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Postglacial evolution of marine and lacustrine water bodies in Bunger Hills

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Abstract: Unglaciated coastal areas in East Antarctica provide records of past ice sheet and glacier fluctuations and subsequent environmental conditions. In this paper we review lithological, geochemical, diatom and radiocarbon data from sediment records from inland and epishelf lakes in Bunger Hills, East Antarctica. While some hilltops were unglaciated during the Last Glacial Maximum, till deposits in lake basins indicate infilling by glacier ice prior to the Holocene. Proglacial sedimentation occurred in lakes during the early Holocene. Around 9.6 ka BP, deposition of marine sapropel started under relatively warm climate conditions. Inland lakes were affected by high clastic input from meltwater runoff until *c.* 7.9 ka BP, when deposition became highly organic and biogenic proxies indicate a period of cooler conditions. Epishelf lakes experienced a decrease in water exchange with the ocean and increased freshwater input around 7.7 ± 0.2 ka BP and after 2.2 ka BP. This probably resulted from grounding line advances of the bounding glaciers, which could be either controlled by relative sea level (RSL) lowering and/or climate-driven glacier dynamics. The absence of marine sediments in the postglacial record of Algae Lake indicates that Holocene RSL probably reached a maximum at or below 10 m above present sea level.

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Key words: East Antarctica, epishelf lakes, glacier fluctuations, lakes, relative sea level, sediments

Introduction

Bunger Hills are located on the eastern flank of Denman and Scott glaciers (Fig. 1), one of the larger glacier systems in East Antarctica that influence mass balance of the ice sheet (Rignot *et al.* 2019). Although unglaciated coastal areas are not directly affected by changes in the larger glacier systems, their relief and sediments provide important paleogeographic information for understanding postglacial changes in climate, sea level and glacial extent (e.g. Gore *et al.* 2001, Verleyen *et al.* 2011, Berg *et al.* 2016, Hodgson *et al.* 2016).

Exposure of Bunger Hills as nunataks from the ice sheet started some time prior to 30 ka BP (Gore *et al.* 2001). The presence of unglaciated terrain during the Last Glacial Maximum (20–18 ka BP) makes Bunger Hills one of a number of potential refuges for Antarctic biota during periods of expanded ice sheets, glaciers and sea ice (e.g. Gibson *et al.* 2009, Berg *et al.* 2016). Optically Stimulated Luminescence (OSL) ages of glaciofluvial and glaciolacustrine sediments reveal gradual downwasting of ice and expansion of nunatak area by 20 ka BP, and drainage of most glacial lakes by the beginning of the Holocene (Gore *et al.* 2001).

Most studies agree on a relatively stable position of the ice sheet margin throughout the Holocene (Verkulich & Hiller 1994, Fitzsimons & Colhoun 1995, Doran *et al.* 2000). However, glaciers to the south-west of Bunger Hills fluctuated in extent (Colhoun & Adamson 1992, Augustinus 2002) and grounding line position (Melles *et al.* 1997). The timing of these advances and retreats is not well constrained. More precise determination of the timing and extent of glacier fluctuations could, however, give important insights into the sensitivity of the drainage system to climatic changes and oceanic forcings (Crosta *et al.* 2018). Isostatic rebound and relative sea level (RSL) is an indirect measure of regional ice loading and deglaciation history (e.g. Hodgson *et al.* 2016). Estimates of the height of a mid-Holocene RSL high stand in Bunger Hills range from 7.5 ± 0.5 m (Colhoun & Adamson 1992) to 9–11 m (Roberts *et al.* 2000, Verkulich *et al.* 2007). Holocene changes in RSL were inferred from diatom records from epishelf lakes (Verkulich *et al.* 2007). Maximum occurrence of open-ocean diatom species in the mid-Holocene as well as an increase in brackish and benthic species since the mid-Holocene point to a decrease in water exchange with the open ocean and decrease in water depth, probably reflecting RSL lowering (Verkulich *et al.* 2007).

The Holocene temperature development in Bunger Hills was deduced from the amount of organic matter deposition in the water bodies and the presence of sea

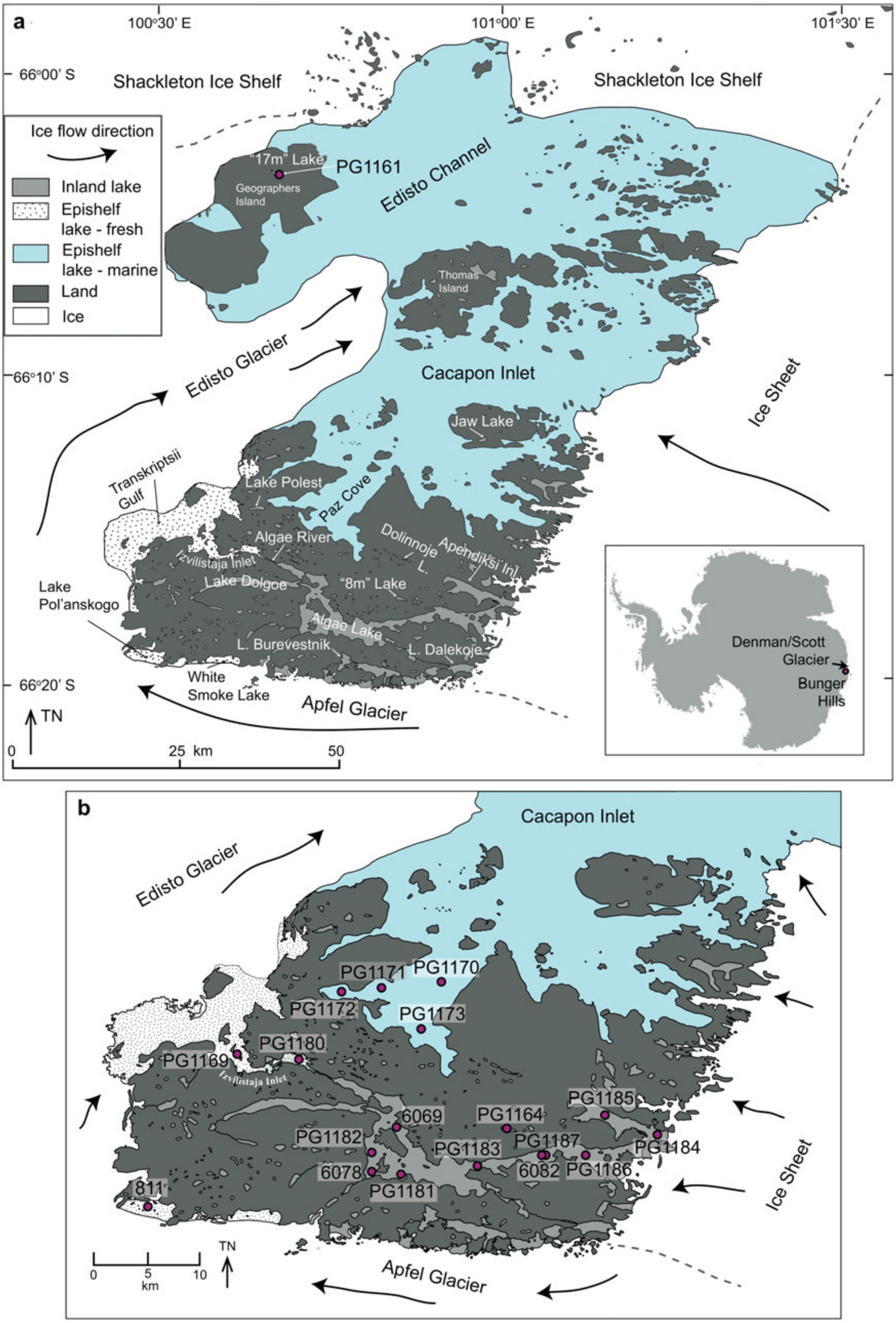

Fig. 1. Bunger Hills, **a.** place names mentioned in the text, and **b.** coring locations in the southern Bunger Hills. The coring location PG1161 on Geographers Island is shown in **a.**

Table I. Cores, coring locations and reference to records discussed in the text.

Site	Core	Latitude	Longitude	Water depth (m)	Core length (cm)	Environment	Reference
17 m lake	PG1161	66°03.0'S	100°41.8'E	7.1	153	FW	Kulbe 1997
8 m lake	PG1164	66°17.5'S	100°51.3'E	12.5	445	FW	Kulbe 1997
Algae Lake	PG1185	66°17.3'S	100°57.8'E	116.7	123	FW	Kulbe 1997
Algae Lake	PG1184	66°17.7'S	101°00.4'E	68.8	250	FW	Kulbe 1997
Algae Lake	PG1186	66°18.1'S	100°56.4'E	123.1	203	FW	Kulbe 1997
Algae Lake	6082	-	-	67.0	136	FW	Melles *et al.* 1994a, Verkulich *et al.* 2002
Algae Lake	PG1187	66°18.1'S	100°53.3'E	75.1	93	FW	Kulbe 1997
Algae Lake	PG1183	66°18.4′S	100°49.5'E	49.7	645	FW	Kulbe 1997
Algae Lake	PG1181	66°18.6'S	100°46.8'E	138.8	214	FW	Kulbe 1997
Algae Lake	6078	66°18'S	100°44'E	39.0	119	FW	Melles *et al.* 1994a, Verkulich *et al.* 2002
Algae Lake	PG1182	66°18.1'S	100°43.6'E	61.9	169	FW	Kulbe 1997
Algae Lake	6069	-	-	56.5	101	FW	Melles et al. 1994a, Verkulich *et al.* 2002
Izvilistaja Inlet	PG1180	66°15'S	100°39.3'E	36.0	1103	ES	Kulbe 1997
Izvilistaja Inlet	PG1169	66°16.1'S	100°36.3'E	11.1	185	ES	Kulbe 1997
Pol'anskogo Lake	811	66°19'S	100°30'E	67.5	103	ES	Melles *et al.* 1997
Paz Cove	PG1170	66°14.3'S	100°47.3'E	101.4	370	ES	Kulbe 1997
Paz Cove	PG1171	66°14.4'S	100°44.3'E	35.4	184	ES	Kulbe 1997
Paz Cove	PG1172	66°14.3'S	100°41.9'E	17.2	355	ES	Kulbe 1997
Paz Cove	PG1173	66°15.2'S	100°46.5'E	90.7	1290	ES	Kulbe *et al.* 2001

FW = fresh water, inland lake, ES = epishelf lake

ice diatoms in marine sediments. In the early Holocene, widespread deposition of biogenic sediments started in the water bodies of southern Bunger Hills indicating relatively warm conditions (e.g. Bolshiyanov *et al.* 1991, Melles *et al.* 1994a, Kulbe 1997, Melles *et al.* 1997, Kulbe *et al.* 2001, Verkulich *et al.* 2002). A climate optimum from 3.5 to 2.5 ka BP was inferred from high accumulation rates and δ^{13}C values of organic carbon in a marine record from Paz Cove (also called Fishtail Bay and Rybiy-Khvost Bay, Fig. 1, Kulbe *et al.* 2001). Warmer water temperatures are also indicated by the diatom assemblage from the same record (Verkulich 2007), however, reduced proportions of sea ice diatoms from 4.3–1.8 ka BP indicate a different timing than suggested from the geochemical data. Both proxies reflect a subsequent cooling and more variable conditions in the late Holocene. Records from Algae Lake (also called Figurnoye Lake) are more sensitive to changes in air temperature, which controls lake ice coverage and water balance of the lake. A multiproxy study on sediment records from Algae Lake showed that cooler conditions characterized the period from 9.0 ± 0.5 to 5.5 ± 0.5 ka BP and also during the late Holocene (Verkulich *et al.* 2002).

In this paper we review lithological, geochemical and diatom assemblage data from sediment records from three inland lakes and two epishelf lakes in Bunger Hills (Fig. 1, Table 1) that were previously presented and discussed by Melles *et al.* (1994a, 1997), Kulbe (1997), Verkulich *et al.* (2002), and Verkulich *et al.* (2007). Some of the data has been presented in German and Russian publications (Kulbe 1997, Verkulich *et al.* 2007) and are now made available to a broader audience. Based on new age-depth models for well-dated sediment cores we discuss evidence for the timing of initial deglaciation and subsequent fluctuations of the ice sheet margin, grounding-line positions of adjacent glaciers and evidence for RSL evolution and temperature. Our re-evaluation of existing data focuses on identifying depositional environments (marine or lacustrine) and transitions between them, which may indicate RSL changes and/or shifts in grounding line related to glacier advances.

Study site

Cacapon Inlet and Paz Cove in central Bunger Hills are presently filled with marine waters and host a rich marine benthic and planktonic flora and fauna (Klokov *et al.* 1990, Melles *et al.* 1994b). A connection with the ocean (evidenced by tidal movement) also exists for epishelf lakes along the margins of Edisto Glacier and western Apfel Glacier, but these lakes today exhibit a freshwater layer due to restricted water exchange underneath the glacier (Doran *et al.* 2000). Transkriptsii Gulf is fed by water flowing from Algae Lake and from direct input of glacier melt from Apfel and Edisto glaciers (Fig. 1), resulting in stable stratification of the water column with fresh water overlying saline and anoxic waters below 88 m (Klokov *et al.* 1990).

In addition to epishelf lakes, numerous inland lakes and ponds are distributed across Bunger Hills. Lakes at low altitudes (< 10 m above sea level, a.s.l.) are mostly saline and their water properties point to an origin as isolated marine basins, inheriting a sea-water signature in their ionic composition (e.g. Lake Polest, Fig. 1; Kaup *et al.*

Table II. Radiocarbon ages discussed in text. ^{14}C analysis were made either by Accelerator Mass Spectrometry (AMS) (Lab ID: Ox) or by miniature counter tube (Lab ID: Hv). Samples of lacustrine origin (lake) were calibrated with atmospheric calibration (SHcal13, Hogg *et al.* 2013), samples of marine orgin (marine) were calibrated with the marine calibration dataset Marine13 (Reimer *et al.* 2013). A reservoir correction of 1300 a was applied for marine samples ($\Delta R = 900$ a). For calibrated ages minimum (min) and maximum (max.) values of the 95.4% confidence intervals are given. (TOC = total organic carbon), carb. = marine carbonate.

Core	Depth (cm)	ID	^{14}C age (a)	+/- (a)	age (cal a BP) min.	age (cal a BP) max.	material dated	origin	reference
PG1161	11	Hv20573	345	155	-1	540	TOC	lake	Kulbe 1997
	21	Hv 20381	1960	165	1530	2310	TOC	lake	Kulbe 1997
	47	Hv20574	4605	200	4660	5715	TOC	lake	Kulbe 1997
	56	Hv20571	6075	195	6450	7318	TOC	lake	Kulbe 1997
PG1164	11	Hv20575	575	150	290	770	TOC	lake	Kulbe 1997
	51	Hv20376	695	155	335	921	TOC	lake	Kulbe 1997
	101	Hv20377	1065	135	685	1260	TOC	lake	Kulbe 1997
	151	Hv20378	2150	165	1705	2680	TOC	lake	Kulbe 1997
	198	Hv20576	2675	160	2350	3140	TOC	lake	Kulbe 1997
	211	Hv20379	3330	160	3085	3960	TOC	lake	Kulbe 1997
	234	Hv20577	4485	165	4625	5580	TOC	lake	Kulbe 1997
	261	Hv20380	4035	200	3905	4970	TOC	lake	Kulbe 1997
	282	Hv20578	5010	170	5320	6175	TOC	lake	Kulbe 1997
	330	Hv20579	5975	215	6320	7255	TOC	lake	Kulbe 1997
	378	Hv20580	8515	220	9000	10155	TOC	lake	Kulbe 1997
	402	Hv20581	6905	380	6985	8445	TOC	lake	Kulbe 1997
PG1181	125	Hv20585	5755	205	6015	7140	TOC	lake	Kulbe 1997
PG1182	11	Hv20591	405	150	-1	634	TOC	lake	Kulbe 1997
	51	Hv20592	5610	195	5935	6780	TOC	lake	Kulbe 1997
	109	OxA-5620	35700	1300	-	-	TOC	lake	Kulbe 1997
	133	OxA-6085	34140	420	-	-	TOC	lake	Kulbe 1997
	157	OxA-6086	34050	650	-	-	TOC	lake	Kulbe 1997
	169	OxA-5621	29150	150	-	-	TOC	lake	Kulbe 1997
PG1183	111	Hv20587	995	170	590	1260	TOC	lake	Kulbe 1997
	171	Hv20588	575	165	150	795	TOC	lake	Kulbe 1997
	291	Hv20589	2575	190	2155	3065	TOC	lake	Kulbe 1997
	437	Hv20590	5185	195	5480	6310	TOC	lake	Kulbe 1997
	500	Hv20586	6495	190	6940	7677	TOC	lake	Kulbe 1997
6082	3	OxA-3930	365	70	155	510	TOC	lake	Melles *et al.* 1994
	39	OxA-3931	1315	65	1050	1305	TOC	lake	Melles *et al.* 1994
	81	OxA-3932	3480	75	3485	3890	TOC	lake	Melles *et al.* 1994
	105	OxA-3933	5640	70	6280	6555	TOC	lake	Melles *et al.* 1994
	135	OxA-3934	7245	70	7875	8175	TOC	lake	Melles *et al.* 1994
PG1187	91	OxA-5622	4980	90	5480	5905	TOC	lake	Melles *et al.* 1994
6069	6	OxA-3935	460	65	325	540	TOC	lake	Melles *et al.* 1994
	30	OxA-3936	2940	70	2850	3315	TOC	lake	Melles *et al.* 1994
	48	OxA-3937	4740	70	5305	5585	TOC	lake	Melles *et al.* 1994
	65	OxA-3938	5315	70	5915	6265	TOC	lake	Melles *et al.* 1994
	83	OxA-3939	7375	80	8000	8335	TOC	lake	Melles *et al.* 1994
	89	OxA-3940	9510	90	10505	11120	TOC	lake	Melles *et al.* 1994
6078	104	OxA-5292	9420	90	9880	10750	TOC	lake	Melles *et al.* 1997
PG1180	21	OxA-5304	955	65	690	935	TOC	lake	Kulbe 1997
	171	OxA-5305	2285	60	785	1065	TOC	marine	Kulbe 1997
	294	OxA-5306	4420	60	3255	3555	TOC	marine	Kulbe 1997
	446	OxA-5307	5045	50	4075	4380	TOC	marine	Kulbe 1997
	586	OxA-5308	5555	55	4775	5045	TOC	marine	Kulbe 1997
	716	OxA-5309	6325	75	5620	5945	TOC	marine	Kulbe 1997
	856	OxA-5310	7420	75	6845	7210	TOC	marine	Kulbe 1997
	946	OxA-5311	8420	130	7725	8265	TOC	marine	Kulbe 1997
	1048	Hv20571	14320	360	-	-	TOC	?	Kulbe 1997
	1068	OxA-5606	28040	55	-	-	TOC	?	Kulbe 1997
	1098	OxA-6087	27900	750	-	-	TOC	?	Kulbe 1997
PG1169	6	Hv20372	1630	170	1185	1885	TOC	lake	Kulbe 1997
	39	Hv20372	2380	175	685	1350	carb.	marine	Kulbe 1997
	40	Hv20511	2430	140	790	1340	carb.	marine	Kulbe 1997

(*Continued*)

TABLE II. (*continued*).

Core	Depth (cm)	ID	^{14}C age (a)	+/- (a)	age (cal a BP) min.	age (cal a BP) max.	material dated	origin	reference
	48	Hv20596	3265	160	3010	3845	TOC		Kulbe 1997
	50	Hv20512	4010	180	2475	3355	carb.	marine	Kulbe 1997
	62	Hv20513	4555	190	3125	4075	carb.	marine	Kulbe 1997
	104	Hv20514	5445	195	4265	5275	carb.	marine	Kulbe 1997
	148	Hv20515	8635	240	7710	8755	carb.	marine	Kulbe 1997
	180	Hv20583	8365	230	8635	9885	TOC	lake	Kulbe 1997
811		OxA-5293	9300	75	8745	9235	TOC	marine	Melles *et al.* 1997
PG1170	11	Hv20597	1285	155	0	350	TOC	marine	Kulbe 1997
	21	Hv 20382	2475	150	805	1415	TOC	marine	Kulbe 1997
	71	Hv20598	3490	165	1905	2695	TOC	marine	Kulbe 1997
	131	Hv20599	4515	165	3130	3950	TOC	marine	Kulbe 1997
	191	Hv20600	5295	175	4080	4995	TOC	marine	Kulbe 1997
	301	OxA-5611	9280	90	8680	9230	TOC	marine	Kulbe 1997
	325	OxA-5612	10500	120	10195	10755	TOC	marine	Kulbe 1997
PG1171	37	OxA-5613	6290	90	5600	5900	TOC	marine	Kulbe 1997
PG1172	15	Hv20593	1910	155	335	885	TOC	marine	Kulbe 1997
	111	Hv20594	5715	205	4600	5575	TOC	marine	Kulbe 1997
	207	Hv20584	7795	230	6930	7840	TOC	marine	Kulbe 1997
	243	OxA-5614	9380	140	8715	9435	TOC	marine	Kulbe 1997
PG1173	21	OxA-5294	1440	50	0	270	TOC	marine	Kulbe 1997
	61	UtC-6697	1709	38	335	510	TOC	marine	Kulbe *et al.* 2001
	101	UtC-6698	1943	37	540	670	TOC	marine	Kulbe *et al.* 2001
	161	OxA-5295	1825	45	470	620	TOC	marine	Kulbe 1997
	201	UtC-6699	2560	60	1075	1320	TOC	marine	Kulbe *et al.* 2001
	251	UtC-6700	2995	44	1555	1795	TOC	marine	Kulbe *et al.* 2001
	291	OxA-5296	3360	45	1985	2270	TOC	marine	Kulbe 1997
	361	UtC-6701	3840	70	2495	2865	TOC	marine	Kulbe *et al.* 2001
	431	OxA-5297	4305	50	3140	3395	TOC	marine	Kulbe 1997
	497	UtC-6702	4808	47	3745	4050	TOC	marine	Kulbe *et al.* 2001
	565	OxA-5298	5220	80	4220	4700	TOC	marine	Kulbe 1997
	645	UtC-6703	5782	45	5040	5305	TOC	marine	Kulbe *et al.* 2001
	715	OxA-5299	6080	60	5410	5680	TOC	marine	Kulbe 1997
	780	UtC-6704	6434	47	5775	6055	TOC	marine	Kulbe *et al.* 2001
	840	OxA-5300	6920	60	6300	6585	TOC	marine	Kulbe 1997
	910	UtC-6705	7643	47	7170	7380	TOC	marine	Kulbe *et al.* 2001
	978	OxA-5301	8165	75	7585	7885	TOC	marine	Kulbe 1997
	1030	UtC-6706	8640	50	8080	8330	TOC	marine	Kulbe *et al.* 2001
	1081	Hv20133	9065	215	8240	9245	carb.	marine	Kulbe 1997
	1110	OxA-5302	9100	100	8470	8985	TOC	marine	Kulbe 1997
	1160	UtC-6707	9610	60	9240	9495	TOC	marine	Kulbe *et al.* 2001
	1205	OxA-5303	9820	80	9435	9825	TOC	marine	Kulbe 1997

1993, Gibson *et al.* 2006). Lakes that are fed by meltwater from the ice sheet or from glaciers show very low electrical conductivities. Low chlorophyll and phytoplankton concentrations in the water column reflect an oligotrophic character (Klokov *et al.* 1990). The largest lake in Bunger Hills is Algae Lake, which is part of a 25 km long drainage system that is fed by meltwater streams from the ice sheet and the margin of Apfel Glacier (Fig. 1; Gibson *et al.* 2002). Meltwater from the ice sheet enters Algae Lake at its eastern end, and via a series of lakes and streams to the south (Fig. 1). To the west, Algae Lake has an outflow across a threshold at *c.* 10 m a.s.l. into Izvilistaja Inlet and further into Transkriptsii Gulf. At present, the outflow is not permanently active and may vary between years and seasons (Gibson *et al.* 2002).

Lakes that presently are not fed by meltwater are particularly sensitive to evaporation and precipitation. Amongst these lakes is 8 m lake (unofficial name) in southern Bunger Hills (Fig. 1), whose surface is located at an altitude of 8 m a.s.l. This lake fills an elongated basin with a maximum water depth of 12.5 m that is surrounded by steep slopes with altitudes of *c.* 40 m. 8 m lake has a restricted catchment area with no surficial outflow. At present, water salinity is higher than in meltwater-fed lakes such as Algae Lake (Melles *et al.* 1994b), consistent with observations from other closed lakes in Bunger Hills (Klokov *et al.* 1990). Instead of

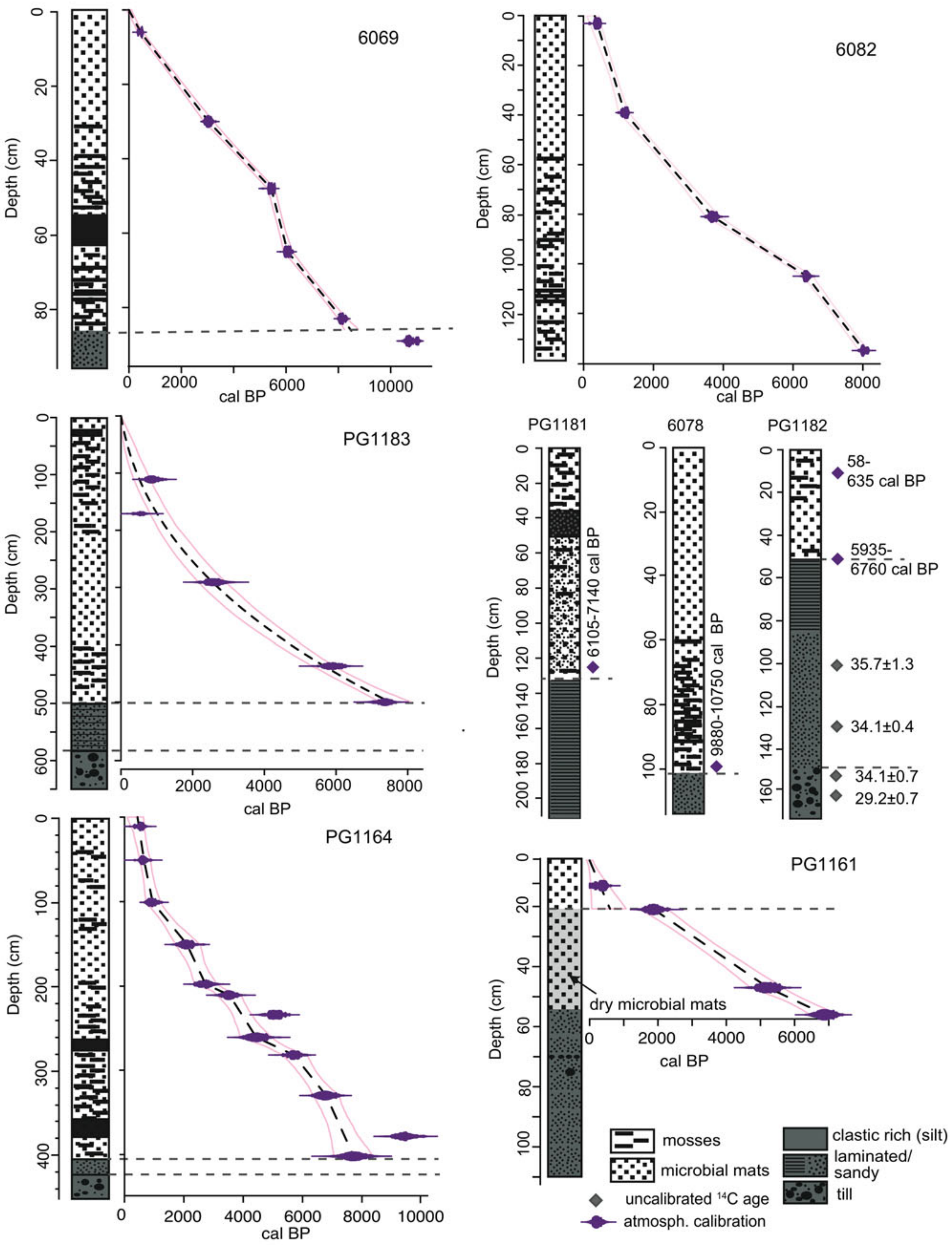

Fig. 2. Lithology and age-depth models for sediment cores from Algae Lake (6069, 6082, PG1183), 8 m lake (PG1164) and 17 m lake (PG1161). Lithology of cores with a few age tie points is also shown (data from Melles *et al*. 1994a, Kulbe 1997, Verkulich *et al.* 2002).

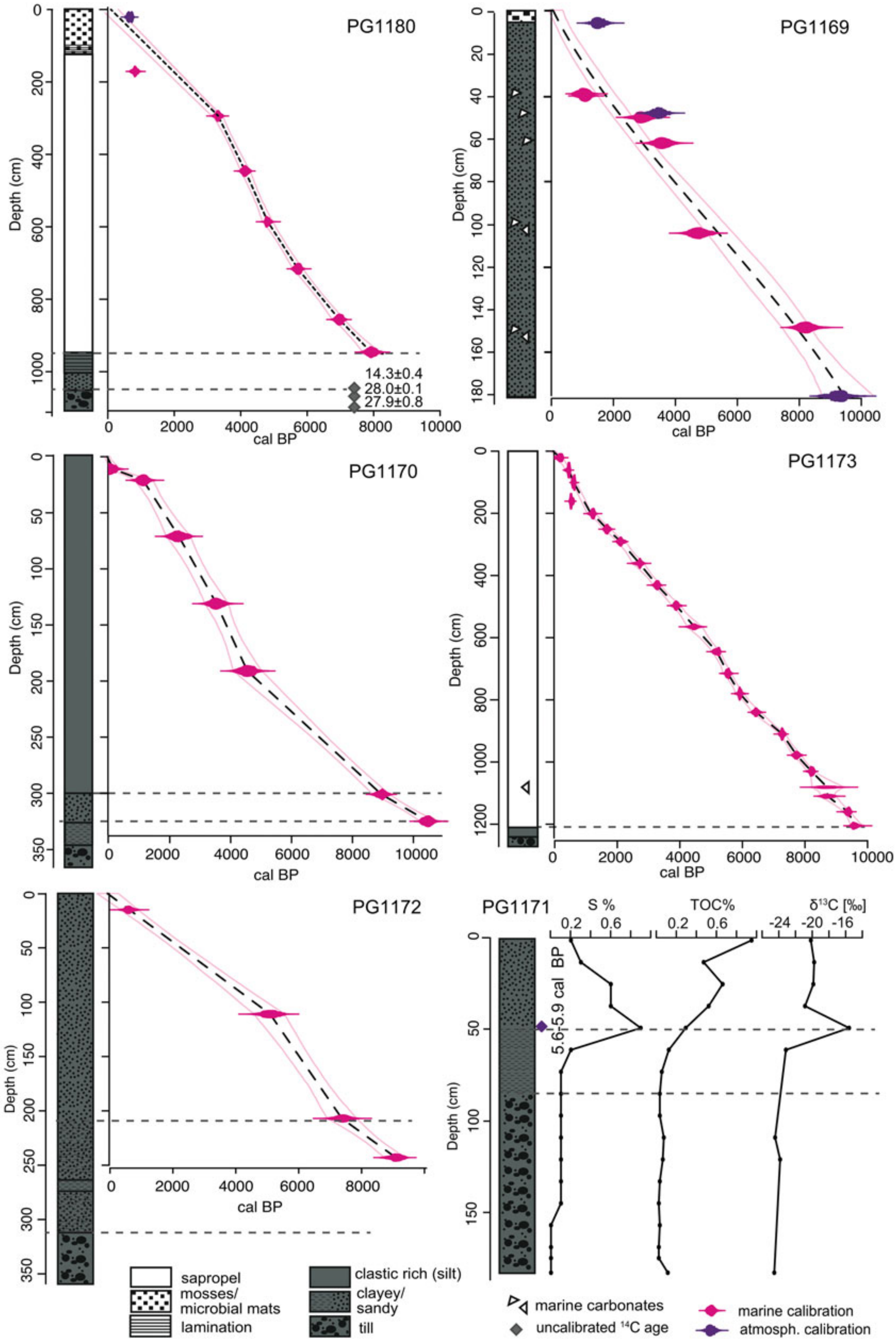

Fig. 3. Age-depth models for sediment cores from Izvilistaja Inlet (PG1180, PG1169) and Paz Cove (PG1170 to PG1173). For core PG 1171 no age model was created due to only one ^{14}C age. Also shown for this core are sulfur (S%), total organic carbon (TOC%) and δ^{13}C of organic carbon.

direct meltwater input, 8 m lake presently receives influx of concentrated groundwater, which probably provides nutrients that lead to intensive growths of algae mats in the littoral zones of the lake (Melles *et al.* 1994b). 17 m lake (unofficial name), in contrast, is a shallow (max. 7.1 m deep) lake on Geographers Island in the northern part of Bunger Hills (Fig. 1), which occupies an enclosed basin at 17 m a.s.l. and is fed by meltwater from adjacent snow banks (Kulbe 1997).

Freshwater lakes in Bunger Hills contain a benthic fauna and flora consisting of cyanobacteria, chlorophytes, diatoms and mosses (Gibson *et al.* 2002). The mats are usually less developed in the marginal areas than in deeper parts of the lakes, since lake ice formation leads to abrasion of benthic mats in shallow waters (Gibson *et al.* 2002, 2006). In lake basins directly fed by meltwater streams from the ice sheet the high supply of suspended matter leads to turbid water and deposition of mainly siliciclastic sediments. This presently occurs, for example, in the eastern basins of Algae Lake (Gibson *et al.* 2002).

Methods

Nineteen sediment sequences were previously presented by Melles *et al.* (1994a, 1994b, 1997), Kulbe (1997), Verkulich *et al.* (2002, 2007) (Table I). Datasets include lithological descriptions (changes in sediment colour, fabric, grain size and organic remains), total organic carbon (TOC), total nitrogen (N) and total sulfur (S) contents, stable carbon isotope ratios of TOC (δ^{13}C) and mineralogical composition. For two cores (PG1173, PG1180) diatom assemblage data was presented in Kulbe *et al.* (2001) and Verkulich *et al.* (2007). Detailed descriptions of the methods are in the respective publications. For 16 cores ^{14}C-ages of TOC and carbonates have been previously published (Table II). Measurements were made either by Accelerator Mass Spectrometry (AMS) (Lab ID: Ox) or by miniature counter tube (Lab ID: Hv) (Kulbe 1997, Verkulich *et al.* 2002).

We selected 10 records for which a minimum of four ^{14}C ages are available and obtained age-depth models with the clam software (Blaauw 2010) by linear interpolation of age tie points or by polynomial regressions. Analyses of freshwater and lacustrine samples were calibrated with atmospheric calibration (SHcal13, Hogg *et al.* 2013). The marine calibration dataset Marine13 (Reimer *et al.* 2013) was used for marine samples, and a reservoir correction of 1300 a (Berkman & Forman 1996) was applied. Age-depth models for postglacial records deposited under lacustrine conditions were created under the assumption that the radiocarbon ages are not affected by a reservoir effect. This is well justified for modern sedimentation, because i) most lakes in Bunger Hills, which are not in direct contact with a glacier, today have a semi-permanent ice cover (Doran *et al.* 1996) and water columns are well-mixed (Klokov *et al.* 1990) inhibiting the build up of reservoir ages, and ii) the radiocarbon ages of most near-surface sediment samples are relatively close to modern.

Age-depth models

In core PG1164 from 8 m lake the age model is based on 12 ^{14}C ages (Fig. 2). Linear extrapolation through the two most recent dating points provides a ^{14}C age of *c.* 400 a for the sediment surface and probably reflects disturbance of the sediment-water interface during coring, possibly due to the very high water content of up to 99% in the upper tens of centimetres of sediment (Kulbe 1997). Age reversals in the sequences PG1164 (Fig. 2) could indicate changes in reservoir ages through time but could also reflect irregular input of reworked older organic carbon (e.g. from the terrestrial catchment). Supply of reworked organic matter, resulting in apparently older sediment ages, is most probable in the highly clastic proglacial sediments, such as those in the lower part of the core 6069 (Fig. 2).

For core PG1161 four ^{14}C ages were obtained (Fig. 2). The sediment properties indicate a hiatus in the record at 21 cm depth due to temporary lake desiccation and associated near-surface sediment freezing. The maximum age of the hiatus is provided by the ^{14}C age of 2.1 ± 0.4 ka BP from the uppermost flaky algal mats at 23 cm depth. The timing of recurrence of algae mat formation, hence the refilling of the lake, was estimated from extrapolation through the modern surface and the only ^{14}C age from the undisturbed algal mat at 11 cm depth.

Age-depth models were obtained for five postglacial records from marine inlets (Fig. 3). For core PG1173, 21 ^{14}C analyses (20 on TOC and one on a carbonate bivalve shell, Table II) provide robust age control, with a basal age of sapropel formation of about 9.5 ka BP (Fig. 3). The TOC age from 161 cm depth is apparently too young, possibly reflecting a period of lower reservoir age, e.g. due to inflow of freshwater from melting glacier ice, and thus was excluded from the age model. In the other marine records from Paz Cove (PG 1170 and PG1172) age control is poorly constrained and does not provide evidence for changes in reservoir ages (Fig. 3).

Estimates of reservoir ages are particularly difficult in epishelf lake settings such as Izvilistaja Inlet (PG1169 and PG1180), where water exchange with the sea is restricted and freshwater inflow is high. In core PG1169, the lower six ^{14}C ages obtained from marine carbonate fossils were corrected for the marine reservoir effect

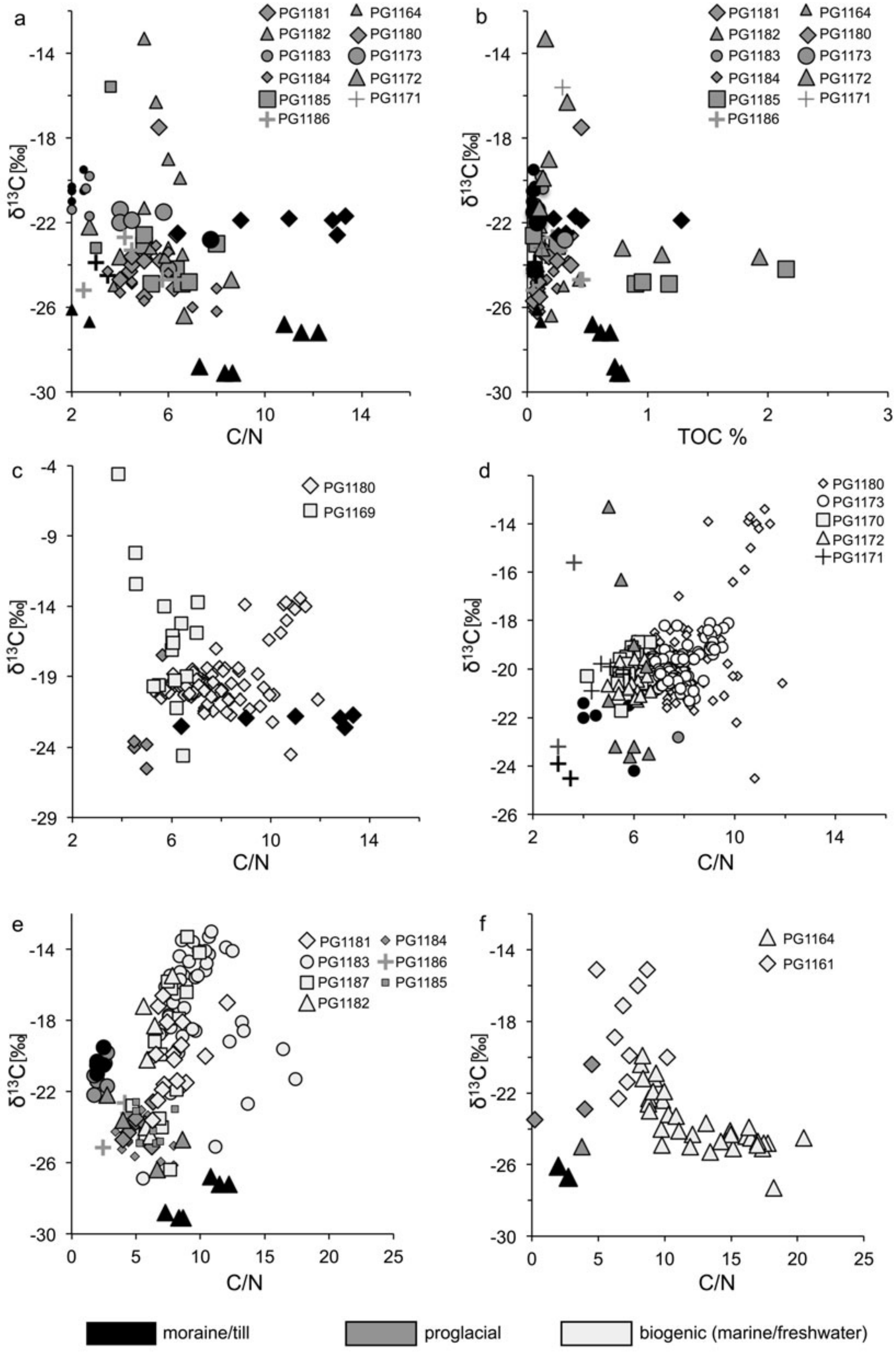

Fig. 4. Scatter plots of $\delta^{13}C$ *vs* C/N and TOC data, with symbols referring to sediment cores and colours distinguishing different lithologies within the respective records **a.** C/N *vs* $\delta^{13}C$, and **b.** TOC [%] *vs* $\delta^{13}C$ for t- and p-sediments in all investigated records, **c.** data for sediment cores from Izvilistaja Inlet, **d.** data for sediment cores from Paz Cove, **e.** data for sediment cores from Algae Lake, and **f.** data for sediment cores from 8 m and 17 m lake (all data from Kulbe 1997, see Fig. 1 for coring locations).

(Fig. 3), while high $\delta^{13}C$ values of TOC indicate an origin from freshwater microbial mats (Fig. 4c). ^{14}C ages of TOC from core PG1169 were therefore calibrated with the atmospheric calibration. Employing a polynomial regression, few ages plot slightly to the side of the age-depth curve, however, the data clearly indicate an

Table III. Samples analysed for the presence (x)/absence (-) of halite in five sediment cores from Bunger Hills (data from Kulbe 1997).

PG 1161	halite	PG 1173	halite	PG 1180	halite	PG 1182	halite	PG 1185	halite
11 cm	-	11 cm	x	31 cm	x	73 cm	-	21 cm	-
56 cm	-	391 cm	x	456 cm	x	109 cm	-	45 cm	-
146 cm	-	770 cm	x	978 cm	x	163 cm	-	81 cm	-
152 cm	-	1225 cm	x	1102 cm	-	169 cm	-	111 cm	-
		1289 cm	-					117 cm	-

age at the core base close to 10 ka BP and an altogether continuous and rather constant sedimentation.

In core PG1180, seven ^{14}C ages from the marine sapropelic sediments and one ^{14}C age from the freshwater part of the record were available (Fig. 3). The uppermost sample in the marine sediments was excluded from the age-depth model, which is based on linear interpolation between data points, since this part of the record was probably deposited under the increasing influence of freshwater and thus the marine reservoir estimate of 1300 a is probably not fully applicable there.

At two sites (PG1180, PG1182), ^{14}C ages were obtained from till deposits (Figs 2 & 3). The ages are 28.0 ± 0.05 and 27.9 ± 0.8 ka BP in core PG1180 and 29.2 ± 0.7 to 35.0 ± 1.3 ka BP in core PG1182. Given the subglacial deposition, the organic carbon in the tills must have been reworked from older deposits. Due to the potentially mixed sources of carbon the ages were neither corrected for a reservoir effect nor calibrated.

Depositional environments

Identification of former depositional environments from sediment cores is crucial for the discussion of RSL changes (lacustrine vs marine depositional environments), shifts in ice sheet margins and glacier extent (subglacial vs proglacial vs open marine/limnic environments) and reconstruction of past climatic conditions (interpretation as proxy data). In this section we review published datasets (TOC, δ^{13}C values, lithology, mineralogy, diatom assemblage) of 19 sediment records in order to characterise different depositional environments and to derive possible interpretations of the data with respect to climate conditions.

Subglacial deposits

Cores PG1161, PG1164, PG1170, PG1171, PG1172, PG1173, PG1180, PG1182, PG1183, PG1184, PG1185 and PG1186 contain highly consolidated, diamictic sediments at their base, interpreted as a till (Kulbe 1997). TOC contents of the tills are generally low (< 0.02%, Fig. 4b). At sites PG1180 and PG1182, however, they reach 0.2 to 1.3%, indicating incorporation of reworked organic matter (Fig. 4b). δ^{13}C values of organic matter (OM) are mostly lower than -21‰, reaching values as low as -29.9‰ at site PG1182 (Fig. 2a), which is in the range of organic matter (OM) of terrestrial and freshwater origin (e.g. Bramley-Alves *et al.* 2015, Yangyang *et al.* 2016 and references therein). Depleted values are found at sites that are terrestrial at present (e.g. sites PG1164, PG1182), but also at site PG1171, which is marine. At sites PG1173 and PG1180 δ^{13}C values of OM in tills (-22.2 ± 1.1‰) overlap within 2σ with the range of Holocene marine samples at site PG1173 (20.0 ± 0.7‰) and site PG1180 (19.8 ± 0.8‰) (Fig. 4c & d). This could indicate marine contributions to OM in the till. However, tills at both sites are free of halite (NaCl; Table III), which instead suggests a terrestrial/freshwater formation.

Proglacial deposits

All cores contain a clastic-rich sediment unit that mostly consists of clayey to sandy silts of olive to brownish colours and either overlies the consolidated, diamictic unit or forms the lowermost unit cored (Kulbe 1997). At some locations, these sediments consist of laminated clays or contain gravel. TOC contents mostly are < 0.5%, but at sites PG1172 and PG1185 reach up to 2% (Fig. 4b). The clastic-rich sediments were probably deposited in a proglacial environment, where input of siliciclastic matter dominated and deposition of OM was strongly restricted due to dilution with siliciclastic components or low contemporaneous productivity. Proglacial sedimentation presently occurs at sites PG1184 and PG1186 in eastern Algae Lake, where meltwater streams from the ice sheet supply large amounts of suspended matter (Gibson *et al.* 2002). Consequently, modern sediments of cores PG1184 and PG1186 consist of laminated clayey silts with very low TOC contents.

OM in the proglacial deposits could be autochthonous, originating from phytoplankton or benthic organisms. Alternatively, it could be reworked from older strata, namely from till deposits, which become exposed and potentially reworked during successive ice retreat. A reworked source is indicated for sites PG1183, PG1164, and PG1171, where the tills and the overlying proglacial sediments have very similar C/N and δ^{13}C values (Figs 4d–f). At sites PG1180 and PG1182, in contrast, δ^{13}C values and C/N ratios of the proglacial deposits differ from the underlying till deposits, suggesting a contemporaneous origin (Fig. 4c & e).

Due to the glaciological setting of Bunger Hills, the depositional environment (marine or lacustrine) of the proglacial sediments can give important information on grounding line positions or changes in RSL. At coring location PG1173 in Paz Cove, $\delta^{13}C$ values from the proglacial sediments (1245 to 1211 cm core depth) are within the range of values for the biogenic marine sediments above (-21.7 ± 0.9‰ vs 20.0 ± 0.7‰, Fig. 4d). In addition to the occurrence of marine salts (1225 cm depth, Table III) and marine diatoms (Verkulich *et al.* 2007) this indicates a marine environment for deposition. In core PG1180 from Izvilistaja Inlet clastic-rich proglacial sediments (1008 to 946 cm core depth) are laminated and have $\delta^{13}C$ values ranging from -25.5 to -23.6‰ (Fig. 4a). The latter is typical for terrestrial mosses, lichen, algae and lacustrine mosses in Antarctica (e.g. Yangyang *et al.* 2016 and references therein) and thus points to a freshwater or terrestrial origin of the OM. However, the OM in these sediments probably was reworked into a marine environment, as suggested by enrichment in sulfur (up to 4%) and the presence of marine salts (at 978 cm, Table III) and marine diatoms above 976 cm core depth (Verkulich *et al.* 2007). The autochthonous production may have been relatively low due to high suspended sediment load in the water column. The terrestrial or lacustrine OM could originate from tills with their respective TOC contents. However, an OM transport from a lake into the marine realm cannot be excluded. A modern example for such a transport is Algae Lake, where benthic microbial mats lift off the lake floor, float to the downwind (western) end of the lake and further via Algae River into Izvilistaja Inlet (Gibson *et al.* 2002).

In Algae Lake, at sites PG1181, PG1184 and PG1185, $\delta^{13}C$ values in the proglacial sediments are more depleted (< -22‰) than in the overlying biogenic sediments (Fig. 4e). This probably reflects a reduced photosynthetic activity of benthic microbial mats and mosses when clastic input is high and light availability is reduced by suspension. In addition, high sediment input leads to high sedimentation rates and potentially unstable lake floor sediments, which may limit the establishment of benthic communities (e.g. Priddle & Heywood 1980). The OM in the proglacial sediments could therefore also contain higher proportions of reworked material, e.g. from terrestrial biomass, that forms in and around meltwater streams and depleted $\delta^{13}C$ values could be a signal for contribution of allochthonous OM.

Biogenic freshwater deposits

Highly biogenic sediments were recovered in the upper core parts at all freshwater lake sites, except for the sites PG1184 and PG1186 proximal to the ice sheet margin, where proglacial sediments extend to the benthic sediment surface. Biogenic sediments are composed of layers of mosses and microbial mats (Fig. 2). TOC contents range from 1.5 to 14%. The high variability within the records may reflect changes in benthic productivity, in terrestrial input and in the preservation of the organic matter. It may also be due to a patchy distribution of the mosses and microbial mats on the lake floors (Kudoh *et al.* 2003).

OM from the lacustrine sediments shows a range of -4.6 to -29.1‰ in $\delta^{13}C$ values (Fig. 2c, e, f). Generally, high (less depleted) $\delta^{13}C$ values point to OM produced under CO_2 limited conditions, either due to high photosynthesis rates, which occur for example in moats, or due to limited CO_2 diffusion as it occurs in shallow waters and glacial cryoconite holes (Doran *et al.* 1998). $\delta^{13}C$ values > -15‰ were found in freshwater algae and microbial mats in shallow water depths (< 2 m) in Antarctic lakes (e.g. Yangyang *et al.* 2016) and in the perennially ice-covered White Smoke Lake, a freshwater epishelf lake in Bunger Hills (Fig. 1, Doran *et al.* 2000). We therefore suggest that organic matter with $\delta^{13}C$ values > -15‰ is of freshwater origin, probably derived from microbial mats and algae growing in shallow waters. In deeper waters, where productivity is low and water is saturated with CO_2, fractionation is much higher, resulting in lower (more depleted) $\delta^{13}C$ values (> -30‰; Doran *et al.* 1998).

In core PG1164 from 8 m lake low $\delta^{13}C$ values (< -24‰) in the biogenic sediments correspond to higher C/N ratios (> 10; Fig. 4f). This probably reflects the higher proportions of subaquatic mosses relative to microbial mats from the shallow marginal areas of the lake. High C/N ratios (18.9) have been reported for subaquatic mosses in oligotrophic lakes from East Antarctica (Kudoh *et al.* 2003), which could indicate mosses in sediments.

In 17 m lake on Geographers Island in north-western Bunger Hills, flaky, dried microbial mats occur between 56 and 21 cm depth in core PG1161 (Fig. 2). These sediments indicate that the lake desiccated in the past or was shallow enough to allow winter freezing of the entire water column and further into the underlying sediments (Melles *et al.* 1994b). Water-rich, undisturbed microbial mats in the upper 21 cm of the core indicate re-filling of the lake. Lower $\delta^{13}C$ values of the OM in 17 m lake than in 8 m lake probably are due to a higher proportion of microbial mats, reflecting the shallower water depths of the lake. At present, 17 m lake is less saline than 8 m lake (Melles *et al.* 1994b). This may reflect a recent infilling with meltwater from permanent snowbanks in the catchment (Adamson & Colhoun 1992). The finding of a desiccation event in the sediment record of 17 m lake, however, suggests that salinities may have changed considerably during the lake's history.

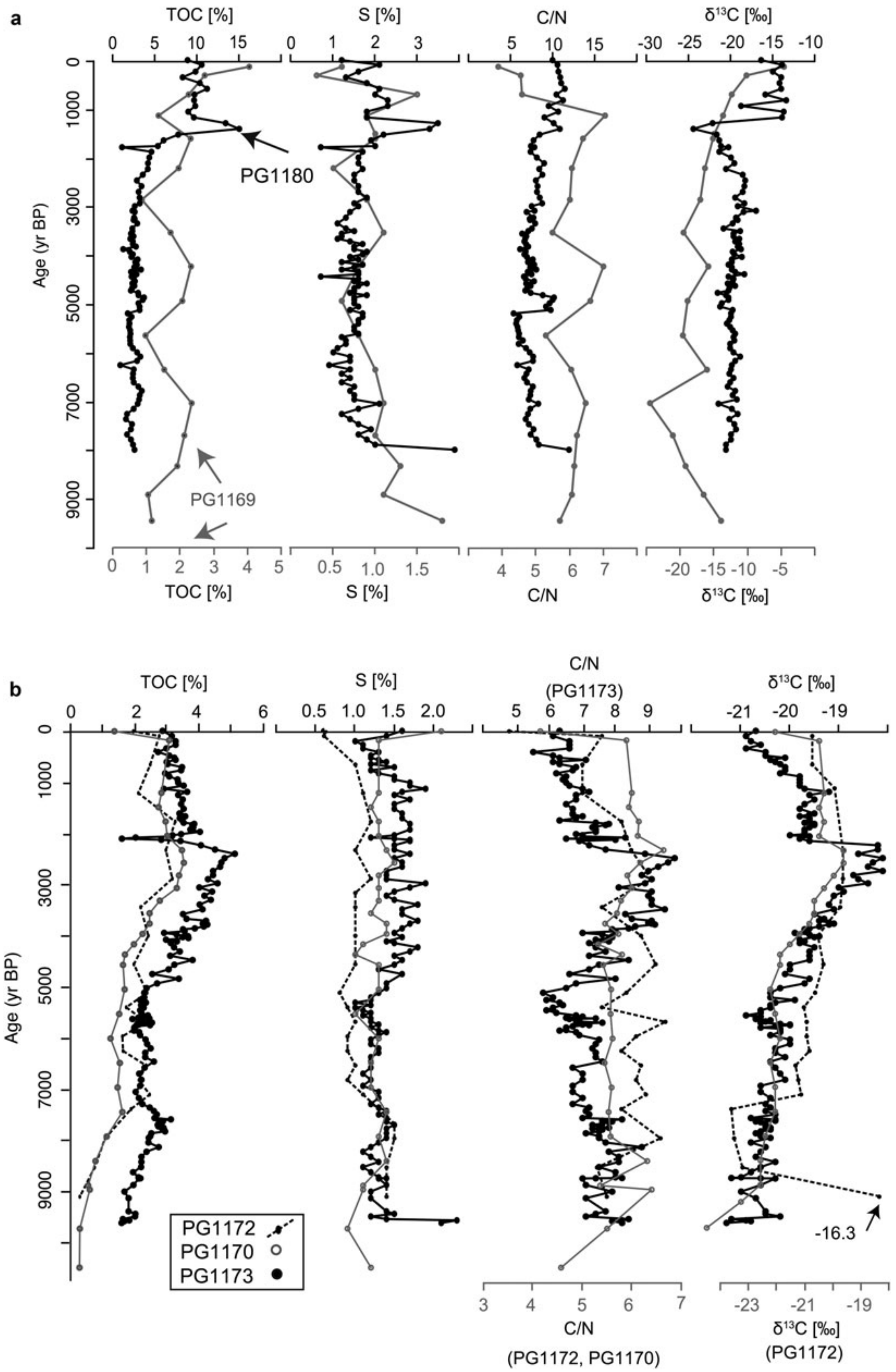

Fig. 5. Proxies shown *vs* age for records from marine inlets **a.** Izvilistaja Inlet and **b.** Paz Cove (data from Kulbe 1997).

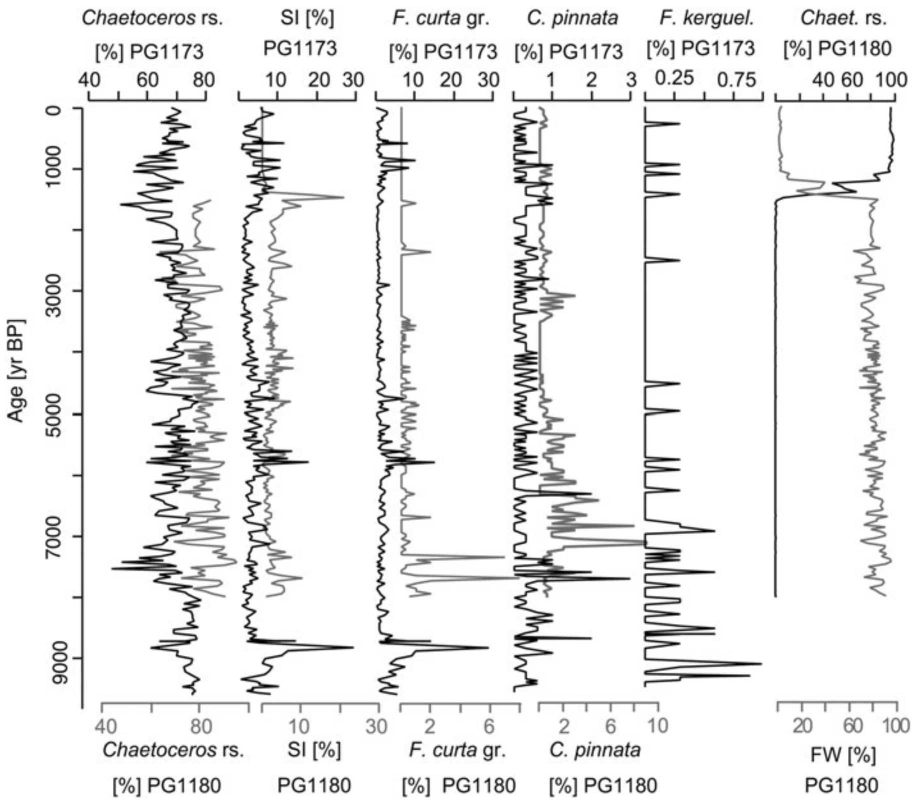

Fig. 6. Selection of diatoms identified in cores PG1173 and PG1180. *Chaetoceros* resting spores (*Chaet.* rs.). Species grouped as sea ice diatoms (SI) are *Entomoneis kjellmannii*, *Fragilariopsis curta*, *F. cylindrus*, *F. obliquecostata*, *F. ritscheri*, *F. sublinearis*, *Porosira glacialis*, *Navicula directa*. *F. curta* gr. comprises *Fragilariopsis curta* and *F. cylindrus*. *Cocconeis pinnata* is a fresh/brackish species and *Fragilariopsis kerguelensis* (*F. kerguel.*). Freshwater (FW) are dominated by *Amphora veneta* (data from Kulbe *et al.* 2001, Verkulich *et al.* 2007).

Marine deposits

In the marine inlets, proglacial sediments are overlain in most cases by sandy silts (Fig. 3), which are mostly massive and have TOC contents from 0.5 to 3.5% in PG1169, PG1170, PG1172 (Fig. 5) and PG1171 (Fig. 3). The lack of stratification may indicate intense bioturbation. At two sites (PG1173, PG1180), the proglacial sediments are overlain by sapropels, which reflect deposition in anoxic bottom waters. They differ from other marine sediments by having generally higher TOC contents (1.5 to 8%), high water contents (*c.* 75%, Kulbe 1997) as well as a high concentration of diatoms (Kulbe *et al.* 2001, Verkulich *et al.* 2007).

In the marine sapropels of core PG1173 from Paz Cove and Izvilistaja Inlet (PG1180) the most abundant diatom frustules are from *Chaetoceros* (mainly resting spores, rs), which comprise 35 to 97% (mean 77.7 ± 10.8%) of the diatom valves in core PG1173 (Fig. 6). In coastal Antarctic environments, intensive formation of *Chaetoceros* resting spores occurs in the upper layer of a well-stratified water column, either from intensive sea ice melt in spring or supply of meltwater from the continent (e.g. Cremer *et al.* 2003, Leventer *et al.* 2006). *Chaetoceros* blooms are supported by iron input from dust or from meltwater, as that supplied to calving bays during deglaciation (e.g. Leventer *et al.* 2006). In the inlets of Bunger Hills, *Chaetoceros* blooms are probably intensified, when nutrient input from land is high, e.g. during periods of high run-off of clastic-rich meltwater, and are probably less intensive when sea ice is more persistent or freshening of the water column exceeds the salinity tolerance of *Chaetoceros* spp. Sea ice-related species (*Entimoneis kjellmannii*, *Fragilariopsis curta*, *F. cylindrus*, *F. obliquecostata*, *F. ritscheri*, *F. sublinearis*, *Porosira glacilis*, *Navicula directa*) comprise 4.0 ± 3.3% in PG1173 (Verkulich *et al.* 2007) and 2.7 ± 1.8% in PG1180 (Verkulich *et al.* 2007), which is much less than found in other marine inlets from the East Antarctic coast (e.g. Cremer *et al.* 2003). In Izvilistaja Inlet (PG1180) *Cocconeis pinnata*, which is a brackish/benthic species (Roberts & McMinn 1998), is abundant in higher proportion than in Paz Cove (PG1173), probably reflecting higher proportions of freshwater, e.g. from Algae Lake or Edisto Glacier. In Paz Cove (PG1173), the presence of *F. kerguelensis* in the lower part of the sediment sequence, points to connection to the open ocean.

The δ^{13}C values of organic carbon show a low variability within and between the marine records compared to the range found in the lacustrine records (Figs 4d & 5). The mean δ^{13}C values in the sapropels (-19.9 ± 0.7‰ in

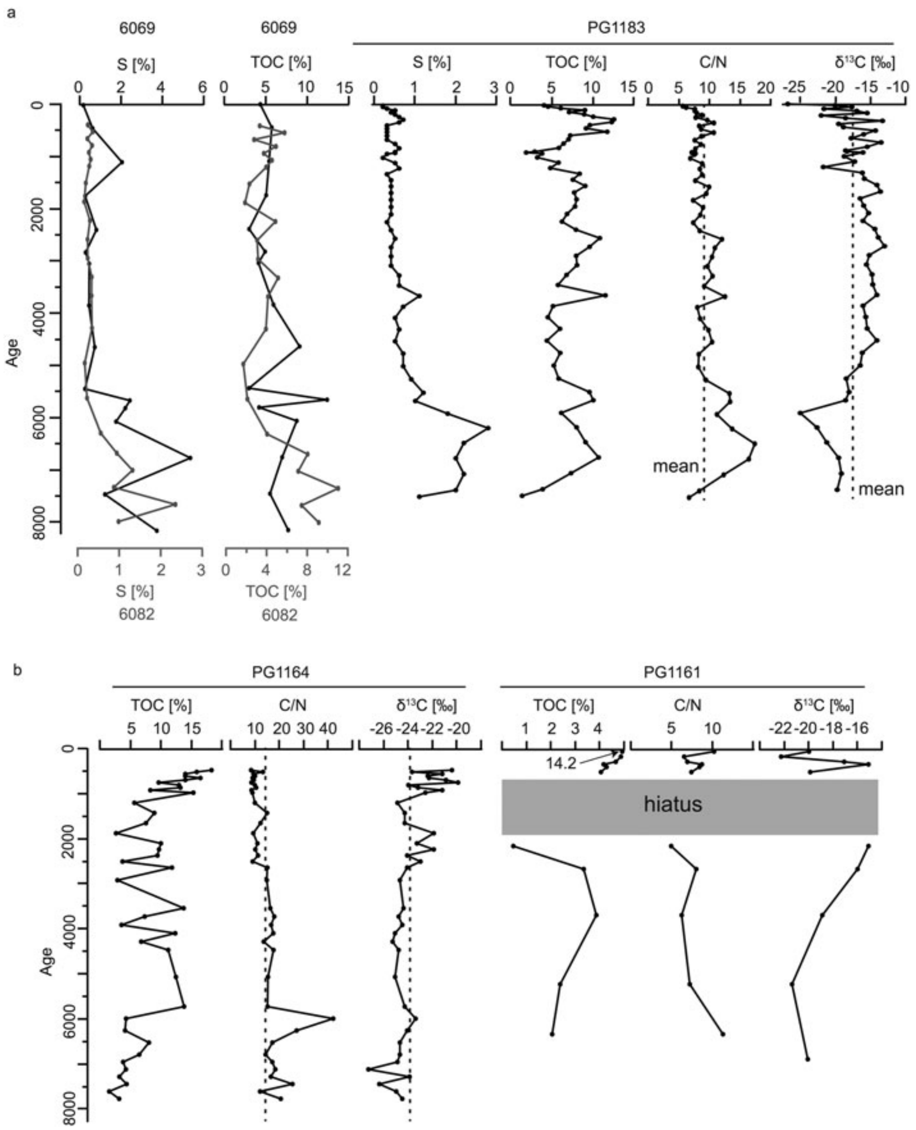

Fig. 7. Proxies shown *vs* age for records from lakes **a.** Algae Lake, and **b.** 8 m lake (PG1164) and 17 m lake (PG1161) (data from Kulbe 1997 and Verkulich *et al.* 2002).

PG1173 and -19.8 ± 0.8‰ in PG1180) are similar to those found at sites with more clastic-dominated sedimentation (-20.0 ± 0.7‰ in PG1170, -20.2 ± 0.5‰ in PG1171 and -20.6 ± 0.6‰ in PG1172). The values are comparable to $\delta^{13}C$ values from sapropels in coastal marine inlets in other East Antarctic oases (-22 to -18‰, Kirkup *et al.* 2002, Berg *et al.* 2013). Gradual trends in $\delta^{13}C$ values as well as the sharp decrease in $\delta^{13}C$ around 2.2 ka BP in both cores is not clearly reflected in the diatom record. In particular, $\delta^{13}C$ values are not associated with peaks in sea ice diatoms or maxima/minima in *Chaetoceros* resting spores (Figs 5 & 6). This suggests that the $\delta^{13}C$ values are not directly controlled by the proportion of sea ice diatoms on biomass and therefore cannot simply be interpreted as an indicator of sea-ice coverage. Changes in $\delta^{13}C$ more probably reflect a signal of phytoplankton productivity, carbon utilisation and carbon source composition.

In Izvilistaja Inlet a transition from marine to freshwater conditions is reflected in core PG1180 from the inner part of Izvilistaja Inlet, by a lithological change from marine sapropels to microbial mats at 131 cm core depth. The transition is accompanied by a shift to higher $\delta^{13}C$ values and enrichment in sulfur (Fig. 5a). The occurrence of mosses above 96 cm and the establishment of a freshwater diatom assemblage show that no marine incursions occurred afterwards (Fig. 6, Verkulich *et al.* 2007). In core PG1169, from the outer part of Izvilistaja Inlet, marine fossils point to deposition under marine conditions (Kulbe 1997, Verkulich *et al.* 2007). The upper *c.* 6 cm of that core are composed of freshwater microbial mats, reflecting the present-day freshwater infill of the inlet. High $\delta^{13}C$ values throughout the record (-16.1 ± 4.4‰; Fig. 5a) suggest that OM mainly is of freshwater rather than marine origin. In the marine sediments, this can be explained by microbial mat supply from Algae Lake. Modern day microbial mats in Algae Lake partly float and drift towards the downwind outlet of the lake, with the dominant wind direction (Gibson *et al.* 2002). The mats may further become transported into Izvilistaja Inlet, when water flows through Algae River. An allochthonous origin of at least parts of the OM in core PG1169 is supported by the high TOC contents (1.9 ± 0.8%) in the sandy sediments of this relatively shallow site (11.1 m water depth).

Depositional histories

Algae Lake

At sites PG1184, PG1185, PG1186, PG1183 and PG1182, till was recovered at the core bases, pointing to inundation of the basin that is presently occupied by Algae Lake by a grounded glacier or ice sheet. ^{14}C ages of 29.2 ± 0.7 to 35.0 ± 1.3 ka BP in the till of core PG1182 provide important information concerning maximum till age, with the latest corresponding with Marine Isotope Stage (MIS) 3. Furthermore, organic matter in the tills and their ages suggest ice-free areas with biogenic accumulation in the catchments of the coring sites some time prior to the Last Glacial Maximum.

Proglacial sediments overlying the till in Algae Lake indicate a period of glaci-lacustrine sedimentation before biogenic sedimentation started in the basins distal to the present-day ice sheet margin (PG1183, 6082, 6069, 6078) around 9.8 to 7.3 ka BP (Fig. 7a). At coring locations PG1181 and PG1182 clastic-dominated sedimentation remained high even until 6.6 ± 0.5 ka BP (Fig. 2). These coring locations are close to streams that presently drain lakes fed from snowbanks (PG1182) and indirectly from the ice sheet via Lake Dalekoje (PG1181). A later onset of biogenic sedimentation at these sites probably indicates that clastic input remained high and unstable lake floor sediments and high suspension load hampered establishment of benthic communities longer than in other parts of Algae Lake.

In core PG1183 low δ^{13}C values and high C/N ratios in the lower biogenic deposits (Figs 2 & 7) indicate high proportions of mosses in the initial sediments formed after proglacial conditions ceased. This interpretation is consistent with high moss abundances described for the lowermost biogenic sediments in cores from sites 6078, 6082 and 6069 (Fig. 2; Verkulich *et al.* 2002). In Antarctica, perennial mosses colonize lake bottoms with oligotrophic conditions and low light intensities (Priddle & Heywood 1980). Oligotrophic conditions in Algae Lake during early Holocene times are suggested by very low diatom abundances in the respective sediments (Verkulich *et al.* 2002). Another common pattern in the records PG1183, 6082, 6069 and 6078 is enrichment in S from the onset of biogenic sedimentation until 5.7 ± 0.2 ka BP (Fig. 7a). High S contents probably result from oxygen depletion during degradation of mosses and microbial mats. Another source of S could be the mineral thenardite (Na_2SO_4), which precipitates in littoral areas of lakes in Bunger Hills during lake ice formation and accumulates in deeper parts of the lakes (Klokov *et al.* 1990). Enrichment in S may point to a more persistent lake-ice cover during that time.

A decrease in TOC values at 5.7 ± 0.2 ka BP (Fig. 7a) could indicate lower productivity but also less efficient preservation of OM in the lake. The latter is more probable, since a contemporaneous increase in δ^{13}C values of OM instead point to an increase in productivity or to an increase in the proportion of algal mats from the shallow littoral areas of the lake, which is consistent with less lake ice and better mixing of the water column. The observed decrease in mosses relative to microbial mats at 5.7 ± 0.2 ka BP is supported by lower C/N ratios (Fig. 7a). The subsequently low variability of δ^{13}C values points to a period of relative stability with respect to nutrient supply and productivity. Flourishing benthic communities in the lake at that time are also indicated by increasing abundance of benthic diatoms in cores 6078, 6082 and 6069 (Verkulich *et al.* 2002).

At 1.3 ± 0.3 ka BP, TOC values decrease and a drop in δ^{13}C values indicates a short-term decrease in productivity. Maximum TOC values from 0.5 to 0.2 ka BP probably reflect recurring high productivity, however, δ^{13}C values are highly variable compared with the time before 1.3 ka BP, pointing to less stable conditions in the lake.

Other lakes

In contrast with Algae Lake, 8 m and 17 m lake today are not fed by meltwater run-off from the ice sheet or glacier margins. Sedimentary records from these lakes, therefore, may reflect changes in temperature and precipitation more sensitively than records from Algae Lake.

In 17 m lake (PG1161), till is overlain by highly clastic sediments that show a fining upward trend from sand to sandy silt and are topped by a gravel layer at 70 cm depth. The clastic sediments were probably deposited during ice retreat, while the gravel layer may reflect a lag deposit indicative of sub-aerial exposure of the lake bottom or winnowing of sediment by water, such as by a meltwater stream (e.g. Gibson *et al.* 2002). Above the gravel, sandy-silty sediments with TOC contents of 0.2 to 0.4% point to lacustrine sedimentation at the site. Around 6.9 ± 0.4 ka BP microbial mats colonized the lake (Figs 2 & 7b), indicating lacustrine fresh conditions.

In 8 m lake (PG1164), biogenic lake sedimentation started around 7.8 ± 0.7 ka BP (Figs 2 & 7b). Increasing

TOC values from 1.5 to 8%, high C/N ratios and low δ^{13}C values until 5.9 ± 0.2 ka BP indicate successive colonisation of the lake bottom by aquatic mosses under oligotrophic conditions. A distinct peak in C/N ratios around 6 ka BP could indicate in-wash of degraded OM from the catchment, which could also explain the lower TOC values during this interval by dilution with clastic matter. From 5.7 ± 0.2 to 2.6 ± 0.3 ka BP, C/N and δ^{13}C values show lower variability than in the previous interval, pointing to more stable conditions in the catchment or within the lake, particularly with respect to nutrient supply and terrestrial input.

After 2.6 ± 0.3 ka BP, higher δ^{13}C values in 17 m lake (Fig. 7b) probably reflect more saline conditions due to successive shallowing, culminating in desiccation of the lake after 2.1 ± 0.4 ka BP (Fig. 7a). At the same time, C/N values in the record from 8 m lake shift from > 14 to < 10 and δ^{13}C values increase from < -24 to > -24‰. This reflects a shift from higher proportions of mosses to higher proportions of microbial mats (Fig. 7b). Productivity of microbial mats in the littoral areas of the lake is enhanced when nutrient supply from surficial and sub-surface runoff is high (Melles *et al.* 1994b) and lake ice coverage is thinner. The shift could therefore reflect a period of less lake ice and higher nutrient input from land. Alternatively, the increase in microbial mats could be due to an increase in salinity, which results in less favourable conditions for freshwater water mosses (Kudoh *et al.* 2003).

The period of increased microbial mat deposition in 8 m lake was interrupted from 1.6 ± 0.3 to 1.1 ± 0.3 ka BP, which could either reflect dilution or an increase in lake ice and a decrease in nutrient input. The latter is supported by the hiatus in the record from 17 m lake (Figs 2 & 7b), which falls within this interval and most probably was connected to colder and drier conditions. After 1.1 ± 0.3 ka BP high δ^{13}C values and maximum TOC contents in 8 m lake indicate recurrence of high productivity of microbial mats, probably coincident with the refilling of 17 m lake *c.* 0.6 ± 0.4 ka BP.

Marine inlets

Till at the base of cores PG1180, PG1170, PG1171, PG1172 and PG1173 (Fig. 3) point to past glacier or ice sheet coverage and grounding in Paz Cove and Izvilistaja Inlet after *c.* 28.0 ka (Table II). In core PG1180 from Izvilistaja Inlet, an age of 14.3 ± 0.3 ^{14}C ka in postglacial sediments could be interpreted as a minimum age of the ice sheet or glacier retreat at this site. However, this age could also be erroneously old, due to admixture of reworked, older organic matter, which is entrained in the underlying till.

Proglacial sediments overlying the tills, coupled with the presence of halite and/or marine diatoms, and high S concentrations, indicate glaci-marine sedimentation at sites PG1171, PG1173 and PG1180. At site PG1172 high δ^{13}C values of -16.3‰ V-PDB indicate incorporation of OM derived from freshwater mosses or microbial mats (Fig. 6), however, this OM may not necessarily be autochthonous, since marine diatoms were identified in the sediments (Verkulich *et al.* 2007). In cores PG1170 and PG1172 from Paz Cove, ^{14}C ages of 10.4 ± 0.3 ka BP and 9.1 ± 0.3 ka BP were obtained from clastic sediments (clayey to sandy silt and clays to silty sands) above the till (Fig. 3) providing a minimum age of ice retreat from these sites.

Biogenic sedimentation of diatomaceous sapropels started at 9.6 ± 0.2 ka BP at site PG1173 (Fig. 3). Around the same time (8.9 ± 0.5 ka BP), sedimentation became more fine-grained and organic rich at site PG1170 (Fig. 5b). At the more coastal coring locations in western Paz Cove, clastic-dominated sedimentation lasted longer, terminating around 7.3 ± 0.4 ka BP (PG1172) and 5.7 ± 0.2 ka BP (PG1171; Fig. 3). This may reflect a successive ice retreat to the west of Paz Cove. An opposite picture is provided by Izvilistaja Inlet, where marine sedimentation started at 9.4 ± 0.9 ka BP in the outer, western part of the inlet (PG1169), while the inner basin was subjected to high clastic input until 7.9 ± 0.1 ka BP (PG1180) (Fig. 5a). However, this does not necessarily reflect ice retreat to the east, it could also be due to a particularly high clastic sediment supply from Algae Lake via Algae River during the early Holocene, possibly reflecting enhanced meltwater supply.

High productivity at site PG1173 in Paz Cove occurred from the onset of sapropel deposition at 9.6 ± 0.2 until 7.9 ± 0.1 ka BP. High *Chaetoceros* rs. concentrations probably reflect high nutrient supply from meltwater input from land (Fig. 6). During the beginning of this period, until *c.* 8.5 ka BP, sea ice diatoms reached a maximum abundance (Fig. 6).

At 7.9 ± 0.1 ka BP a reduction in clastic input led to the onset of marine sapropel deposition in Izvilistaja Inlet (PG1180). The decrease in *Chaetoceros* blooms in Paz Cove at the same time could be due to reduced nutrient input, increased water column mixing and/or freshening, which reduces the photosynthetic efficiency of *Chaetoceros* sp. (Petrou & Ralph 2011). A relatively high proportion of the brackish *C. pinnata* in Izvilistaja Inlet (PG1180) from 7.9 ± 0.1 ka BP to *c.* 5.7 ± 0.3 ka BP point to reduced water exchange with the ocean and could be an effect of RSL lowering or thickening of Edisto Glacier. More restricted exchange with the ocean is also indicated by a reduction in open ocean *F. kerguelensis* in Paz Cove (PG1173) after 7.0 ± 0.1 ka BP. This was accompanied by lower productivity in both inlets as indicated by lower TOC and S contents and relatively low δ^{13}C values throughout this period (Figs 5 & 9). From 5.7 ± 0.3 to 2.2 ± 0.1 ka BP, higher abundances of

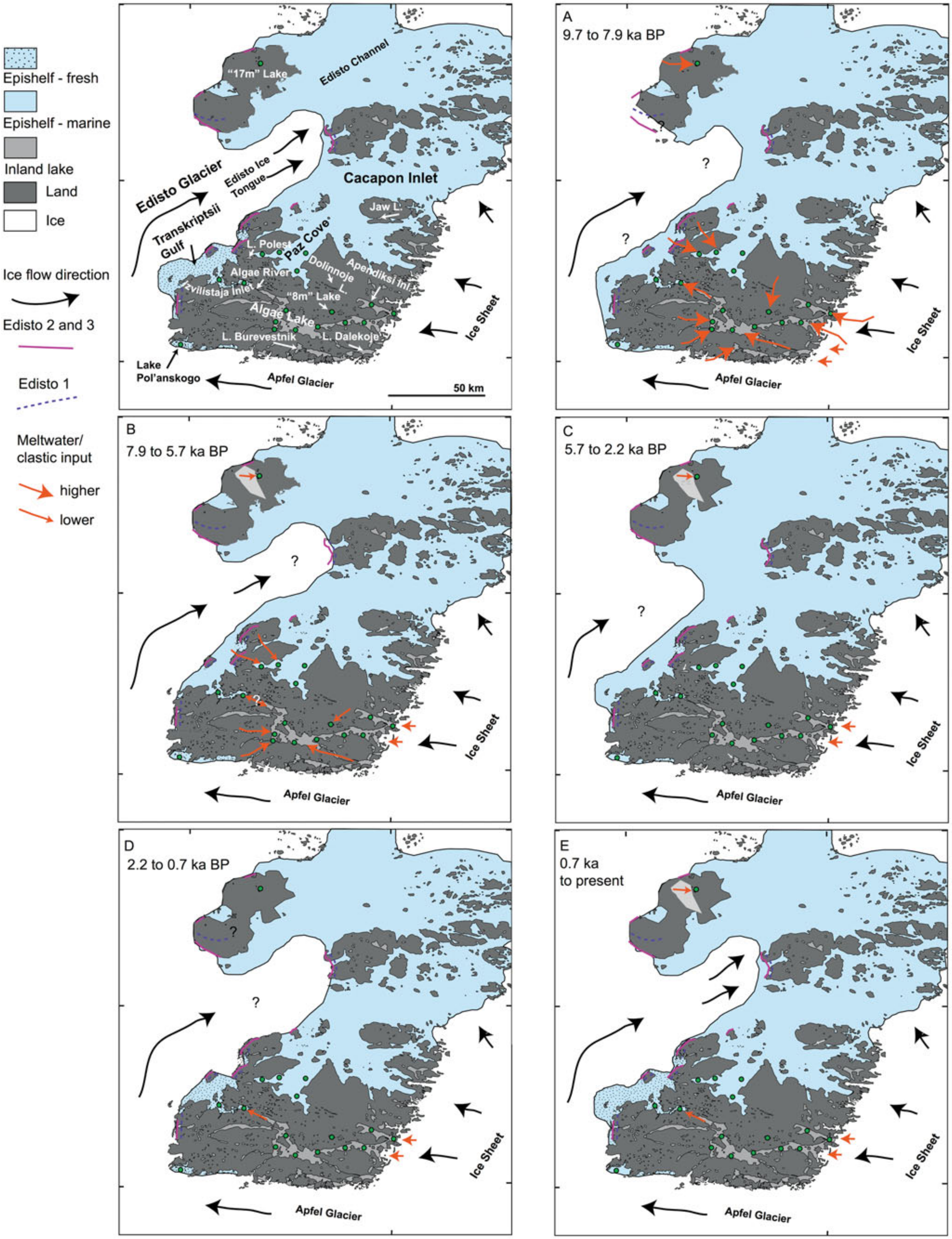

Fig. 8. Reconstruction of glacier fluctuations and clastic matter input into lakes and marine inlets. Time slices are also distinguished in Fig. 9.

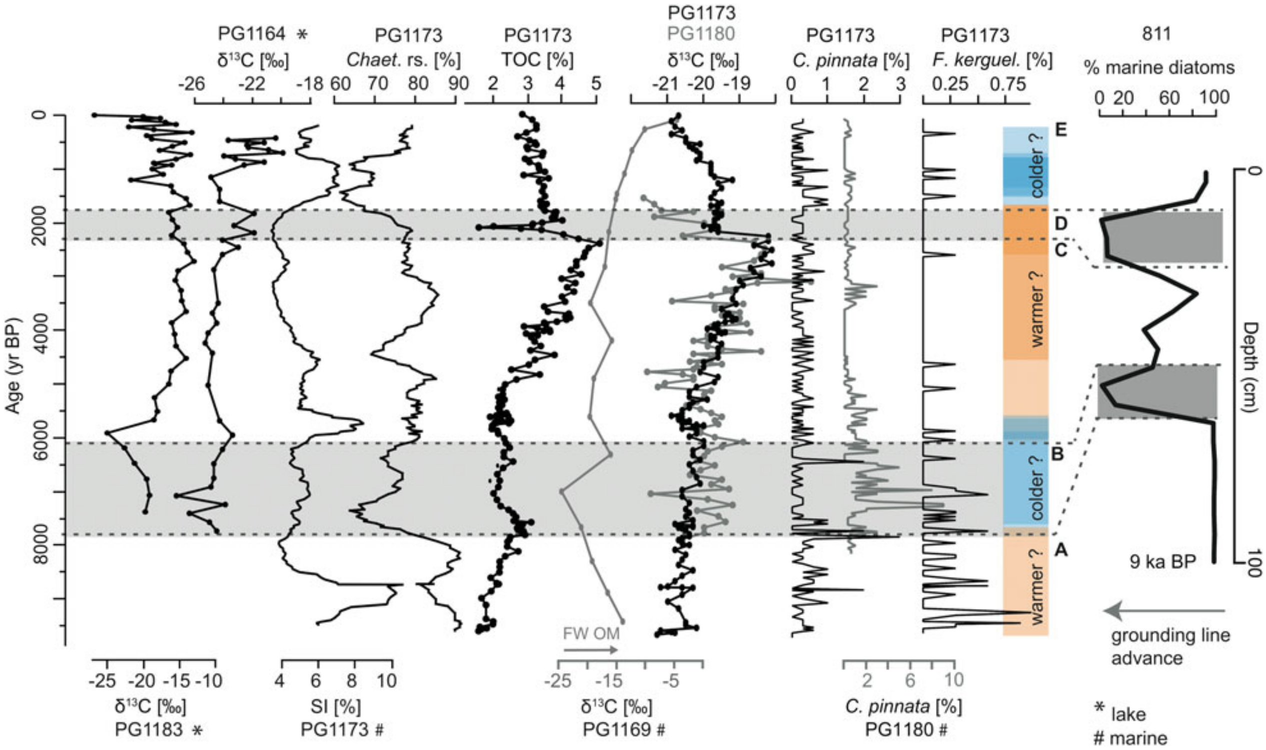

Fig. 9. Paleoclimatic interpretation of marine and lacustrine records from Bunger Hills. Periods underlain in blue were probably cooler than periods underlain in orange colours. Some disagreement between records probably arises from uncertainties in the age models of each of the records. Horizontal dotted lines indicate correlation with the record from Pol'anskogo Lake (core 811, Melles *et al.* 1994a) and are interpreted as periods of advanced grounding line of Apfel Glacier and expanded Edisto Glacier. SI = sea ice diatom species, FW = freshwater diatom species. Sea ice diatoms and *Chaetoceros* rs. for core PG1173 are shown as 10 point running average.

Chaetoceros rs. (generally > 78%), increasing TOC contents and less depleted δ^{13}C values indicate high productivity in both marine inlets (Figs 5 & 6). The trend was interrupted by a short period from 4.5 to 4 ka BP when nutrient supply was lower and conditions were less favourable for *Chaetoceros* blooms. The most prominent shift in the marine δ^{13}C records occurs at 2.2 ± 0.1 ka BP, when δ^{13}C values decrease (PG1180, PG1173, PG1170), and TOC contents decrease in some records from Paz Cove (PG1173, PG1170) (Fig. 5). The shift in the δ^{13}C record is accompanied by a decrease in *Chaetoceros* rs., but not so much in sea ice diatoms, which points to a change in water column properties, probably related to changes in stratification/mixing or salinity rather than an increase in sea ice (Cremer *et al.* 2003). The decrease in δ^{13}C values could reflect reduced phytoplankton productivity or change in phytoplankton assemblage, which could be induced by freshening of the water column. In PG1169 (outer Izvilistaja Inlet) δ^{13}C values continuously increase after *c.* 2.2 ka BP, which points to an increase in allochthonous OM deposition of freshwater microbial mats, probably from Algae Lake and could be an indication for successive reduction in marine water contribution to Izvilistaja Inlet. In inner Izvilistaja Inlet (PG1180), increasing TOC contents probably reflect increasing preservation of organic matter due to increasingly stable water column stratification since *c.* 2.2 ka BP. The site became permanently fresh at 1.4 ± 0.1 ka BP (Figs 5 & 9). At site PG1169, further to the west, freshwater microbial mats occur later (0.25 + 0.2/-0.1 ka BP), which probably reflects the onset of a permanent freshwater layer in the adjacent Transkriptsii Gulf.

Environmental history

Ice sheet and glacier fluctuations

Tills at the base of the marine and lacustrine sediment sequences suggest ice sheet or glacier ice coverage of the core sites during the last glacial advance in Bunger Hills. This is consistent with OSL dating of hillside glaciofluvial sediments, which indicate that nunataks emerged from the downwasting ice sheet and most hilltops were completely exposed by *c.* 20 ka BP, while sites at lower altitudes, like the Algae Lake trough, remained ice-filled (Gore *et al.* 2001). Ages of *c.* 35 to 28 ^{14}C ka, obtained from organic carbon entrained in the tills at coring sites PG1180 and PG1182 are probably from reworked terrestrial deposits and probably support the timing of late Pleistocene exposure of Bunger Hills.

In south-western Bunger Hills deglaciation was associated with the formation of ice-dammed glacial lakes, which are indicated by terraces at altitudes of *c.* 20 m a.s.l. (Colhoun & Adamson 1989). The largest and highest glacial lake (Dolgoe Lake; Fig. 1) was dammed by ice lying in the present-day Algae Lake basin. OSL ages from glacial lakeshore sediments indicate that it had drained substantially by 15 ka BP and attained its present lake level after 12.4 ka BP (Gore *et al.* 2001). The timing of initial deglaciation and the duration of proglacial siliciclastic deposition cannot be well constrained from the lacustrine and marine sediment records investigated in this study due to a lack of age control on these strata. The records are, however, consistent with a formation that post-dates drainage of the glacial lakes. Further evidence for the onset of deposition during progressive deglaciation comes from Izvilistaja Inlet (PG1180) and Paz Cove (PG1173), where laminated, clastic-rich sediments were deposited under marine conditions, before highly biogenic sedimentation commenced at 7.9 ± 0.3 ka BP and 9.6 ± 0.2 ka BP, respectively. The presence of marine water in the bays of Bunger Hills during that time suggests that at least parts of Shackleton Ice Shelf and/or glaciers surrounding the hills were not completely grounded, allowing marine waters to fill the depressions.

Clastic input into eastern and central Paz Cove decreased around 9.6 ± 0.2 ka BP (PG1173, PG1170), but remained high in western Paz Cove (PG1172, PG1171), Algae Lake (PG1183, 6069, 6078, 6082) as well as in adjacent Izvilistaja Inlet (PG1180) and in the lakes upstream in the drainage system (e.g. Burevestnik Lake; Bolshiyanov *et al.* 1991) (Fig. 8a). This indicates that ice sheet margins had retreated to a more distal position (relative to the coring locations) in Cacapon Inlet as also suggested by sediment burial ages (Gore *et al.* 2001) and ^{14}C ages of mumiyo deposits, which indicate snow petrel colonisation of southern Bunger Hills since *c.* 10.1–11.5 ka BP (Verkulich & Hiller 1994). The flow direction of water from Algae Lake into Izvilistaja Inlet is confirmed by the presence of marine conditions in Izvilistaja Inlet, with no clear indication of a marine ingression found in the proglacial sediments from Algae Lake (PG1182, Fig. 8a). Input of clastic matter via Algae River is also supported by the virtually synchronous onset of biogenic sedimentation in Algae Lake (PG1183) and of marine sapropels in Izvilistaja Inlet (PG1180) around 7.5 ± 0.4 and 7.9 ± 0.3 ka BP, respectively. While large-scale ice retreat ceased around 8.0 ± 0.3 ka BP, melting of remnant local ice masses probably continued in southern and northern Bunger Hills until 6.6 ± 0.5 ka (Fig. 8b). The latter is indicated by a delayed onset of biogenic sedimentation at coring locations PG1181 and PG1182 in Algae Lake, higher input of reworked organic matter into 8 m lake until 5.9 ± 0.2 ka BP and freshwater influence in western Paz Cove, indicated by low δ^{13}C values in proglacial clastic sediments in cores PG1172 (9.0 ± 0.3 ka to 7.3 ± 0.5 ka BP) and PG1171 (prior to 5.7 ± 0.2 ka BP) (Fig. 9).

Two sets of moraines flanking the present-day extent of Edisto Glacier were ascribed to two to three Holocene glacier advances (Adamson & Colhoun 1992, Augustinus 2002). Grounding-line fluctuations of Apfel Glacier during the Holocene are also consistent with the diatom record from core 811 from epishelf Pol'anskogo Lake, which reflects two to three periods of freshening (Figs 7 & 8, Melles *et al.* 1997) that may be associated with a restriction of marine water intrusion due to glacier advance (Fig. 8b & d). ^{14}C age assignment for the medial moraine was obtained from a reworked shell that gives a maximum age of the advance of 7.0 ± 0.2 ka BP (Adamson & Colhoun 1992). The only radiocarbon age from the base of core 811 (Table I) does not provide reliable ages for the freshening events, but constrains their ages to be younger than 9.0 ka BP (Melles *et al.* 1997). Diatom, as well as stable isotope data indicate that marine conditions prevailed in Izvilistaja Inlet (core PG1180) from prior to 7.9 ± 0.3 ka BP until 1.4 ka BP and since 9.6 ± 0.2 ka BP in Paz Cove (cores PG1173, PG1170) (Fig. 8a–c). This shows that Cacapon Inlet as well as Transkriptsii Gulf were connected to the open ocean and probably to each other, as the parallel δ^{13}C trends in the marine cores indicate (Fig. 9). An advance and thickening of the Edisto Glacier ice tongue may have reduced water exchange with the ocean underneath the floating parts of the glacier when the grounding line advanced towards the coring locations. This probably occurred around 7.7 ± 0.2 ka BP, when brackish/benthic *C. pinnata* were high in PG1180 (Fig. 9). A decrease in *Chaetoceros* rs. in Paz Cove (core PG1173) between 7.9 ± 0.1 ka BP and 5.7 ± 0.3 ka BP could also reflect freshening due to basal melt and melting icebergs from increased calving into the bay (Fig. 9). After 7 ± 0.1 ka BP, the open ocean species *F. kerguelensis* is almost absent in core PG1173. This shows that connection to the ocean underneath the ice shelf or Denman Glacier became more restricted than during the early Holocene. The advance was probably not very extensive, since marine conditions continued in Transkriptsii Gulf and Cacapon Inlet (Fig. 8b). A second, late Holocene advance of Apfel Glacier and a possible expansion of the Edisto Glacier tongue into Transkriptsii Gulf and Cacapon Inlet probably occurred at 2.2 ± 0.1 ka BP, when circulation of marine waters into Izvilistaja Inlet started to decline and a sudden decline in phytoplankton productivity and a decrease in *Chaetoceros* blooms occurred in Paz Cove (Fig. 9). The shift in the biogenic records of the marine inlets is not well represented in the lacustrine records, pointing to changes that mainly affected the marine environment. In order to correlate our lake and marine core records with the moraine ridges described by Augustinus (2002), better age constraint of the geomorphological features is necessary. The late Holocene glacier advance we suggest was probably more extensive than the advance in the early to mid-Holocene, since marine connection of Transkriptsii Gulf became more restricted. However, freshening of Transkriptsii Gulf was probably also supported by lowering of RSL (Verkulich *et al.* 2007).

Relative Sea Level changes

Evidence for RSL change during the early Holocene comes from PG1180 in inner Izvilistaja Inlet, which is connected to Transkriptsii Gulf across a sill, which is 3 m below current sea level. RSL must have been higher than 3 m below present day sea level since at least 7.9 ± 0.3 ka BP to allow marine water to enter Izvilistaja Inlet. This site could provide important information on an early Holocene sea-level rise similar to coastal oases in Prydz Bay (Hodgson *et al.* 2016). However, due to a lack of age information of the proglacial sediment unit in this core no reliable RSL information can be derived from this earlier part of the record.

A RSL curve for Bunger Hills has been established based on raised beaches and incorporated marine fossils and diatom records (Colhoun & Adamson 1992, Verkulich *et al.* 2007, Poleschuk & Verkulich 2014). Saline water in Jaw Lake indicates a RSL maximum at or above 10 m a.s.l., however, the poorly dated sediment record from Jaw Lake does not allow determination of the timing of this level (Roberts *et al.* 2000). A marine ingression in Algae Lake was discussed (outlet sill at *c.* 10 m a.s.l.), since fragments of marine diatom frustules were found in cores 6069, 6078 and 6082 (Melles *et al.* 1997, Verkulich *et al.* 2002). Geochemical data (high δ^{13}C values, no halite) throughout the records as well as the dominance of freshwater diatom species in the biogenic sediments (Verkulich *et al.* 2002), however, point to deposition under continuously fresh conditions. Water flowing from Transkriptsii Gulf into Algae Lake via Izvilistaja Inlet may not have led to a pronounced marine signal in the sediments of Algae Lake, when filled with freshwater as at present day. However, the diatom record from Izvilistaja Inlet shows marine conditions until 2.2 ± 0.2 ka BP, which postdates a proposed mid-Holocene sea level high stand. Marine diatom frustules in the Algae Lake record are not restricted to a specific period during the Holocene and could be from aeolian supply from Cacapon Inlet, since strong winds transported sea spray across the adjacent land areas (Gore & Leishman 2020).

The diatom record from Paz Cove (PG1173) indicates a decrease in open ocean species (*F. kerguelensis*, Fig. 6) after *c.* 6 ka BP, which could indicate a successive decrease in water exchange underneath Denman Glacier and Shackleton Ice Shelf and may be an effect of lowering RSL (Verkulich *et al.* 2007, Poleschuk & Verkulich 2014). Lower connectivity after 6 ka BP is consistent with a RSL high stand at around 5.5 to 6.4 ka BP with subsequent sea level fall afterwards as reconstructed from raised beaches (Colhoun & Adamson 1992). RSL lowering probably led to increasing freshwater influence in Izvilistaja Inlet (PG1180) after 2.2 ± 0.2 ka BP resulting in permanently fresh conditions from 1.4 ± 0.1 ka BP (Fig. 9). However, since the hydrology of the epishelf lakes is also affected by the dynamics of the surrounding glaciers, it is difficult to extract a clearly sea level driven signal.

Evidence for climatic conditions

In the early Holocene, climate conditions were probably relatively warm, which promoted the deglaciation of Bunger Hills and is consistent with other reconstructions from East Antarctic coastal areas, marine records and ice cores (Denis *et al.* 2010, Verleyen *et al.* 2011). An increase in sea ice diatoms from 9.1–8.5 ka BP in core PG1173 indicates a short term cooling, but could also be explained by more persistent sea ice in freshened surface waters under high freshwater run-off (Fig. 9).

The widespread onset of biogenic sedimentation in lakes in southern Bunger Hills around 7.9 ± 0.1 ka BP indicates a decrease in meltwater run-off and associated decrease in high input of siliciclastic matter into the lakes, which allowed lake bottoms to be colonized by benthic organisms. The decrease in meltwater run-off could indicate colder conditions and reduced surface melt, but could also reflect the advanced state of deglaciation in southern Bunger Hills. From 7.9 ± 0.1 to 5.7 ± 0.2 ka BP, benthic communities in Algae Lake and 8 m lake were dominated by mosses, which are the first to colonize formerly proglacial environments, however, they also indicate low mineralisation of the water column and oligotrophic conditions (Priddle & Heywood 1980). Enrichment in S in the Algae Lake sediments could indicate restricted water-column mixing and more persistent lake-ice cover related to cooler climate during that time. However, other indications for cooler climate conditions are equivocal. 17 m lake on Geographers Island filled with water around 6.9 ± 0.4 ka BP, which could be due to the initial deglaciation of the site, or enhanced snowfall and the formation of snow fields providing meltwater to the lake basin, which is inconsistent with cold climate. In the marine record (PG1173) sea ice diatoms are of low abundance from 8.5 to 6 ka BP and show only a short increase from 6 to

5.5 ka BP, which argues against a period of pronounced colder conditions (Fig. 9).

After 5.7 ± 0.2 ka BP, $\delta^{13}C$ records from Algae Lake and 8 m lake indicate relatively stable conditions and probably warmer temperatures (Fig. 9). While high $\delta^{13}C$ values in Algae Lake indicate high contributions of microbial mats, probably related to thin and less persistent lake ice, low $\delta^{13}C$ values in 8 m lake indicate dilute water salinity, probably due to permanent run-off from snow fields in the catchment that balance water loss by evaporation. At the same time, sea ice diatoms decreased (PG1173), TOC increased and higher $\delta^{13}C$ values in Izvilistaja Inlet and Paz Cove point to increased productivity, which could reflect warmer conditions (Fig. 9). The period from 4 to 1.8 ka BP probably was the climatic optimum in Bunger Hills, indicated by high marine productivity, marine water exchange between Transkriptsii Gulf and Cacapon Inlet (reduced extent of Edisto Glacier ice tongue until 2.2 ka BP) and high nutrient input in 8 m lake, which probably resulted from a thicker active (seasonally thawed) layer in sediment in the catchment (Fig. 9).

The drop in TOC and $\delta^{13}C$ in core PG1173 at 2.2 ka BP was previously interpreted as an abrupt cooling (Kulbe *et al.* 2001). However, this shift clearly predates a late Holocene increase in sea ice diatoms at 1.7 ± 0.1 ka BP (Fig. 9). The decrease in $\delta^{13}C$ is recorded in most marine cores (PG1180, PG1173, PG1171) and could also reflect an advance of Edisto Glacier ice tongue (see previous paragraphs). Lakes were also affected by changing environmental conditions, which resulted in desiccation of 17 m lake after 2.1 ± 0.4 ka BP and lower $\delta^{13}C$ values in Algae Lake and 8 m lake around 1.5 ka BP, which points to lower productivity and/or lower contribution of microbial mats, probably due to thicker lake ice. The increase in sea ice diatoms and thicker lake ice indicate a cooling in Bunger Hills. A cooler and drier climate was probably followed by warming around 0.5 ka BP as indicated by refilling of 17 m lake and recurring microbial mats in 8 m lake (Fig. 9). A shift from drier to wetter (colder to warmer) conditions is also reflected in a diatom-based salinity record from Jaw Lake (Fig. 1), which shows a decrease in salinity in the late Holocene (Roberts *et al.* 2000). Conditions were probably variable during the last centuries since $\delta^{13}C$ values show large variability in the lakes (Fig. 9).

The relatively short period of cooler conditions we suggest for Bunger Hills is in contrast to reconstructions from marine records from Prydz Bay and Wilkes Land, which show a cooling with more sea ice since 4 ka BP (Denis *et al.* 2010). Other coastal oases in East Antarctica also experienced cooling during the past two millennia and some were also affected by relatively short-term drying/cooling events (Verleyen *et al.* 2011). A cooler climate on land was probably a result of atmospheric cooling over the continent as recorded in ice cores (Crosta *et al.* 2018). A late Holocene grounding line advance of Apfel and Edisto glaciers could be associated with cooling on land. However, Denman/Scott Glacier and Shackleton Ice Shelf also respond to changes in basal melt rates, which have been increasing since *c.* 4 ka BP around Antarctica and were probably promoted by intrusion of warmer water subsurface waters on the shelf (Crosta *et al.* 2018). The advance of Apfel and Edisto glaciers probably occurred in response to basal melting and thinning of the ice tongue prior to 2.2 ka BP.

Conclusions

Age-depth models for existing records from epishelf and inland lakes in Bunger Hills reveal common regional patterns of environmental changes for the Holocene epoch. While the timing of deglaciation was well known from the onset of biogenic sedimentation in inland lakes and epishelf lakes in the early Holocene (around 9.6 ka BP), the re-evaluation of records from Algae Lake, 8 m lake and Izvilistaja Inlet now show that intensive melting and discharge of clastic matter from the ice sheet continued until *c.* 7.9 ka BP. After that, only local ice melt, probably from remnant ice or snowfields, affected the inland lakes, which is in agreement with previous findings of a relatively stable ice sheet margin after the early Holocene. In contrast, the epishelf lakes in Bunger Hills responded to changes in grounding line position linked to glacier mass balance and/or RSL change. The records show that the inner parts of Bunger Hills were connected to marine waters since at least 9.6 ka BP, pointing to grounding line positions of Denman/Scott glaciers and Shackleton Ice Shelf that allowed marine water to reach the present-day coast. Based on diatom assemblages and geochemical data we infer at least two periods of advances of Edisto and Apfel glaciers for the Holocene. The first advance probably occurred around 7.7 ± 0.2 ka BP after a period of relatively free water exchange between the epishelf lakes and the ocean. Around 2.2 ka BP a drop in marine productivity and successive freshening of Izvilistaja Inlet afterwards could have resulted from grounding line advance into Transkriptsii Gulf. However, to distinguish effects of RSL from climate/ocean driven glacier dynamics, further studies are necessary to better i) constrain the RSL history of Bunger Hills (e.g. with new records from isolation basins), ii) quantify possible thinning and mass loss of the glaciers (e.g. from terrestrial records from Bunger Hills and other outcrops from the Denman/Scott glacier system) and to, iii) confirm the timing and intensity of meltwater discharge into the Southern Ocean (e.g. from marine records from the East Antarctic margin).

Although the records considered here display common trends, it is difficult to extract a clear climate signal based on the proxies considered. Some biogenic signals, which were previously interpreted in terms of climatic conditions, could also be explained by a natural evolution of the lakes after ice retreat (such as successive enrichment in nutrients from progressive rock weathering in the catchment and input of sea spray, or stabilisation of benthic habitats). Other, short-term (millennial to centennial) fluctuations are difficult to correlate between records, due to uncertainties in the age models. Nevertheless, the synchronicity of changes in the biogenic records of lakes and marine inlets point to regional relevance of environmental changes, which could indicate climatic forcing.

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Author contributions

SB conceived the paper and led the writing of the manuscript. All authors contributed to the discussion and interpretation and in drafting and editing the article.

References

Adamson, D.A. & Colhoun, E.A. 1992. Late Quaternary glaciation and deglaciation of the Bunger Hills, Antarctica. *Antarctic Science*, **4**, 435–446.

Augustinus, P.C. 2002. Weathering characteristics of the glacial drifts, Bunger Hills, East Antarctica. *Arctic, Antarctic, and Alpine Research*, **34**, 65–75.

Berg, S., Leng, M.J., Kendrick, C.P., Cremer, H. & Wagner, B. 2013. Bulk sediment and diatom silica carbon isotope composition from coastal marine sediments off East Antarctica. *Silicon*, **5**, 19–34.

Berg, S., White, D.A., Bennike, O., Fülöp, R.H., Fink, D., Wagner, B. & Melles, M. 2016. Unglaciated areas in East Antarctica during the Last Glacial (Marine Isotope Stage 3) – new evidence from Rauer Group. *Quaternary Science Reviews*, **153**, 1–10.

Berkman, P.A. & Forman, S.L. 1996. Pre-bomb radiocarbon and the reservoir correction for calcareous marine species in the Southern Ocean. *Geophysical Research Letters*, **23**, 633–636.

Blaauw, M. 2010. Methods and code for 'classical' age-modelling of radiocarbon sequences. *Quaternary Geochronology*, **5**, 512–518.

Bramley-Alves, J., Wankek, W., French, K. & Robinson, S.A. 2015. Moss δ ^{13}C: an accurate proxy for past water environments in polar regions. *Global Change Biology*, **21**, 2454–2464.

Bolshiyanov, D., Verkulich, S.R., Klokov, V. & Arslanov, H. 1991. Some features of the late Pleistocene and Holocene history of the Bunger Hills (East Antarctica). *Abstracts Sixth International Symposium on Antarctic Earth Sciences*. National Institute of Polar Research, Japan, 66–71.

Cremer, H., Gore, D., Melles, M. & Roberts, D. 2003. Palaeoclimatic significance of late Quaternary diatom assemblages from the southern Windmill Islands, East Antarctica. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **195**, 261–280.

Crosta, X., Crespin, J., Swingedouw, D., Marti, O., Masson-Delmotte, V., Etourneau, J., Goosse, H., Braconnot, P., Yam, R., Brailovski, I. & Shemesh, A. 2018. Ocean as the main driver of Antarctic ice sheet retreat during the Holocene. *Global and Planetary Change*, **166**, 62–74.

Colhoun, E.A. & Adamson, D.A. 1989. Former glacial lakes of the Bunger Hills, Antarctica. *Australian Geographer*, **20**, 125–136.

Colhoun, E.A. & Adamson, D.A. 1992. Raised beaches of the Bunger Hills, Antarctica. *ANARE Reports*, **136**, 47 pp.

Denis, D., Crosta, C., Barbara, L., Massé, G., Renssen, H., Ther, O. & Giraudeau, J. 2010. Sea ice and wind variability during the Holocene in East Antarctica: insight on middle-high latitude coupling. *Quaternary Science Reviews*, **29**, 3709–3719.

Doran, P.T., McKay, C.P., Meyer, M.A., Andersen, D.T., Wharton, R.A. & Hastings, J.T. 1996. Climatology and implications for perennial lake ice occurrence at Bunger Hills Oasis, East Antarctica. *Antarctic Science*, **8**, 289–296.

Doran, P.T., Wharton, R.A., Des Marais, D.J. & McKay, C.P. 1998. Antarctic paleolake sediments and the search for extinct life on Mars. *Journal of Geophysical Research*, **103**, 28481–28493.

Doran, P.T., Wharton, R.A., Lyons, W.B., Des Marais, D.J. & Andersen, D.T. 2000. Sedimentology and geochemistry of a perennially ice-covered epishelf lake in Bunger Hills Oasis, East Antarctica. *Antarctic Science*, **12**, 131–140.

Fitzsimons, S.J. & Colhoun, E.A. 1995. Form structure and stability of the Antarctic ice sheet, Vestfold Hills and Bunger Hills, East Antarctica. *Antarctic Science*, **7**, 171–179.

Gibson, J.A.E., Gore, D.B. & Kaup, E. 2002. Algae River: an extensive drainage system in the Bunger Hills, East Antarctica. *Polar Record*, **38**, 141–152.

Gibson, J.A.E, Roberts, D. & Van de Vijer, B. 2006. Salinity control of the distribution of diatoms in lakes of the Bunger Hills, East Antarctica. *Polar Biology*, **29**, 694–704.

Gibson, J.A.E., Paterson, K.S., White, C.A. & Swadling, K.M. 2009. Evidence for the continued existence of Abraxas Lake, Vestfold Hills, East Antarctica during the Last Glacial Maximum. *Antarctic Science*, **21**, 269–278.

Gore, D.B., Rhodes, E.J., Augustinus, P.C., Leishman, M.R., Colhoun, E.A. & Rees-Jones, J. 2001. Bunger Hills, East Antarctica: Ice free at the Last Glacial Maximum? *Geology*, **29**, 1103–1106.

Gore, D.B. & Leishman, M.R. 2020. Tafoni show postglacial and modern wind azimuths that are similar at Bunger Hills. *Antarctic Science*, **32**, 10.1017/S095410201900035X.

Hodgson, D.A., Whitehouse, P.L., DeCort, G., Berg, S., Verleyen, E., Tavernier, I., Roberts, S.J., Vyverman, W., Sabbe, K. & O'Brien, P. 2016. Rapid early Holocene sea-level rise in Prydz Bay, East Antarctica. *Global and Planetary Change*, **139**, 128–140.

Hogg, A.G., Hua, Q., Blackwell, P.G., Buck, C.E., Guilderson, T.P., Heaton, T.J., Niu, M., Palmer, J.G., Reimer, P.J., Reimer, R.W., Turney, C.S.M. & Zimmerman, S.R.H. 2013. Shcal13 southern hemisphere calibration, 0–50 000 years cal bp. *Radiocarbon*, **55**, 1889–1903.

Kaup, E., Haendel, D. & Vaikmäe, R. 1993. Limnological features of the saline lakes of the Bunger Hills (Wilkes Land, Antarctica). *Antarctic Science*, **5**, 41–50.

Kirkup, H., Melles, M. & Gore, D.B. 2002. Late Quaternary environment of southern Windmill Islands, East Antarctica. *Antarctic Science* **14**, 385–394.

Klokov, V., Kaup, E., Zierath, R. & Haendel, D. 1990. Lakes of the Bunger Hills (East Antarctica): chemical and ecological properties. *Polish Polar Research* **11**, 147–159.

KUDOH, S., TSUCHIYA, Y., AYKAWA, E., IMURA, S. & KANDA, H. 2003. Ecological studies of aquatic moss pillars in Antarctic lakes. 1. Macro structure and carbon, nitrogen and chlorophyll a contents. *Polar Bioscience* **16**, 11–22.

KULBE, T. 1997. The late Quaternary climatic and environmental history of Bunger Oasis, East Antarctica. *Reports on Polar Research*, **254**, 130 pp.

KULBE, T., MELLES, M., VERKULICH, S.R. & PUSHINA, Z.V. 2001. East Antarctic climate and environmental variability over the last 9400 years inferred from marine sediments in the Bunger Oasis. *Arctic, Antarctic and Alpine Research*, **33**, 223–230.

LEVENTER, A., DOMACK, E., DUNBAR, R., PIKE, J., STICKLEY, C., MADDISON, E., BRACHFELD, S., MANLEY, P. & MCCLENNEN, C. 2006. Marine sediment record from the East Antarctic margin reveals dynamics of ice sheet recession. *GSA Today*, **16**, 4–10.

MELLES, M., VERKULICH, S. & HERMICHEN, W.-D. 1994a. Radiocarbon dating of lacustrine and marine sediments from the Bunger Hills, East Antarctica. *Antarctic Science*, **6**, 375–378.

MELLES, M., KULBE, T., OVERDUIN, P.P. & VERKULICH, S. 1994b. The expedition Bunger Oasis 1993/94 of the AWI Research Unit Potsdam. *Reports on Polar and marine Research*, **148**, 27–80.

MELLES, M., KULBE, T., VERKULICH, S., PUSHINA, Z. & HUBBERTEN, H.-W. 1997. Late Pleistocene and Holocene environmental history of Bunger Hills, East Antarctica, as revealed by fresh-water and epishelf lake sediments. *In* RICCI, C.A., *ed. The Antarctic region: geological evolution and processes.* Siena, Italy: Terra Antarctica Publications, 809–820.

PETROU, K. & RALPH, P.J. 2011. Photosynthesis and net primary productivity in three Antarctic diatoms: possible significance for their distribution in the Antarctic marine ecosystem. *Marine Ecology Progress Series*, **437**, 27–40.

POLESCHUK, K.V. & VERKULICH, S.R. 2014 Reconstruction of Holocene relative sea-level changes in the Bunger oasis region (East Antarctica). *Problems of Arctic and Antarctic*, **2**, 15–24. [in Russian].

PRIDDLE, J. & HEYWOOD, R.B. 1980. Evolution of Antarctic lake ecosystems. *Biological Journal of the Linnean Society*, **14**, 51–66.

REIMER, P., BARD, E., BAYLISS, A., BECK, J.W., BLACKWELL, P.G., BRONK RAMSEY, C., *et al.* 2013. INTCAL13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal bp. *Radiocarbon*, **55**, 1869–1887.

RIGNOT, E., MOUGINOT, J., SCHEUCHL, B., VAN DEN BROEKE, M., VAN WESSEM, M.J. & MORLOGHEM, M. 2019. Four decades of Antarctic Ice Sheet mass balance from 1979–2017. *PNAS*, **116**, 1095–1103.

ROBERTS, D. & MCMINN, A. 1998. A weighted-averaging regression and calibration model for inferring lakewater salinity from fossil diatom assemblages in saline lakes of the Vestfold Hills: a new tool for interpreting Holocene lake histories in Antarctica. *Journal of Paleolimnology*, **19**, 99–113.

ROBERTS, D., MCMINN, A. & ZWARTZ, D. 2000. An initial palaeosalinity history of Jaw Lake, Bunger Hills based on a diatom-salinity transfer function applied to sediment cores. *Antarctic Science*, **12**, 172–176.

VERKULICH, S.R & HILLER, J. 1994. Holocene deglaciation of the Bunger Hills revealed by ^{14}C measurements on stomach oil deposits in snow petrel colonies. *Antarctic Science*, **6**, 395–399.

VERKULICH, S.R., MELLES, M., HUBBERTEN, H.-W. & PUSHINA, Z.V. 2002. Holocene environmental changes and development of Figurnoye Lake in the southern Bunger Hills, East Antarctica. *Journal of Paleolimnology*, **28**, 253–267.

VERKULICH, 2007. Reconstruction of Holocene climate changes in the coastal zone of East Antarctica based on a study of bottom deposits of the lakes and marine bays. *Izvestia RAN Geographical Series*, **4**, 38–43. [in Russian].

VERKULICH, S.R., PUSHINA, Z.V., SOKRATOVA, I.N., MELLES, M., HULTSCH, N. & DIEKMANN, B. 2007. Changes in sea level and glacio-isostasia on the Antarctic coast in the Holocene. *Data on Glaciological Studies*, **102**, 23–31. [in Russian].

VERLEYEN, E., HODGSON, D.A., SABBE, K., CREMER, H., EMSLIE, S.D., GIBSON, J., *et al.* 2011. Post-glacial regional climate variability along the East Antarctic coastal margin - evidence from shallow marine and coastal terrestrial records. *Earth-Science Reviews*, **104**, 199–212.

YANGYANG, W., JING, J., YAGUANG, N., XIN, C., LIBIN, W., PINGQING, F., XIAODONG, L. & EMSLIE, S.D. 2016. Sources of organic matter and paleo-environmental implications inferred from carbon isotope compositions of lacustrine sediments at Inexpressible Island, Ross Sea, Antarctica. *Advances in Polar Science*, **27**, 233–244.