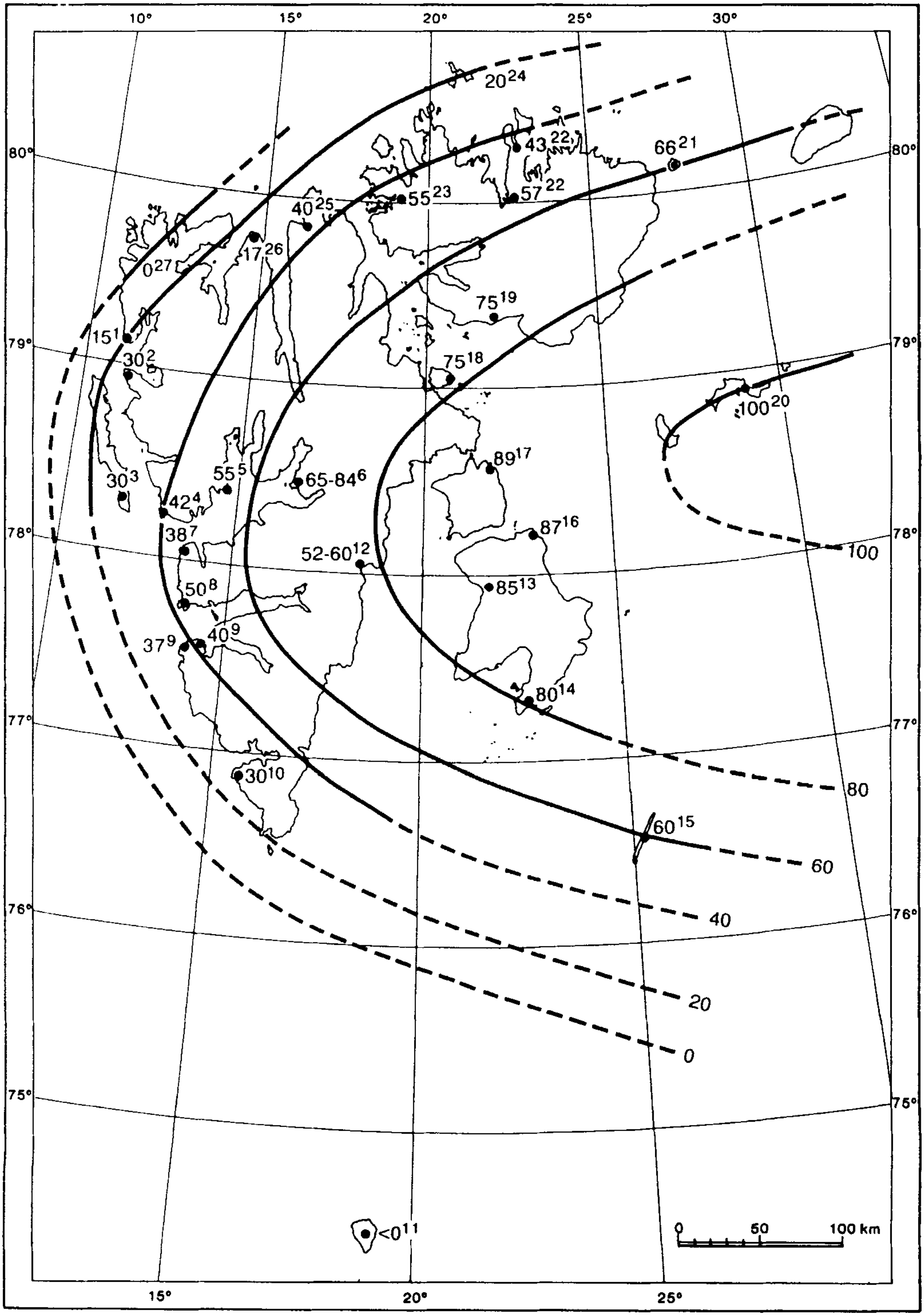

Fig. 17. Isobase map for Svalbard showing the present elevation of shorelines formed approximately 10,000 ^{14}C yrs BP. The altitude (first number) and locality (raised number, see table 6) are given for each site.

error in elevation. In eastern Svalbard, however, emergence was rapid, and the estimated sea level at the time of deglaciation may underestimate the altitude of the 10,000 ^{14}C level.

The uplift dome has a circular/elliptic shape and is limited in extension towards the north, south and west. The distance between the isobases increases from the edge towards the centre, indicating a relatively thin and low gradient ice sheet over eastern Svalbard and adjacent parts of the Barents Sea, as previously shown by the modelling of glacial rebound in the Svalbard-Barents Sea area (Lambeck 1995; Elverhøi 1993). The observations from Edgeøya and Barentsøya confirm this general picture of emergence on Svalbard. The almost identical curves together with similar marine limit observations suggest that the area between Diskobukta-Humla-Kapp Ziehen has emerged without any noticeable tilting. Thus the localities should be found on the same isobases throughout the Holocene. Most data fit well with the isobase map (Fig. 17), but one evident exception is Agardhbukta. According to the constructed map, the sea level 10,000 ^{14}C yrs BP should be close to 80 m a.s.l. (Fig. 17), whereas the observations suggest a marine limit between 52 and 60 m a.s.l. (Table 6). The reason for this is unknown, but one alternative is that this discrepancy was caused by large scale faulting (in Storfjorden?).

Indications of an earlier and larger uplift-centre in the southern Barents Sea?

The emergence rate on southern Edgeøya was greater than at Kapp Ziehen through the last 7000 cal years (Fig. 15), even though the marine limit is lower on southern Edgeøya. Storøya and Hopen, situated northeast and southeast of Barentsøya-Edgeøya, respectively (Fig. 1), show the same pattern. The marine limit on Storøya is 66 m a.s.l. and was formed approximately 11,000 cal years ago (Jonsson 1983). On Hopen the postglacial marine limit is more than 60 m a.s.l. (Hoppe et al. 1969; Zale & Brydsten 1993). By extrapolating the curve from Hopen, the sea level at 11,000 cal yrs BP is ca 60 m o.h. During the first 2000 years after the deglaciation the emergence curves are parallel (Fig. 18), but at about 7000 cal years the curves start to diverge. During the last 3000 years the emergence on Storøya has been only ca 2 m whereas at Hopen it has been ca 7 m (numbers are corrected for different present-day driftwood limits).

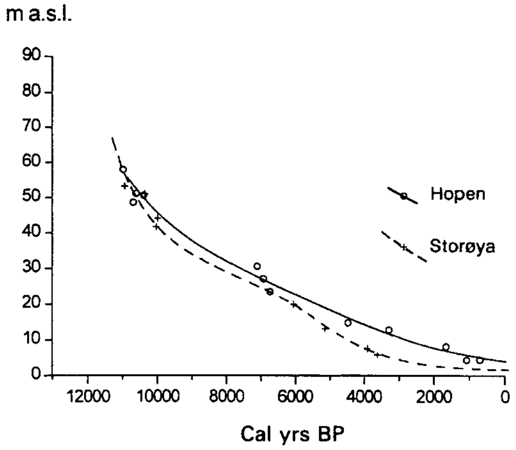

Fig. 18. Calibrated ^{14}C dates of driftwood samples (mean value) for Storøya (Jonsson 1983) and Hopen (Hoppe et al. 1969; Zale & Brydsten 1993). The curves through the datapoints are drawn as originally published. The datings between 11,000 and 9000 cal yrs BP coincide for both localities, but after 7000 cal yrs BP the two datasets clearly diverge with the data from Storøya being 5–6 m below the data from Hopen.

The observed differences in emergence rates between southern Edgeøya and Kapp Ziehen and between Storøya and Hopen could be caused by an *isostatic memory* of a larger and earlier downwarping in the southern Barents Sea. From 11,000 to 9000 cal yrs BP the emergence at all discussed sites was dominated by the rapid isostatic uplift due to the final rapid glacial unloading of Svalbard and the northern Barents Sea, as also is shown on the western coast of Spitsbergen (Landvik et al. 1987; Forman 1990; Mangerud et al. 1992a). When the uplift from that centre decreased (after 7000 cal yrs BP), the remnant isostatic rebound from the loading of the southern Barents Sea became visible as faster uplift in the southern area than further north.

Fjeldskaar (pers. comm. 1994) and Breuer & Wolf (1995) point out the possibility of a lateral change in mantle viscosity from east to west to explain the difference in uplift rates between western and eastern Svalbard. This could be an alternative explanation to the different emergence rate between Storøya and Hopen, and between Kapp Ziehen and southern Edgeøya, with increasing mantle viscosity towards the south, away from the plate boundary north of Nordaustlandet.

Sea ice conditions in the Arctic Ocean

Häggblom (1982) noticed zones on the shore of Hopen where the amount of driftwood was small; he speculated that this might indicate climatic conditions with "long summers" and a northerly position of the sea ice limit. The most distinct zone was between ca 10,000 to 8000 cal yrs BP (9000–7000 ^{14}C yrs BP) where almost no driftwood occurred. As shown by the sea-level curves (Figs. 11–14), driftwood reached Edgeøya and Barentsøya during all time intervals (Tables 1–4). Thus, the Arctic Ocean has been covered with drifting sea ice throughout the Holocene.

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Conclusions

Due to frequent and well-preserved driftwood, relative sea-level changes in eastern Svalbard can be mapped in great detail. The sea-level curves from Edgeøya-Barentsøya are among the most accurate and best dated Holocene sea-level curves from the Arctic.

Between 11,000 and 10,000 cal yrs BP, the sea-level curves show a rapid emergence (40–20 mm/year).

All curves indicate a slower rate of emergence between 9000 and 7000 cal yrs BP with a minimum at ca 8200 cal yrs BP. This is explained by a sustained eustatic sea-level rise parallel with a decreased isostatic uplift.

The terrestrial plant remains on Talaveraflya (Feyling-Hanssen 1965) that have been used as a proof of a transgression in mid Holocene time must have been redeposited in shallow sea water. The name *Talavera Transgression* should thus be abandoned.

The uplift rates on southern Edgeøya are higher than on northern Edgeøya and Barentsøya during the last 7000 cal yrs. Through further comparison of the sea-level curves from Storøya and Hopen, we suggest that a memory of an earlier and larger glacio-isostatic downwarping in the southern Barents Sea is detected in the sea-level curves from Hopen and southern Edgeøya.

The sea-level curves and marine limit observations from the northern part of Edgeøya (Diskobukta and Humla) and Barentsøya (Kapp Ziehen) are almost identical. This fact provides strong evidence that no major vertical faulting occurred between these locations during the last 11,000 cal years.

References

Aarefjord, F. 1969: Frozen up Littorina saxatilis Olivi in the icefoot in Spitsbergen. *Norsk Polarinst. Årbok 1967*, 240–241.

Andrews, J. T. 1970: *A geomorphological study of post-glacial uplift with particular reference to Arctic Canada.* Institute of British Geographers, Special Publication, No 2. 156 pp.

Andrews, J. T. 1986: Elevations and age relationships; raised marine deposits and landforms in glaciated areas. Examples based on Canadian Arctic data. Pp. 67–95 in Orson van de Plassche (ed): *Sea-level research: a manual for the collection and evaluation of data.* Free University, Amsterdam.

Blake, W., Jr. 1961: Radiocarbon dating of raised beaches in Nordaustlandet, Spitsbergen. Pp. 133–145 in Raasch, G. O. (ed): *Geology of the Arctic.* University of Toronto, Toronto.

Blake, W., Jr. 1970: Studies of glacial history in Arctic Canada. I. Pumice, radiocarbon dates, and differential postglacial uplift in the eastern Queen Elizabeth Islands. *Can. J. Earth Sci. 7*, 634–664.

Blake, W., Jr. 1975: Radiocarbon age determinations and postglacial emergence at Cape Storm, southern Ellesmere Island, Arctic Canada. *Geogr. Ann. 57*, series A, 1–71.

Bondevik, S. 1993: *Postglasial strandforskyving på Svalbard.* Unpublished thesis, University of Bergen. 70 + 81 pp.

Boulton, G. S., Baldwin, C. T., Peacock, J. D., McCabe, A. M., Miller, G., Jarvis, J., Horsefield, B., Worsley, P., Eyles, N., Chroston, P. N., Day, T. E., Gibbard, P., Hare, P. E. & von Brunn, V. 1982: A glacio-isostatic facies model and amino acid stratigraphy for Late Quaternary events in Spitsbergen and the Arctic. *Nature 298*, 437–441.

Breuer, D. & Wolf, D. 1995: Deglacial land emergence and lateral upper-mantle heterogeneity in the Svalbard Archipelago – I. First results for simple load models. *Geophys. J. Int. 121*, 775–788.

Büdel, J. 1962: Die Abtragungs-Vorgänge auf Spitzbergen im Umkreis der Barents Insel auf Grund der Stauferlands-Expedition 1959/60. *Deutcher Geographentag Köln 22.–26. Mai 1961, Tagungsbericht und Wissenschaftliche Abhandlungen*, 337–375.

Büdel, J. 1968: Die junge Landhebung Spitzbergens im Umkreis des Freeman-Sundes und der Olga-Strasse. *Würzb. Geogr. Arb.* 22/1, 21.

Dyke, A. S., Morris, T. F. & Green, D. E. C. 1991: Postglacial tectonic and sea level history of the central Canadian arctic. *Geol. Survey Can. Bull.* 397, 1–56.

Eggertsson, O. 1994: Driftwood as an indicator of relative changes in the influx of Arctic and Atlantic water into the coastal areas of Svalbard. *Polar Res. 13*, 209–218.

Elverhøi, A., Fjeldskaar, W., Solheim, A., Nyland-Berg, M. & Russwurm, L. 1993: The Barents Sea ice-sheet: A model of its growth and decay during the last ice maximum. *Quat. Sci. Rev. 12*, 863–873.

Fairbanks, R. G. 1989: A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature 342*, 637–642.

Feyling-Hanssen, R. W. 1965: Shoreline displacement in central Vestspitsbergen and a marine section from the Holocene of Talavera on Barentsøya in Spitsbergen. *Norsk Polarinst. Medd. 93*, 1–34.

Fjeldskaar, W. 1989: Rapid eustatic changes-never globally uniform. Pp. 13–19 in Collinson, J (ed): *Correlation in Hydrocarbon Exploration.* Norwegian Petrol. Soc., Graham & Trotman, London.

Fletcher III, C. H., Fairbridge, R. W., Moller, J. J. & Long, A. J. 1993: Emergence of the Varanger Peninsula, Arctic Norway, and climate changes since deglaciation. *The Holocene 3*, 116–127.

Forman, S. L. 1990: Post-glacial relative sea-level history of northwestern Spitsbergen, Svalbard. *Geol. Soc. Am. Bull. 102*, 1580–1590.

Forman, S. L., Mann, D. H. & Miller, G. H. 1987: Late Weichselian and Holocene relative sea-level history of Brøggerhalvøya, Spitsbergen. *Quat. Res. 27*, 41–50.

Forman, S. L., Lubinski, D., Miller, G. H., Snyder, J., Matishov, G., Korsun, S & Myslivets, V. 1995: Postglacial emergence and distribution of Late Weichselian ice-sheet loads in the northern Barents and Kara seas, Russia. *Geol. 23*, 113–116.

Glaser, U. 1968: Junge Landhebung im umkreis des Storfjord (SO-Spitsbergen). *Würzburger Geographische Arbeiten* 22/II, 22.

Gulliksen, S. 1980: Isotopic fractionation of Norwegian material for radiocarbon dating. *Radiocarbon 22*, 980–986.

Häggblom, A. 1982: Driftwood as an indicator of sea ice conditions. *Geogra. Ann. 64A*, 81–94.

Hjort, C., Mangerud, J., Adrielsson, L., Bondevik, S., Landvik, J. Y. & Salvigsen, O. 1995: Radiocarbon dated common mussels *Mytilus edulis* from eastern Svalbard and the Holocene marine climatic optimum. *Polar Res. 14(2)*, 239–243.

Hoppe, G., Schytt, V., Häggblom, A. & Österholm, H. 1969: Studies of the glacial history of Hopen (Hopen Islands), Svalbard. *Geogr. Ann. 51A*, 185–192.

Hyvärinen, H. 1969: Trullvatnet: A Flandrian stratigraphical site near Murchisonfjorden Nordaustlandet, Spitsbergen. *Geogr. Ann. 51A*, 42–45.

Ingólfsson, O., Rögnvaldsson, F., Bergström, H., Hedenäs, L., Lemdahl, G., Lorio, J. M. & Sejrup, H. P. 1995: Late Quaternary glacial and environmental history of Kongsøya, Svalbard. *Polar Res. 14(2)*, 123–139.

Jonsson, S. 1983: On the geomorphology and past glaciation of Storøya, Svalbard. *Geogr. Ann. 65A*, 1–17.

Knape, P. 1971: *C-14 dateringar av höjda strandlinjer, synkrona pimpstensnivåer och iakttagelser av högsta kustlinjen på Svalbard.* Licent Thesis, Stockholms Universitet, Naturgeografiska Institutionen. 142 pp.

Lambeck, K. 1995: Constraints on the Late Weichselian ice sheet over the Barents Sea from observations of raised shorelines. *Quat. Sci. Rev. 14*, 1–16.

Landvik, J. Y., Mangerud, J. & Salvigsen, O. 1987: The late Weichselian and Holocene shoreline displacement on the west-central coast of Svalbard. *Polar Res. 5*, 29–44.

Landvik, J. Y., Hansen, A., Kelly, M., Salvigsen, O., Slettemark, Ø. & Stupdrup, O. P. 1992: The last deglaciation and glacimarine/marine sedimentation on Barentsøya and Edgeøya, eastern Svalbard. *LUNDQUA Rep. 35*, 61–83.

Lefauconnier, B. & Hagen, J. O. 1991: Surging and calving glaciers in eastern Svalbard. *Norsk Polarinst. Medd. 116*, 1–130.

Lehman, S. J. & Forman, S. L. 1987: Glacier extent and sea level variation during the Late Weichselian on northwest Spitsbergen. *Polar Res. 5*, 271–272.

Lehman, S. J. & Forman, S. L. 1992: Late Weichselian glacier retreat in Kongsfjorden, west Spitsbergen, Svalbard. *Quat. Res. 37*, 139–154.

Mangerud, J. & Gulliksen, S. 1975: Apparent radiocarbon ages of Recent marine shells from Norway, Spitsbergen and Ellesmere Island. *Quat. Res. 5*, 263–273.

Mangerud, J. & Svendsen, J. I. 1992: The last interglacial-glacial period on Spitsbergen, Svalbard. *Quat. Sci. Rev. 11*, 633–664.

Mangerud, J., Bolstad, M., Elgersma, A., Helliksen, D., Landvik, J. Y., Lønne, I., Lycke, A. K., Salvigsen, O., Sandahl, T. & Svendsen, J. I. 1992a: The last glacial maximum on Spitsbergen, Svalbard. *Quat. Res. 38*, 1–31.

Mangerud, J., Bondevik, S., Ronnert, L. & Salvigsen, O. 1992b: Shore displacement and marine limits on Edgeøya and Barentsøya, eastern Svalbard. *LUNDQUA Rep 35*, 51–60.

Miller, G. H. 1982: Quaternary depositional episodes, western Spitsbergen, Norway: Aminostratigraphy and glacial history. *Arct. Alp. Res. 14*, 321–340.

Pirazzoli, P. A. 1991: *World atlas of Holocene sea-level changes* Elsevier Science Publishers B.V., Amsterdam. 300.

Reineck, H. E. & Singh, I. B. 1980: *Depositional Sedimentary Environments.* Springer-Verlag, Berlin Heidelberg. 549 pp.

Salvigsen, O. 1978: Holocene emergence and finds of pumice, whalebones and driftwood at Svartknausflya, Nordaustlandet. *Norsk Polarinst. Årbok 1977*, 217–228.

Salvigsen, O. 1981: Radiocarbon dated raised beaches in Kong Karls Land, Svalbard, and their consequences for the glacial history of the Barents Sea area. *Geogr. Ann. 63A*, 283–292.

Salvigsen, O. 1984: Occurrence of pumice on raised beaches and Holocene shoreline displacement in the inner Isfjorden area, Svalbard. *Polar Res. 2 n.s.*, 107–113.

Salvigsen, O. & Österholm, H. 1982: Radiocarbon dated raised beaches and glacial history of the northern coast of Spitsbergen, Svalbard. *Polar Res. 1*, 97–115.

Salvigsen, O. & Mangerud, J. 1991: Holocene shoreline displacement at Agardhbukta, eastern Spitsbergen, Svalbard. *Polar Res. 9*, 1–7.

Salvigsen, O. & Elgersma, A. 1993: Radiocarbon dating of deglaciation and raised beaches in northwestern Sørkapp Land, Spitsbergen, Svalbard. *Zeszyty Naukowe Uniwersytetu Jagiellonskiego Prace Geograficzne z. 94*, 39–47.

Salvigsen, O. & Slettemark Ø. 1995: Past glaciation and sea levels on Bjørnøya, Svalbard. *Polar Res. 14(2)*, 245–251.

Salvigsen, O., Elgersma, A., Hjort, C., Lagerlund, E., Liestøl, O. Svendsson, N-O. 1990: Glacial history and shoreline displacement on Erdmannflya and Bohemanflya, Spitsbergen, Svalbard. *Polar Res. 8*, 261–273.

Salvigsen, O., Elgersma, A. & Landvik, J. Y. 1991: Radiocarbon dated raised beaches in northwestern Wedel Jarlsberg Land, Spitsbergen, Svalbard. *Wyprawy Geografizne na Spitsbergen*, Lublin 1991.

Sandahl, T. J. 1986: *Kvartærgeologiske undersøkelser i området Lewinodden – Kapp Starostin – Linnévannet ytre Isfjorden, Svalbard.* Unpublished thesis. University of Bergen. 196 + 112 pp.

Schytt, V., Hoppe, G., Blake Jr, W. & Grosswald, M. G. 1968: The extent of the Würm glaciation in the European Arctic. *Int. Assoc. Sci. Hydrol. 79*, 207–216.

Stubdrup, O. 1992: *Sen- og postglaciale sedimenter fra Vis- og Raddedalen, Edgeøya, Svalbard.* Unpublished thesis. University of Aarhus. 247 pp.

Stuiver, M. & Polach, H. A. 1977: Reporting of ^{14}C data. *Radiocarbon 19*, 355–363.

Stuiver, M. & Reimer, P. J. 1993: Extended ^{14}C database and revised CALIB radiocarbon calibration program. *Radiocarbon 35*, 215–230.

Zale, R. & Brydsten, L. 1993: The pre-Holocene marine limit on Hopen, Svalbard. *Boreas 22*, 159–164.

Österholm, H. 1990: The late Weichselian glaciation and Holocene shore displacement on Prins Oscars Land, Nordaustlandet, Svalbard. *Geogr. Ann. 72A*, 301–317.