Late Quaternary environmental history of central Prins Karls Forland, western Svalbard

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This paper presents the results from stratigraphic and geomorphologic investigations in the Poolepynten area, Prins Karls Forland, western Svalbard. Field mapping, soil profile development and ^{14}C dating reveal the existence of at least two generations of raised beach deposits. Well-developed raised beaches rise to the Late Weichselian marine limit at 36 m a.s.l. Discontinuous pre-Late Weichselian beach deposits rise from the Late Weichselian marine limit to approximately 65 m a.s.l. Expansion of local glaciers in the area during the Late Weichselian is indicated by a till that locally overlies pre-Late Weichselian raised beach deposits. Stratigraphic data from coastal sections reveal two shallow marine units deposited during part of oxygen isotope stage 5. The two shallow marine units are separated by a subglacially deposited till that indicates an ice advance from Prins Karls Forland into the Forlandsundet basin some time during the latter part of stage 5. Discontinuous glaciofluvial deposits and a cobble-boulder lag could relate to a Late Weichselian local glacial advance across the coastal site. Late Weichselian/early Holocene beach deposits cap the sedimentary succession. Palaeotemperature estimates derived from amino acid ratios in subfossil marine molluscs indicate that the area has not been submerged or covered by warm based glacier ice for significant periods of time during the time interval *ca*. 70 ka to 10 ka.

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Research in the past two decades has focused on elucidating Quaternary ice-sheet and sea-level variations in the Barents Sea area, principally to address the timing and extent of Weichselian glaciations in northern Eurasia (Troitsky *et al.* 1979; Boulton *et al.* 1982; Miller 1982; Miller *et al.* 1989; Forman 1990; Lehman & Forman 1992; Mangerud & Svendsen 1992; Ingólfsson *et al.* 1995; Forman *et al.* 1996). Although there is compelling evidence for a large marine-based ice-sheet on the Barents Sea shelf in the Late Weichselian (Salvigsen 1981; Salvigsen & Nydal 1981; Solheim *et al.* 1990), there remains uncertainty on the extent and deglacial chronology for many marginal areas (Lehman & Forman 1992; Elverhøi *et al.* 1993, 1995; Tveranger *et al.* 1995).

Recent terrestrial and marine investigations position a Late Weichselian ice-sheet expanding beyond Svalbard and terminating at the continental shelf edge (Mangerud *et al.* 1992; Mangerud & Svendsen 1992; Svendsen *et al.* 1992, 1996; Andersen *et al.* 1996; Landvik *et al.* 1998). In addition, geophysical modelling based on the regional glacioisostatic response reconstruct a 3200-m-thick central ice-dome in the Barents Sea with a parabolic-shaped ice-sheet margin over west Spitsbergen, attaining thickness of 1000 to 500 m (Lambeck 1995, 1996). In contrast, numerous studies infer a restricted Late Weichselian glaciation, with the expansion of outlet glaciers into the fjords and sounds of west and north Spitsbergen fed by ice caps or an ice-sheet from the east (Salvigsen 1977, 1979; Boulton 1979; Troitsky *et al.* 1979; Salvigsen & Nydal 1981; Boulton *et al.* 1982; Miller 1982; Forman & Miller 1984; Forman 1989; Miller *et al.* 1989; Lehman & Forman 1992).

Seismic stratigraphic investigations along the west Spitsbergen margin indicate that the area has been repeatedly glaciated during late Cenozoic time, with sediments being transported along the fjord troughs and deposited as large sediment fans on the continental slope (Solheim *et al.* 1996). For the Late Weichselian, marine geological investigations in the Isfjorden trough (Fig. 1A) document a diamicton overlain by glaciomarine sediments. ^{14}C ages from the glaciomarine sediments indicate deglaciation of the outer Isfjorden trough before 14.8 ka BP (Svendsen *et al.* 1996). In addition, marine geological data from the Kongsfjorden trough (Fig. 1A) reveal a diamicton overlain by marine sediments with the obtained ages of 13.6 and 12.5 ka BP (Lehman *et al.* unpublished, cited in Landvik *et al.* 1998). However, the question remains whether the entire west coast of Spitsbergen and the shelf area in between the major fjord troughs were buried beneath an expanding Barents Sea ice-sheet (Svendsen *et al.* 1996; Landvik *et al.* 1998), or if the Late Weichselian situation on west Spitsbergen was characterized by a more dynamic situation, with ice streams draining the

Table 1. Conventional and AMS ^{14}C ages BP, Poolepynten, Prins Karls Forland, Svalbard.

Field no.	Unit [1]	Lab. no. [2]	^{14}C age $\pm 1\sigma$ BP	Corrected ^{14}C age[3]	δ ^{13}C ‰ [4]	Dated material	m a.s.l.
F84-287 [5]		I-13795	11 650 ± 180	11 350 ± 180 [5]	−19.2	Whale jaw bone	35
F95-P9		AA-19038	41 670 ± 1500		+2.4	Fragment of Hiatella arctica from marine terrace [6]	30–35
TAPKF-010	D2	GX-21065G [7]	9280 ± 135	8810 ± 135	−17.3	Whale rib from beach sediments [9]	9.0
		GX-21065A [8]	9800 ± 430	9330 ± 430	−14.6		
TAPKF-015	D2	AA-19035	11 810 ± 150	11 340 ± 150	+1.6	Paired valve of Hiatella arctica from beach sediments [6]	8.5
TAPKF-007	C	GX-21066	>41 520		−17.3	Kelp from shallow marine sand [10]	4.0
TAPKF-018	C	AA-19036	>49 000		−21.2	Kelp from shallow marine sand [10]	6.0
TAPKF-036	A	AA-19037	>49 000		−19.9	Kelp from shallow marine sand [10]	5.0

[1] For location of individual samples, see Figs. 1C & 7.
[2] AA numbers refer to accelerator mass spectrometry (AMS) ^{14}C dates performed at the NSF Arizona AMS Facility, University of Arizona, U.S.A.
GX numbers refer to conventional ^{14}C dates performed at the Geochron Laboratories, Cambridge, Massachusetts, U.S.A.
[3] Corrected for a marine reservoir effect of 470 years (Stuvier & Braziunas, 1993).
[4] As per convention all ^{14}C ages have been normalized to −25‰ δ^{13}C.
[5] From Forman (1990). The reported ^{14}C age was corrected for a marine reservoir effect of 300 years (Olsson 1980).
[6] Pretreatment of shells prior to dating include a 50% leach in hydrochloric acid.
[7] ^{14}C age on the gelatin extract.
[8] ^{14}C age on the apatite extract.
[9] Treated with dilute acetic acid prior to dating. ^{14}C ages on the gelatin and apatite extract overlap at one sigma and indicate no contamination. We use the collagen extract in constraining the deposition of the enclosing sediment.
[10] Pretreated with hot, dilute hydrochloric acid.

main Spitsbergen ice dome, and with fringing marginal areas remaining ice-free (Forman 1989; Miller *et al.* 1989; Larsen *et al.* 1991).

Prins Karls Forland (Fig. 1A), situated on the west margin of the Svalbard archipelago, is at a strategic position for recording the passage of ice-sheets advancing from the Barents Sea during the Late Quaternary. The focus of this study was on re-examining previously identified stratigraphic successions on Prins Karls Forland (Miller 1982; Forman 1986), in conjunction with a re-assessment of raised beaches and glacial landforms, to provide constraints on Weichselian glacier activity.

Methods

Dating methods

^{14}C dating of included organic material (Table 1) and two infrared stimulated luminescence ages (Table 2) provide chronological control. In addition, alloisoleucine/isoleucine (aIle/Ile) amino acid ratios on well-preserved marine molluscs (Table 3) provide additional criteria for correlation between sections and to aminozones established for Brøggerhalvøya/Site 15 on the other side of Forlandsundet (Miller *et al.* 1989).

Six samples of shell, whalebone and marine kelp were dated by ^{14}C. Radiocarbon ages on shells are on a single valve by AMS analysis. Prior to dating, all shells received a 50% leach in HCl to remove potential contaminants. For the whalebone dated (TAPKF-010; Table 1), the collagen-dominated gelatin extract and the apatite fraction were isolated for ^{14}C analyses. These fractions yielded statistically similar ages (overlap at one sigma) and indicate no secondary contamination of this whalebone. To compensate for the marine ^{14}C-reservoir effect, 470 years was subtracted from finite ^{14}C ages on whalebone and shell (Stuvier & Braziunas 1993).

Infrared stimulated luminescence (IRSL) dating was attempted on the fine-grained (4–11 µm) fraction of seven samples from the Poolepynten sections. IRSL dating procedures are identical to those presented in Kaufman *et al.* (1996) and Forman (in press). Only two of the seven samples yielded sufficient ingrowth with additive beta dose acceptable for calculating an equivalent dose (ED). Because of the limited number of IRSL analyses, the reported ages provide broad temporal constraint, rather than definitive age assignment. Presented are ages calculated for two residual levels, one assuming full solar resetting and the other near complete resetting of the luminescence after a 60-minute exposure to filtered sunlight. Previous studies indicate that the full-solar-reset level provides a maximum limiting age and the residual level after a 60-minute-filtered sunlight exposure gives a close limiting age (Forman *et al.* 1994; Forman in press).

A total of 39 individual mollusc shells representing nine collections were analysed for aIle/Ile ratios on both the Hydrolysed (Total) and Free fractions of amino

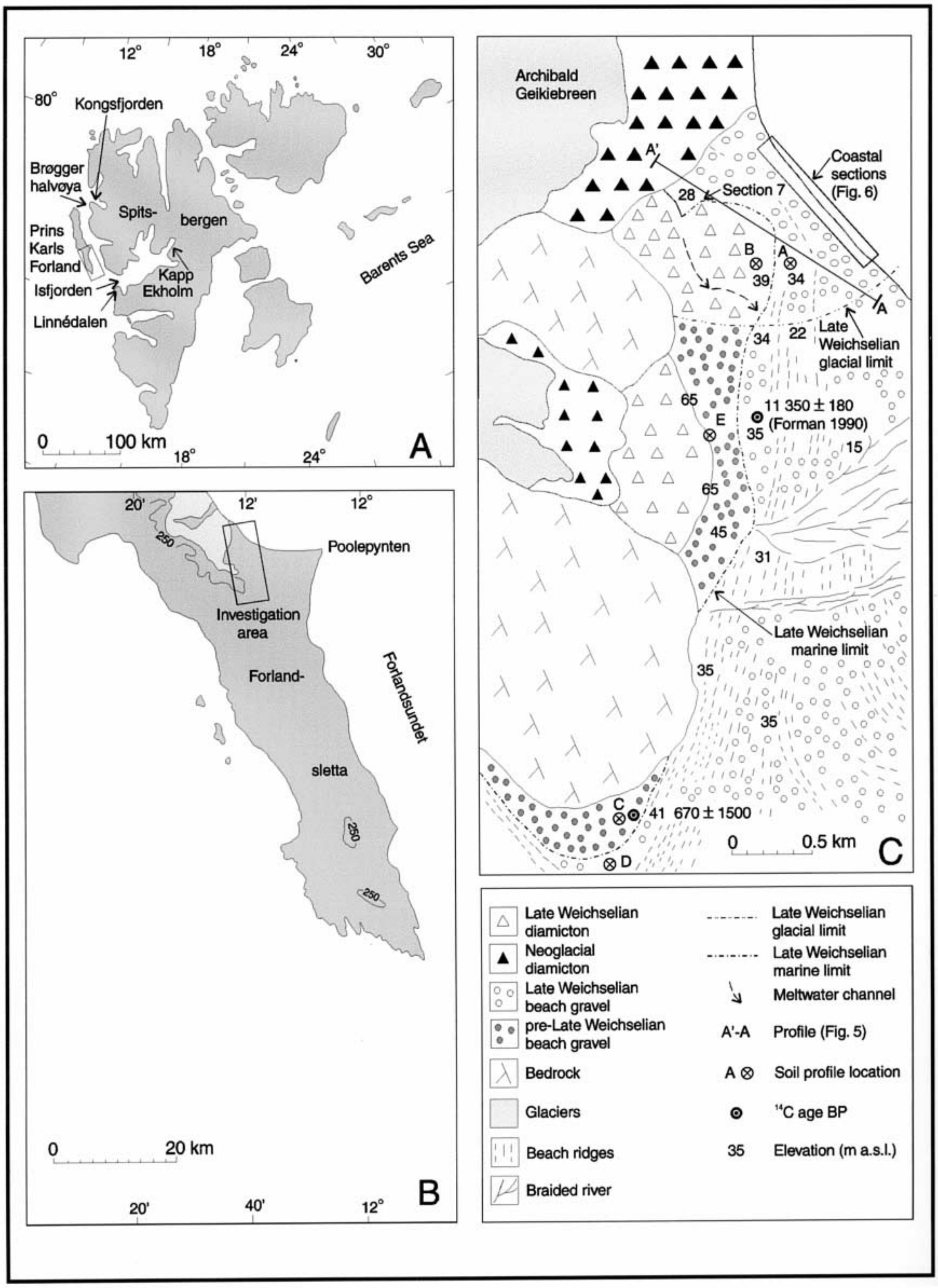

Fig. 1. □ A. Svalbard base map with localities mentioned in the text. □ B. Map over southern part of Prins Karls Forland. □ C. General geomorphologic map over the investigated area. Reconstructed from air photo interpretation of Norwegian Polar Institute aerial photograph S 69: 2145–46 in connection with reconnaissance work in selected areas.

Table 2. Infrared stimulated luminescence equivalent doses and age estimates for sediment samples from coastal sections, Poolepynten, Prins Karls Forland, Svalbard.

Field no.	Unit [1]	Sample no. [2]	Filter and measured wavelength	Preheat time (hrs) and temperature (°C)	Anomalous fade ratio ± 1σ	Apparent equivalent dose (E.D.; gray) ± 1σ and luminescence age estimate (ka) ± 1σ — Filtered sunlight exposure — 60 minutes: E.D.	60 minutes: Age	Full solar reset: E.D.	Full solar reset: Age
TAPKF-006	C	IRSL568	BG-39: blue	160° C @ 5 hrs	0.97 ± 0.02	135.9 ± 1.3	47 ± 5	190.3 ± 1.6	66 ± 7
TAPKF-046	A	IRSL574	BG-39: blue	160° C @ 16 hrs	0.99 ± 0.03	201.8 ± 2.9	90 ± 9	139.6 ± 13.8	140 ± 14

[1] For location of individual samples, see Fig. 7.
[2] IRSL numbers refer to luminescence dates performed at the Luminescence Dating Research Laboratory, Byrd Polar Research Center, the Ohio State University, Columbus, Ohio, U.S.A.

acids (Table 3). The majority of shells are *in situ* paired valves of *Mya truncata* and *Hiatella arctica*. In order to avoid complications arising from surface heating, each sample was collected at least a meter below the exposure surface. Standard deviations are reported to characterize analytical precision and inter-shell variability, and are not intended to encompass variation within a normally distributed population of data. The Total aIle/Ile ratios exhibit good reproducibility; standard deviations on replicate analyses average ± 0.001. Ratios on the two mollusc species should be closely comparable. Sample preparation and analysis followed standard procedures (Miller *et al.* 1983).

Fieldwork

Geomorphologic work was carried out by the means of air photo interpretation and field examination in selected areas. Reported elevations (m a.s.l.) are measured by the use of a hand-held, AIR-HB-1A digital barometer/altimeter with the present-day high-tide swash mark as the calibration datum. Instrument accuracy is ± 0.1 m, but considering the variable relief of landforms and reproducibility of elevation determinations, the maximum inferred error in elevation is ± 2 m. Stratigraphic work was carried out by excavation, logging and correlation of traceable stratigraphic units between excavated sections in the coastal cliffs.

The raised beach succession and associated soil profiles

The Poolepynten area constitutes the northernmost part of the Forlandsletta plain (Fig. 1B). It is characterized by a gently, westwards rising plain, covered by beach sediments and laterally continuous beach ridges (Figs 1C & 2).

Previous studies on western Svalbard (Salvigsen 1977, 1979; Salvigsen & Nydal 1981; Salvigsen & Österholm 1982; Forman & Miller 1984; Forman 1989) have revealed the existence of multiple generations of raised beaches. In the Poolepynten area (Figs 1C & 2) field mapping and associated ^{14}C ages indicate the existence of at least two generations of raised beach successions.

The quantifying of secondary silt accumulation in the soil B horizon in raised beach deposits can provide additional data to subdivide the raised beach succession (Forman & Miller 1984; Mann *et al.* 1986). Five soil profiles (A–E on Figs 1C & 2) on selected surfaces were sampled and analysed for grain-size distribution on the <2 mm fraction. Also recorded is the weight percent of the >2 mm fraction (Fig. 3). Previous studies indicate that the extent of B*l* horizon formation identified by the translocation of pedogenically produced silt is indicative of the landform relative age. Specifically, ^{14}C-dated Late Weichselian/Early Holocene raised beaches exhibit soil B*l* horizons of 15 to 350 cm thickness, whereas raised marine surfaces above the Late Weichselian marine limit (LWML), yielding ^{14}C ages >40 ka BP, exhibit soil B*l* horizons in excess of 40 cm (Forman & Miller 1984). Grain-size distribution in soil profiles on ^{14}C controlled surfaces from the Poolepynten area (Fig. 3) parallel observations of Forman & Miller (1984).

Late Weichselian raised beaches

A minimum limiting age of 11 350 ± 180 BP (I-13795; Table 1) is inferred for formation of the LWML at 36 m a.s.l. (Forman 1990). This feature can be traced over a distance of 3 km (Figs 1C & 2). Below the LWML, well-preserved series of raised beach deposits of Late Weichselian/Holocene ages extend to the present-day coastline. Soil profiles A & D on inferred Late Weichselian surfaces below the LWML (Fig. 1C & 2) exhibit B*l* horizons of 23 cm and 13 cm thickness (Fig. 3), respectively.

Pre-Late Weichselian raised beaches

Discontinuous beach deposits rise from the LWML at 36 m a.s.l. to 65 m a.s.l., which is the highest recognized

Table 3. Amino acid aIle/Ile ratios in *Mya truncata* and *Hiatella arctica* shells from Poolepynten, Prins Karls Forland, Svalbard.[1]

Field no.	Unit [2)]	Lab no.[3)]	Species	Mean hydrolysed aIle/Ile ratio ± 1σ	n	Mean free aIle/Ile ratio ± 1σ	n	Comments
TAPKF-003	D2	AAL-7918A	M.t.	0.019 ± 0.001	3	0.100	1	wave abraded shells from
		AAL-7918B	M.t.	0.020 ± 0.001	2	0.103	1	beach sediments
		AAL-7918C	M.t.	0.023 ± 0.002	2	0.129	1	
		AAL-7918D	M.t.	0.022 ± 0.002	2	0.143	1	
				0.021 ± 0.002	**4**	**0.119 ± 0.021**	**4**	
TAPKF-015	D2	AAL-7921A	H.a.	0.020 ± 0.000	2	ND [4)]	–	whole paired valves from
		AAL-7921B	H.a.	0.022 ± 0.002	2	ND	–	beach sediments
		AAL-7921C	H.a.	0.021 ± 0.001	2	ND	–	
		AAL-7921D	H.a.	0.020 ± 0.000	2	ND	–	
		AAL-7921E	H.a.	0.021 ± 0.001	3	ND	–	
				0.021 ± 0.001	**5**	**ND**	**5**	
TAPKF-035	D2	AAL-7923A	M.t.	0.020 ± 0.001	2	ND	–	abraded valves from
		AAL-7923B	M.t.	0.018 ± 0.001	2	ND	–	beach sediments
		AAL-7923C	M.t.	0.019 ± 0.000	2	ND	–	
		AAL-7923D	M.t.	0.018 ± 0.000	2	ND	–	
		AAL-7923E	M.t.	0.019 ± 0.001	2	ND	–	
				0.019 ± 0.001	**5**	**ND**	**5**	
TAPKF-052	D2	AAL-7925A	M.t.	0.023 ± 0.001	2	ND	–	abraded fragments from
		AAL-7925B	M.t.	0.018 ± 0.003	2	ND	–	beach sediments
		AAL-7925C	M.t.	0.018 ± 0.001	2	ND	–	
		AAL-7925D	M.t.	0.017 ± 0.000	2	ND	–	
		AAL-7926A	M.t.	0.018 ± 0.002	3	ND	–	
		AAL-7926B	M.t.	0.016 ± 0.001	2	ND	–	
		AAL-7926C	M.t.	0.018 ± 0.001	2	ND	–	
				0.018 ± 0.002	**7**	**ND**	**7**	
TAPKF-005	C	AAL-7920A	M.t.	0.023 ± 0.001	2	0.286	1	whole paired valves from
		AAL-7920B	M.t.	0.025 ± 0.002	2	0.163	1	shallow marine sand
		AAL-7920C	M.t.	0.019 ± 0.001	2	0.189	1	
		AAL-7920D	M.t.	0.019 ± 0.000	2	0.230	1	
		AAL-7920E	M.t.	0.018 ± 0.000	2	0.217	1	
				0.021 ± 0.003	**5**	**0.217 ± 0.046**	**5**	
TAPKF-023	C	AAL-7922A	M.t.	0.025 ± 0.001	2	0.223	1	whole valves from
		AAL-7922B	M.t.	0.018 ± 0.000	2	0.252	1	shallow marine sand
		AAL-7922C	M.t.	0.023 ± 0.001	2	0.194 ± 0.070	3	
		AAL-7922D	M.t.	0.019 ± 0.001	2	0.260	1	
		AAL-7922E	M.t.	0.022 ± 0.001	2	0.174	1	
				0.021 ± 0.003	**5**	**0.221 ± 0.037**	**5**	
TAPKF-038	A	AAL-7924A	M.t.	0.024 ± 0.001	3	0.179 ± 0.013	2	whole paired valves from
		AAL-7924B	M.t.	0.026 ± 0.001	3	0.164	1	shallow marine sand
		AAL-7924C	M.t.	0.024 ± 0.001	2	0.227	1	
				0.025 ± 0.001	**3**	**0.190 ± 0.033**	**3**	
TAPKF-053	A	AAL-7927A	M.t.	0.026 ± 0.001	2	0.186	1	whole paired valves from
		AAL-7927B	M.t.	0.027 ± 0.000	2	0.187	1	shallow marine sand
				0.027 ± 0.001	**2**	**0.187 ± 0.001**	**2**	
TAPKF-055	A	AAL-7928A	H.a.	0.046 ± 0.000	2	0.189	1	whole paired valves from
		AAL-7928B	H.a.	0.044 ± 0.001	2	0.181	1	shallow marine sand
				0.045 ± 0.001	**2**	**0.185 ± 0.006**	**2**	

[1] Analysis procedures outlined by Miller *et al.* (1983). Mean and standard deviation are also shown for each collection.
[2] For location of samples, see Fig. 7.
[3] AAL numbers refer to analyses performed on the High Performance Liquid Chromatography System at the amino acid laboratory at INSTAAR, University of Colorado at Boulder, U.S.A.
[4] ND = non-detectable.

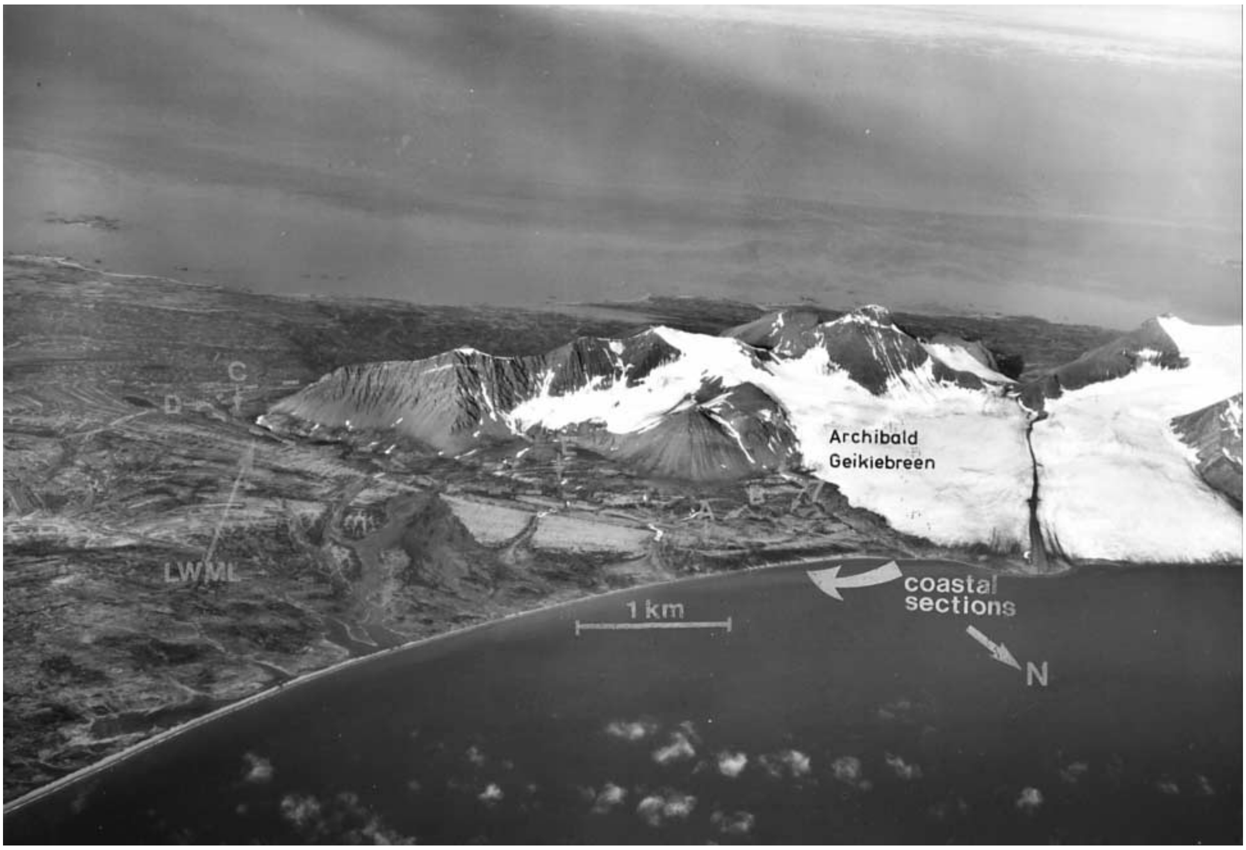

Fig. 2. Norwegian Polar Institute oblique aerial photograph S 36: 28, showing the investigated area with the coastal sections, location of soil profiles A–E, section 7 and the Late Weichselian Marine Limit (LWML).

occurrence of beach gravels/terrace surface (Figs. 1C). Soil profiles C & E on surfaces inside the LWML (Figs 1C & 2) exhibit B*l* horizons of >80 cm and 60 cm thickness (Fig. 3), respectively. The lower parts of soil profile C were littered with mm- to cm-sized shell fragments. Sample AA-19038 (Table 1), collected at a depth of 60 cm, and submitted for ^{14}C dating, yielded an age of 41 670 $\pm$ 1500 BP. The reported age is regarded as a minimum age. Soil profile B, on an inferred pre-Late Weichselian terrace at 39 m a.s.l. (Figs 1C, 2 & 5), exhibit a 20 cm thick B*l* horizon that is truncated and directly overlain by a 5 cm thick greyish-black diamicton (see below).

A diamicton overlying pre-Late Weichselian beaches

A silty, matrix-supported and massive diamicton overlying pre-Late Weichselian raised beach deposits (Fig 4) is documented at soil profile B and at section 7, located approximately 200 m outside the Neoglacial limit (Figs 1C, 2 & 5). The diamicton is characterized by a greyish-black colour and dominance of subangular and angular clasts. At section 7, the diamicton varies in thickness between 10 and 20 cm and individual particles reach boulder size (Fig. 4). The contact to the underlying beach deposit is unconformable and sharp. The diamicton is interpreted as a till deposit. Scattered patches of diamicton and erratics of local provenance occur on top of beach gravels within approximately 500 m outside Neoglacial deposits (Fig. 1C), indicating deposition during a local advance of the Archibald Geikiebreen glacier. A till sample from section 7 was analysed for foraminifera content; it was devoid of marine fauna, which might indicate a terrestrial provenance for the till. The placement of the till between Neoglacial deposits and the Late Weichselian raised beach succession, and truncating pre-Late Weichselian raised beach deposits, indicate a Late Weichselian age for the till. A drop in the marine limit from 34 to 28 m a.s.l. along profile A–A′ (Fig. 5) could indicate that a glacier was in the vicinity of section 7 when the LWML was established.

Stratigraphy of the Poolepynten sections

Sediments are exposed in up to 10 m high coastal sections over a distance of about 800 m (Fig. 6).

Table 4. Marine mollusc fauna from coastal sections, Poolepynten, Prins Karls Forland, Svalbard.[1] Identified by S. Funder.

Field no. Stratigraphic unit [2]		TAPKF-034 A	TAPKF-009 [3] C
GASTROPODA			
Lunatia pallida	Broderip & Sowerby	–	1
Oenopota cancellata	Mighels & Adams	–	c
Oenopota decussata	Couthouy	–	f
Oenopota nobilis	Møller	–	c
Cylichna occulta	Mighels & Adams	–	f
BIVALVIA			
Nucula tenuis	Montagu	–	f
Musculus niger	Gray	–	s
Axinopsida orbiculata	Sars	f	f
Thyasira flexuosa	Montagu	–	1
Astarte warhami	Hancock	–	1
Astarte crenata	Gray	1	–
Serripes groenlandicus	Bruguière	–	c
Macoma calcarea	Gmelin	f	f
Mya truncata	Linné	–	c
Hiatella arctica	Linné	2	s
Thracia septentrionalis	Jeffreys	–	1
Lyonsia arenosa	Møller	–	1
ECHINODERMATA			
Strongylocentrotus droebachensis	Møller	–	s

f: frequent (>20), c: common (10–19), s: scarce (4–9), 1–3: rare, number of shells/fragments.
[1] All recorded species in unit A and unit C presently occur on Svalbard (Feyling-Hanssen 1955).
[2] For location of samples, see Fig. 7.
[3] Sample TA PKF-009 also contains unidentified juvenile gastropods, Spirorbis, bryozoan and crustacea remains.

Presented below is the stratigraphy for sediments in the Poolepynten coastal sections, revealing four main lithostratigraphic units (A–D) and corresponding depositional events (Figs 7 & 10).

Unit A

Lithostratigraphy. – Unit A is recognized in sections 2 to 6. It is the lowermost exposed unit in the coastal sections (Figs 6 & 7). The base of the unit was not observed. It is characterized by horizontally to subhorizontally planar, parallel beds of fine-to-medium sand. Beds containing marine kelp and marine molluscs occur commonly in the unit. Pebbles and cobbles occur randomly in the sediment. The unit shows signs of soft-sediment deformation in the form of convolute bedding and lamination, dewatering and diapir structures.

Unit A is interpreted as a pro-delta formation, deposited from sediment gravity flows/turbidites in a nearshore, shallow marine environment. Individual beds display features related to deposition during waning flow, i.e. graded bedding followed by planar parallel lamination and ripple lamination (Collinson & Thompson 1989). Scattered gravel clasts, locally with deformed laminae beneath clasts, are interpreted as ice-rafted debris. The turbidites were probably fed by sediment-laden meltwater discharge from a nearby local glacier.

Molluscs and foraminifera. – The mollusc fauna of unit A contains four bivalve species (Table 4). Many of the bivalves are well preserved, and occur in living position in the sediment. All recorded species in unit A presently occur on Svalbard. The species are ubiquitous and could live under conditions which were either harsher or more favourable than the present.

A detailed study of the foraminiferal stratigraphy of the Poolepynten deposits has been presented by Bergsten *et al.* (1998). The study shows that unit A contains an abundant and diversified foraminiferal fauna dominated by arctic species, but with a number of boreal and boreal-arctic species present. Bergsten *et al.* (1998) conclude that the foraminifera fauna of unit A is similar to modern fauna in shallow sites on Svalbard, as described by Hansen & Knudsen (1995) and Hald & Korsun (1997), and that the fauna of unit A reflects an arctic, open marine environment, influenced by glacier input and advection of warm North Atlantic water.

Age constraint. – A ^{14}C date on kelp from the shallow marine sediments within unit A yielded an infinite age of >49 ka BP (AA-19037; Table 1). One sediment sample collected for IRSL dating (IRSL574) yielded a statistically reliable response and provides an age envelope between 80 and 150 ka.

Molluscs of *Hiatella arctica* and *Mya truncata* from unit A yielded a range of aIle/Ile ratios (Table 3). Collection AAL-7928 from the lowermost part of unit A gave a mean Total ratio of 0.045 ± 0.001. The mean

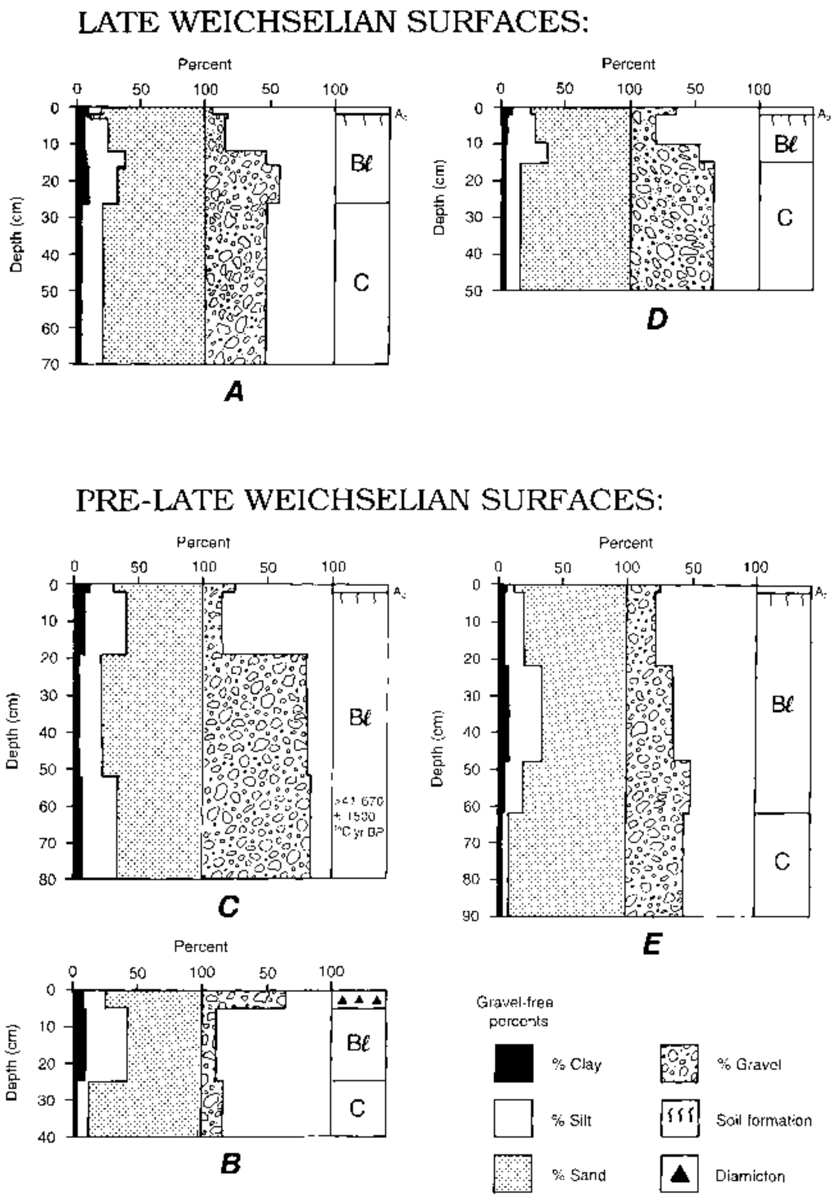

Fig. 3. Grain-size diagrams for soil profiles A–E. Right column displays master soil horizon. The lower capital *l* in B*l* indicates the presence of pedogenic silt accumulations. For location of individual profiles (see Figs. 1C & 2).

Total ratio of collections AAL-7924 and AAL-7927, sampled at higher levels in the unit, is 0.025 ± 0.001.

Unit B

Unit B, recognized in sections 2 and 3 (Figs 6 & 7), comprises two different lithofacies and has been divided into two subunits, B1 & B2.

Subunit B1. – Subunit B1 is a massive, matrix-supported, silty/clayey diamicton that could be traced for over 100 m in the sections (Fig. 6). The thickness of the diamicton varies from 0.5 to 1.3 m. The contact to the underlying unit A is partly sharp and in some places diffuse. In a few places the diamicton has been wedged into the underlying unit A. Many clasts in the diamicton are subangular stones of black dolomite; a bedrock source crops out below 200 m a.s.l. approximately 2 km inland. Shell fragments occur throughout the unit. A clast-fabric analysis of a-axis trend and plunge show a strong preferred clast orientation indicating ice movement from the west (Fig. 8). Several of the particles used for fabric analysis have striated surfaces, and larger, striated and bullet-shaped boulders occur in the

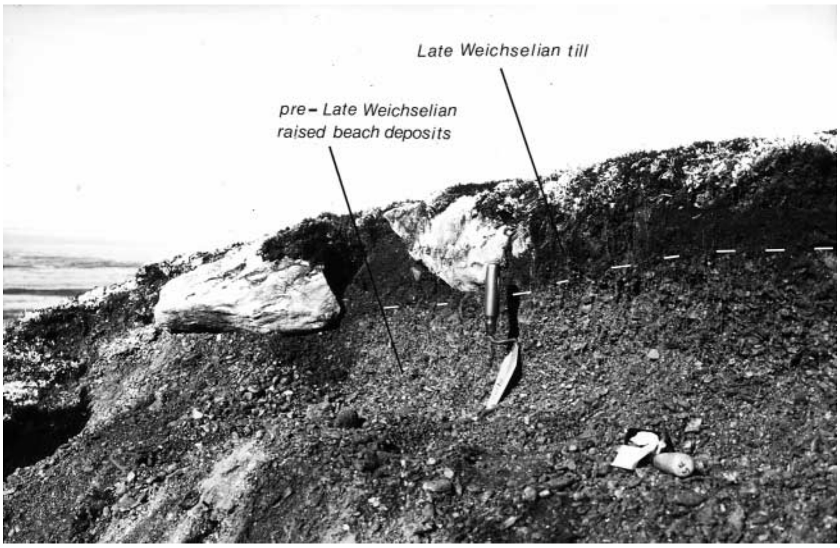

Fig. 4. Diamicton, interpreted as a till, overlying pre-Late Weichselian raised beach deposits at section 7. For location of section, see Figs. 1C & 2. The handle of the trowel is 13 cm long.

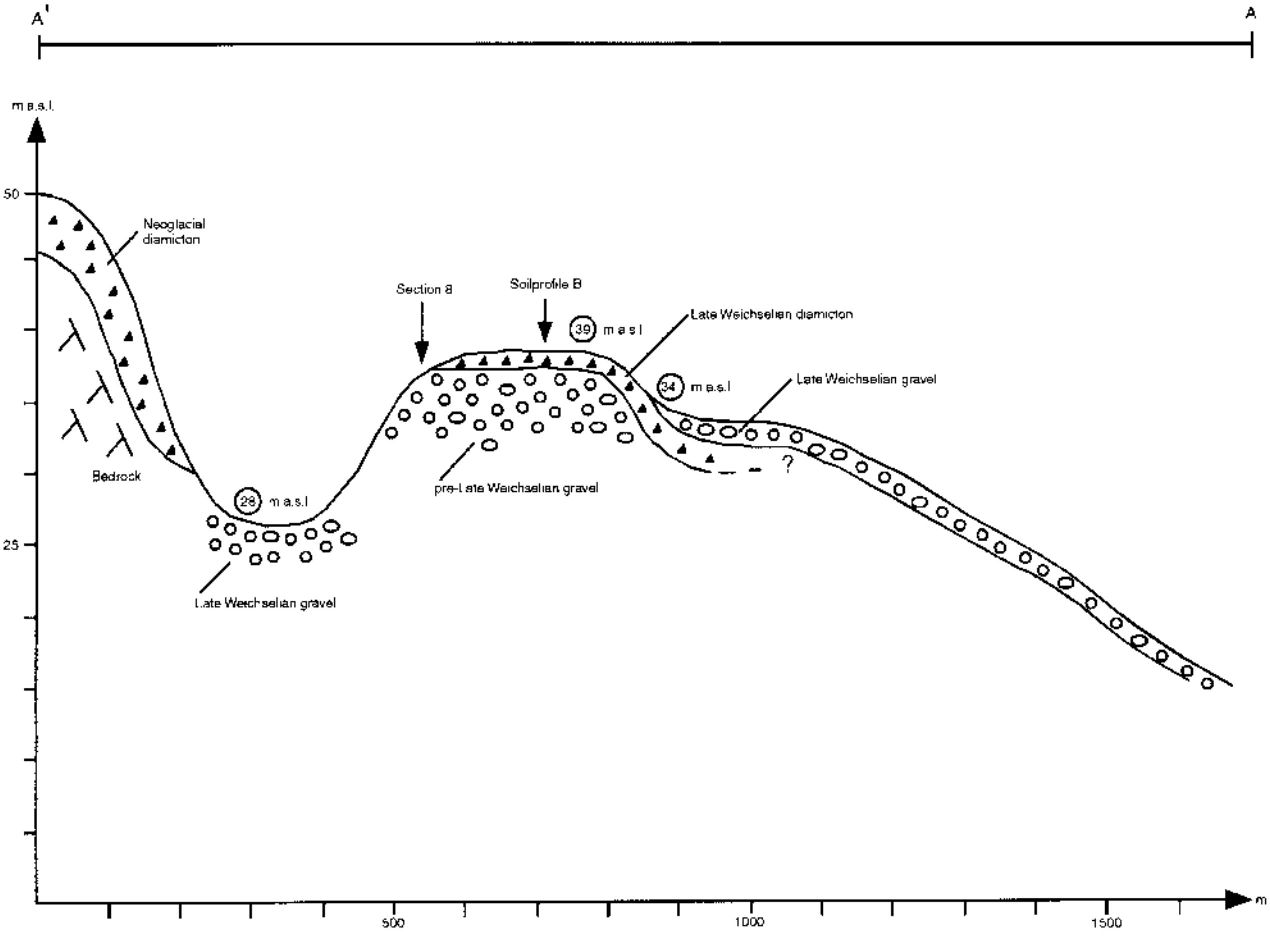

Fig. 5. Schematic cross section for profile A′-A outlined in Fig. 1C.

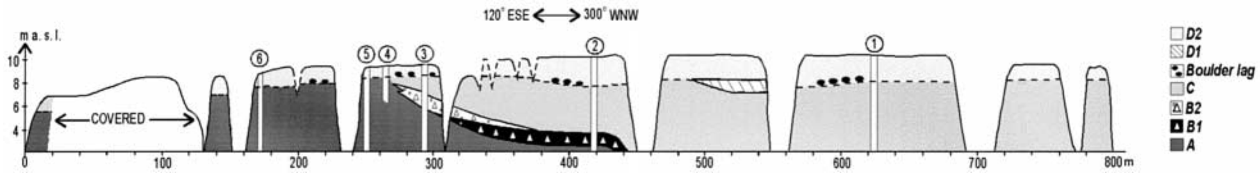

Fig. 6. Schematic presentation of the general stratigraphy in the coastal sections. Sedimentary environments for units A–D are shown in Fig. 10. Location of investigated sections numbered 1–6.

diamicton. We interpret the diamicton to be a subglacially deposited till, emplaced by expansion of glaciers on Prins Karls Forland, into the Forlandsundet basin.

Subunit B2. – Subunit B2 is recorded at section 3 (Figs 6 & 7). It is 1 to 3 m thick in the section and can be traced for about 65 m. It is composed of two major lithofacies: a stratified to massive diamicton and poorly sorted, sandy gravel. The diamicton facies consists of pebble and cobble clasts in a silty-sandy matrix. Many clasts are striated. Stratification in the diamicton is due to minor layers and laminae of silt and sand as well as erosive lower boundaries of individual diamicton beds. The gravel facies is coarse-grained clast-to-matrix-supported deposit of subangular to subrounded pebbles and cobbles; occasional clasts reach boulder size. Several of the clasts are striated. The two facies occur both superimposed and in lateral successions, giving the overall impression of the subunit as being poorly sorted and crudely stratified. The contact to the underlying unit A sediments is disturbed and in some places sharp and erosive, in others diffuse. The lower contact to subunit B1 is sharp to gradational. Subunit B2 thins out laterally to the east (Fig. 6). The upper contact to unit C is conformable, some places sharp but in other places it interfingers with unit C, indicating continuous sedimentation between units B2 and C. The stratified diamicton

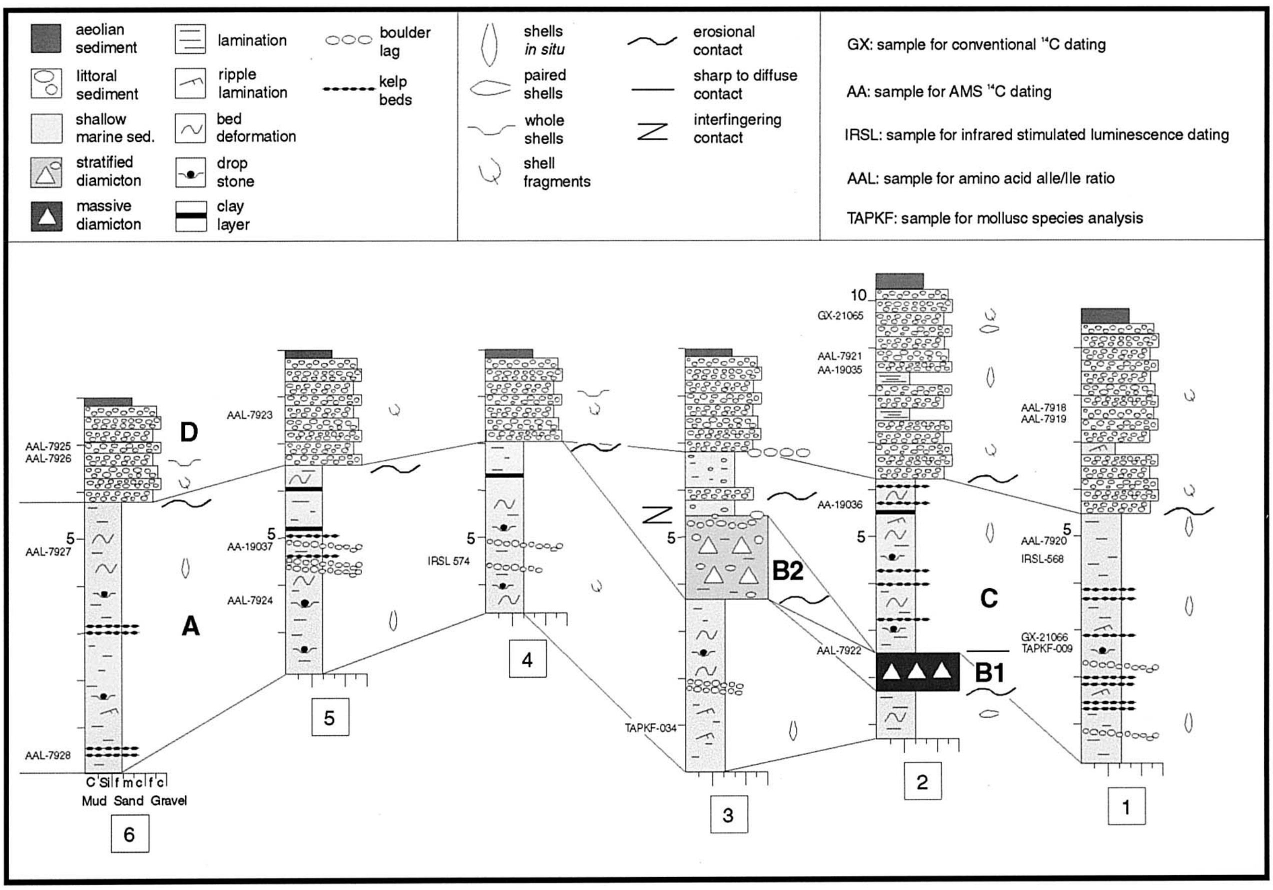

Fig. 7. Lithostratigraphy of the Poolepynten coastal sections. Vertical scale in meters above sea level (m a.s.l.).

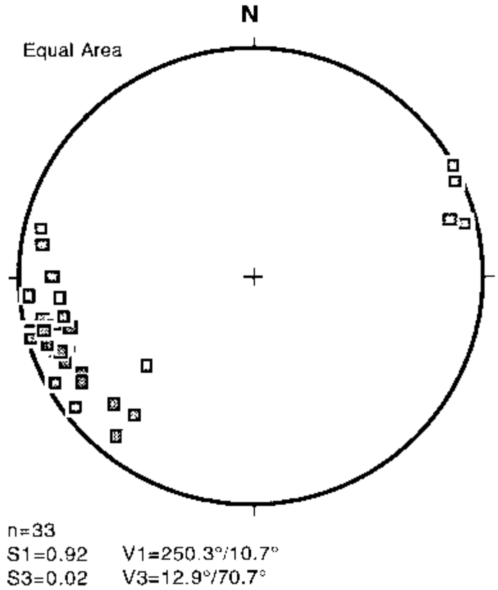

Fig. 8. Fabric analyses of the subunit B1 diamicton.

facies of subunit B2 is interpreted as a subaquatic redeposition of the B1 till by slumping. The unit B geometry is interpreted to define a glacier-eroded basin. In connection with the glacial retreat, under conditions of a relatively high sea level, subunit B1 till deposits on the slopes have slumped into the basin. The gravely facies of unit B2 is interpreted as glaciofluvial sediment.

Unit C

Lithostratigraphy. – Unit C sediments, with a thickness of up to 5 m, constitute the bulk of the western part of the cliffs. It is recorded in sections 1, 2 and 3 (Figs. 6 & 7). They are multiple, horizontal to subhorizontal planar parallel beds of fine to medium sand (Fig. 9). The contact to the underlying subunit B1 in section 2 is sharp. At section 3, the unit C sediments interfinger with the underlying subunit B2 sediments, indicating continuous sedimentation between units B2 and C. Individual beds in unit C are up to 5 cm thick, and commonly are normally graded from bottom to top. Up to 5 cm thick beds of massive to weakly stratified fines occur sporadically. Pebbles and cobbles up to 10 cm, sometimes with deformed laminae below clasts, occur scattered throughout the unit. A striking feature within unit C sediments is the frequency of kelp beds. In the lower 4 m of section 1, 70 kelp beds were identified. The kelp beds are often associated with a lag of fine gravel, followed by normally graded sand, and occasionally grading into silt. Clay intraclasts are frequently associated with the kelp beds. Convolute bedding and lamination, dewatering and diapir structures, indicative of soft sediment deformation and rapid sedimentation, occur within the sediments. They alternate with laterally continuous and undisturbed successions showing well-preserved primary structures.

Fig. 9. Horizontal to subhorizontal sandy beds of unit C, interpreted as deposited from sediment gravity flows in a nearshore, shallow marine environment.

Unit C is interpreted as a pro-delta formation deposited from sediment gravity flows/turbidites in a nearshore, shallow marine environment. The thin, weakly stratified, clayey silt beds are interpreted as reworked and resuspended fines from slumps of water saturated sediments down the fan slope. The kelp beds may reflect repeated storm events, with storm wave base dislodging kelp and clay intraclasts, and subsequent deposition in shallow marine environment. Gravel clasts piercing and locally deforming beds are interpreted as ice-rafted debris. As for unit A, the turbidites were probably fed by sediment-laden meltwater discharge from a nearby local glacier.

Molluscs and foraminifera. – In situ marine molluscs, many with well-preserved periostracum and siphons, and whole single valves and shell fragments, are common in the sediments of unit C. The fauna is

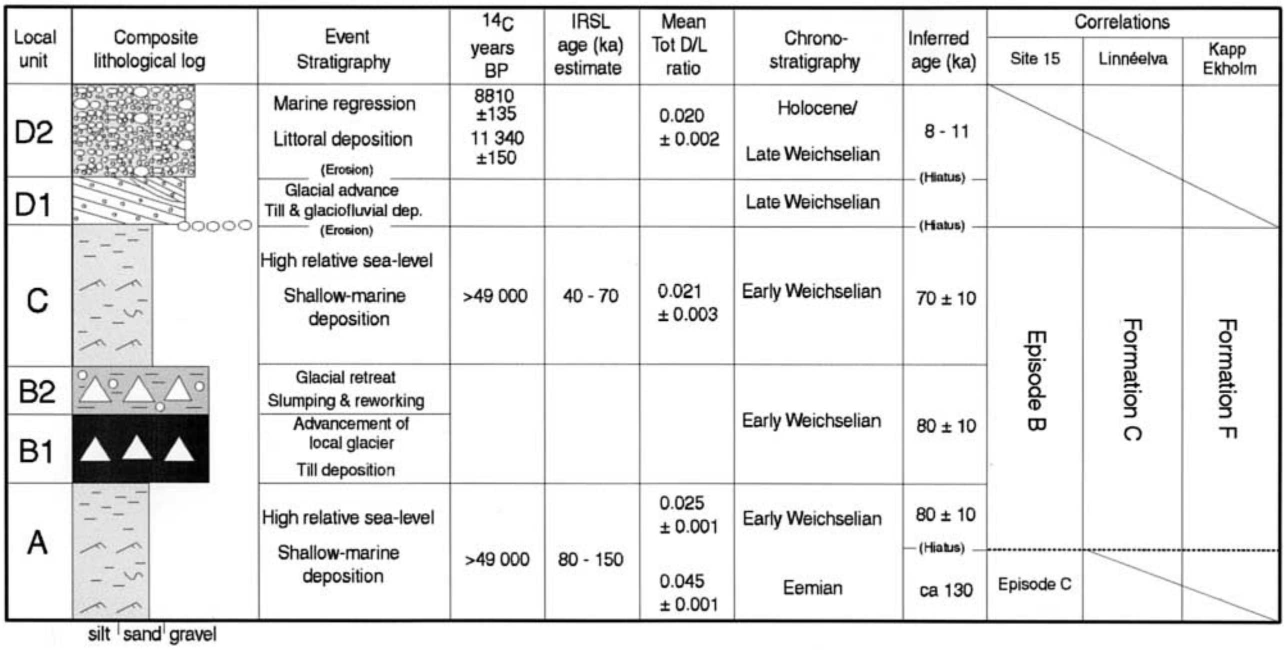

Fig. 10. Composite log for the stratigraphy of sediments exposed in the Poolepynten coastal sections, Prins Karls Forland. Unit thicknesses are arbitrary. Lithological legend in Fig. 7.

diverse; a total of 18 marine mollusc species are identified (Table 4). The faunal assemblage is indicative of a shallow marine environment. Juvenile gastropods in combination with the many juvenile individuals of *Macoma calcarea* indicate that carbonate dissolution has been of minor importance since deposition. All of the species occur around Svalbard, and indicate nearshore marine conditions similar to those of today.

The foraminiferal fauna of unit C is less diversified than that of unit A, but the concentration of foraminifera is still relatively high (Bergsten *et al.* 1998). The fauna is a mixture of arctic species and arctic-boreal elements related to a North Atlantic water influence and seasonally ice-free conditions.

Age constraint. – Two ^{14}C dates, GX-21066 and AA-19036 (Table 1), on marine kelp from unit C yielded infinite ages of >41 250 and >49 000 BP, respectively. Sample IRSL568 (Table 2), collected for luminescence dating, provides a one-sigma age envelope between 40 and 70 ka. Collections AAL-7920 & 7922 (Table 3) of well-preserved, pristine *Mya truncata* shells, gave a mean aIle/Ile ratio of the Total fraction of 0.021 ± 0.003.

Unit D

Lithostratigraphy. – The unit comprises two different lithofacies and has been divided into two subunits, D1 and D2. Unit D1 can be observed at intervals on top of unit C, where it appears alternately as discontinuous lenses, lag of cobbles and boulders, or as channel-fills cut into unit C (Fig. 6). The lower contact of unit D1 is erosive and sharp everywhere. It is a massive to stratified deposit of well-rounded pebble-cobble gravels, with sandy-gravelly intrabeds. Crossed bedding was observed in the channel-fills, with foreset dip towards northerly directions. It is interpreted as a glaciofluvial gravel deposit. The cobble- and boulder lag horizons observed on top of unit C could be erosional remains of either coarse-grained glacofluvium or till

Unit D2 is characterized by clast- and matrix-supported stratified gravel with numerous sandy or sandy-gravelly intrabeds. It varies in thickness from 2 m to 4 m, and unconformably overlies units A, C and D1. The contact to units A, C and D1 is erosive and can be found at an altitude of approximately 8 m a.s.l. throughout the coastal exposure (Fig. 6). Shell fragments as well as whole shells are common in the unit. Unit D2 is interpreted as a beach deposit. Overlying this unit in places there is a thin veneer, up to 40 cm thick, of aeolian sand.

Age constraint. – Subunit D2 is constrained by ^{14}C ages (Table 1) on a whale rib (GX-21065G) and a paired valve of *Hiatella arctica* (AA-19035). The ^{14}C ages suggest that deposition took place some time during the time interval between 8 and 11 ka BP. Remaining shell samples collected in subunit D2 yielded a mean Total aIle/Ile ratio of 0.020 ± 0.002 and low Free ratios or non-detectable concentrations of Free alloisoleucine (Table 3), indicative of Holocene age shells on Svalbard (Miller 1982). The age of unit D1 is constrained by the minimum ages for units C and D2 as being younger than 70 ka and older than 11 ka BP. It could relate to a Late Weichselian ice advance towards the coastal section.

Correlation

The time constraints for the Poolepynten stratigraphy alone provide only broad temporal constraint. On the assumption that raised marine sediments in the Poolepynten sections reflect broad regional ice loading in the near vicinity of the area, rather than local ice loading, an inferred chronology of events is discussed by correlating stratigraphic data from Poolepynten unit A and unit C to previously investigated raised stratigraphic successions on central and western Spitsbergen (Fig. 10).

Correlation to Brøggerhalvøya/Site 15, Episodes B and C

The infinite ^{14}C ages of >49 ka BP provide minimum limiting ages for unit A and unit C at Poolepynten (Table 1). The IRSL age estimates of 80 to 150 ka and 40 to 70 ka for unit A and unit C (Table 2), respectively, only provide slim age control and are considered broad and not definitive age estimates.

The mean Total aIle/Ile ratio of 0.045 ± 0.001 for the lower parts of unit A at Poolepynten (Table 3) is correlative with the mean Total value of 0.044 ± 0.004 for the inferred Eemian, Episode C (125 ± 10 ka; Miller *et al.* 1989) deposit at Brøggerhalvøya/Site 15, and may indicate that the lower parts of unit A at Poolepynten were deposited during isotope substage 5e. The mean Total aIle/Ile ratios of 0.025 ± 0.001 and 0.021 ± 0.003 for the upper parts of unit A and unit C, respectively, are substantially lower than reported values for Episode B at Site 15, which is described with Total ratios of 0.031 ± 0.003, and with limiting ^{14}C and U-Th ages of 70 ± 10 ka (Miller *et al.* 1989). However, considering possible differences in palaeotemperature histories (see below), we conclude that the upper part of unit A may correlate with the onset of Episode B. This implies that there is a hiatus between the lower and upper part of unit A, and that unit A represents parts of two different periods of high relative sea level during Episode C (*c.* 125 ka) and Episode B (*c.* 70 ± 10 ka), respectively.

Correlation to Linnédalen, Formation C

Radiocarbon ages of 42 500 + 1700/−2600 and >43 100 BP provide minimum limiting ages for Formation C at Linnédalen (Lønne & Mangerud 1991). Thermoluminescence (TL) ages of 118 ± 12 ka and 87 ± 10 ka provide maximum limiting ages (Lønne & Mangerud 1991). More recently, the Linnédalen section has been redated using different luminescence dating techniques (Mangerud *et al.* 1998). The mean for the single aliquot regeneration and added dose (SARA), optically stimulated luminescence (OSL) and TL ages on Formation C is 54 ± 5, 70 ± 7 and 68 ± 7 ka, respectively (Mangerud *et al.* 1998). Forman (in press), using IRSL and RSL stimulated luminescence dating techniques, reports a close limiting age estimate of *c.* 80 ± 10 ka for Formation C at Linnédalen.

The mollusc fauna of unit C at Poolepynten (Table 4) resembles the fauna from Formation C at Linnédalen (Funder 1993). Both faunas are diverse and characterized especially by the occurrence of *Astarte warhami*. A mean Total ratio of 0.028 ± 0.002 on shells of *Mya truncata* from Formation C at Linnédalen correlate to the mean Total aIle/Ile ratio of 0.031 ± 0.003 for the inferred 70 ± 10 ka Episode B deposits at Brøggerhalvøya/Site 15. Correlative lower ratios for unit C at Poolepynten are discussed in detail below.

Correlation to Kapp Ekholm, Formation F

A minimum limiting age for Formation F at Kapp Ekholm is provided by ^{14}C ages of >45 ka BP (Mangerud & Svendsen 1992). Three OSL ages of 59 ± 3, 80 ± 7 and 50 ± 2 ka (Mangerud & Svendsen 1992), and more recent SARA and TL mean ages of 63 ± 25 and 60 ± 26 ka (Mangerud *et al.* 1998) are comparable to the IRSL age estimates for the Poolepynten deposits (Table 2). Forman (in press) reports a close finite IRSL age estimate of 71 ± 6 ka for Formation F at Kapp Ekholm.

The mollusc fauna of unit C at Poolepynten is correlative with the fauna of Formation F at Kapp Ekholm. Both faunas are characterized by a high diversity and presence of *Astarte warhami*. The mean Total aIle/Ile ratio of 0.026 ± 0.004 and 0.031 ± 0.005 for *in situ* shells of *Mya truncata* and *Hiatella arctica*, respectively, from Formation F at Kapp Ekholm are similar to the mean Total aIle/Ile ratio of 0.031 ± 0.003 for the inferred 70 ± 10 ka Episode B deposits at Brøggerhalvøya/Site 15. Correlative lower ratios for unit C at Poolepynten are discussed in detail below.

Inferred chronology of events

The correlation of time constraints and biostratigraphic data to stratigraphic successions at Brøggerhalvøya/Site 15, Linnédalen and Kapp Ekholm provide constraints on the age of unit A and C at Poolepynten. It is concluded that the lower parts of unit A may be associated with deposition during isotope substage 5e (Eemian). The inferred ages for the upper part of unit A and unit C at Poolepynten lie between 70 and 90 ka, and imply that deposition took place in the later part of isotope stage 5, during which global sea level was rising to −20 m (Chappell *et al.* 1996). The litho- and biostratigraphic data show that deposition took place in a shallow-marine environment under climatic conditions similar to the present. This implies seasonally ice-free conditions and advection of Atlantic water into the area; this conclusion is supported by Polar North Atlantic coccolith data, indicating a strong inflow of North Atlantic water and open water conditions similar to today during most of isotope stage 5 and the oldest part of isotope stage 4 (Gard 1988).

Constraints of amino acid palaeothermometry on glacial activity

Laboratory and empirical studies have shown that the temperature dependency of the racemization reaction can be utilized to estimate the integrated ground temperature experienced by a mollusc after burial (the effective diagenetic temperature, or EDT; Miller *et al.* 1983; McCoy 1987). Commonly, EDT for a single sample can be estimated to within 2 to 4°C. Changes in EDT among samples of known age can be estimated typically within 1 to 2°C. At high latitudes, amino acid palaeothermometry is particularly useful for discriminating between periods of subaerial exposure with air temperatures well below 0°C, and intervals of marine submergence or thick glacier-ice cover with temperatures at or just above 0°C (Miller *et al.* 1983; Mangerud & Svendsen 1992).

Most striking among the Poolepynten aIle/Ile data is the limited extent of racemization in molluscs from upper unit A (0.025 ± 0.001) and unit C (0.021 ± 0.003) relative to unit D (0.020 ± 0.002; Table 3). Nearly all of the racemization induced in these samples has occurred during and after deposition of unit D, i.e. during the Holocene. The EDT for unit D, assuming an age of 10 ka, is approximately -1°C (cf. equations in McCoy 1987). This temperature is higher than the current mean annual temperature of about -5°C, and probably reflects the relative warmth of ocean water during earliest Holocene submergence. Assuming an age of 70 ka for unit C, EDT for the period 70 ka to 10 ka is about -20°C. Calculations such as these, when the difference in aIle/Ile between units is small, are associated with errors greater than 1 to 2°C (McCoy 1987). Nonetheless, the data indicate that during 70 to 10 ka the sections were exposed to relatively cold subaerial temperatures with low rates of racemization. If a Late Weichselian ice sheet had covered unit C for as little as a few thousand years during 70 to 10 ka, the EDT for the remainder of this period must have been substantially lower than -20°C. Subaerial temperatures as low as -25°C to -30°C are much lower than expected for temperature depression relative to the present in the Barents Sea area during the Weichselian (Dokken & Hald 1996). We thus conclude that the low aIle/Ile ratios in upper unit A and in unit C indicate that the Poolepynten sections have not been covered by warm-based glacier ice during the Late Weichselian for any significant period of time. Similarly, the aIle/Ile data indicate that the Poolepynten sections have not been submerged below sea level for significant periods of time during the period *c*. 70–10ka. Higher ratios for Early Weichselian deposits elsewhere in western Spitsbergen are likely due to longer post-depositional submergence (Brøggerhalvøya/Site 15 and Linnédalen) and/or post-depositional glacier cover (Kapp Ekholm).

Late Weichselian glacial activity

The stratigraphic (Fig. 10) and morphologic investigations provide new field data to constrain Late Weichselian glacial activity along this part of Prins Karls Forland. A minimum Late Weichselian glacial limit for the Poolepynten area is presented in Fig. 1C. The limit is based on the observed placement of a locally deposited till that truncates pre-Late Weichselian raised beach deposits, as well as the occurrence of erratics of local provenance on top of beach gravels. It indicates a Late Weichselian expansion of the Archibald Geikiebreen glacier. Unit D1 in the coastal stratigraphy could relate to a Late Weichselian glacial advance, which reached the coastal cliff site.

Our glacial geologic observations are not consistent with earth-rheology based ice-sheet models that place the western terminus of the Barents Sea ice sheet at the continental shelf margin (Lambeck 1995; Peltier 1996). These models reconstruct over 0.5 km thick ice-sheet over Poolepynten; there is no firm glacial geologic evidence to support this magnitude of ice-sheet coverage. This discrepancy may reflect intrinsic limitations of rheological-based ice-sheet models. It is important to note that the extent of the modelled ice sheet is fixed to enable the ice sheet to be generated and tested against glacioisostatic response. The 50 to 100 km^2 grid resolution of ice-sheet models provides an insensitive representation of marginal processes. The single dome geometry prescribed by rheologically-based models over the central Barents Sea may not accurately represent ice-sheet geometry and flow, particularly in coastal areas with mountains, such as on the western and northern coasts of Svalbard. Coastal satellite ice caps, with diameters greater than lithosphere thickness (50 to 80 km), would produce locally greater loads and more reactive margins that could rapidly advance and retreat as ice streams across the shallow shelf; similar to coastal areas along the present margin of the east Antarctic ice-sheet. Static earth-rheology-based ice-sheet models do not capture the variable and dynamic responses that are characteristic of ice-sheet margins.

We suggest that the Late Weichselian Barents Sea ice-sheet was drained out through the main fjords on the west coast of Spitsbergen, possibly leaving relative large areas ice-free. This interpretation is consistent with the presence of a Late Weichselian subglacially deposited till in the Isfjorden trough (Svendsen *et al.* 1992, 1996).

Conclusions

Stratigraphic data from the Poolepynten sections indicate a shallow marine deposition during part of isotope stage 5.

An ice advance from Prins Karls Forland, into the Forlandsundet basin interrupted the shallow marine deposition.

Two generations of raised beach deposits of Late Weichselian/Early Holocene and pre-Late Weichselian age are recognized in the Poolepynten deposits.

The Late Weichselian marine limit at 36 m a.s.l. reflects the nearby presence of an ice sheet with a volume substantial enough to cause isostatic down-loading of the studied area.

Palaeotemperature estimates derived from aIle/Ile ratios suggest that a warm-based ice-sheet during the Late Weichselian has not covered the Poolepynten sections for any significant period of time. Low aIle/Ile ratios for Early Weichselian deposits indicate insignificant post-depositional ice cover, and minimal post-depositional submergence, relative to other Early Weichselian deposits on western Svalbard.

Geomorphologic and stratigraphic data indicate that glacial activity during the Early Weichselian and the Late Weichselian was characterized by a limited expansion of local glaciers.

We propose that during the Late Weichselian the Barents Sea ice sheet drained through the main fjords on the west coast of Spitsbergen, possibly leaving relatively large areas ice-free.

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