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Twenty-thousand-year gap between deglaciation and peat formation on sub-Antarctic Marion Island attributed to climate and sea level change

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ABSTRACT: Radiocarbon dating of basal peats has been a key factor in determining minimum ages for deglaciation on sub-Antarctic islands. On Marion Island, peat bogs dominate the landscape below 300 m a.s.l., and palynological assessments of peat cores have been used to assess the vegetation history and succession rates as well as the sensitivity of the indigenous flora to climatic change. Initiation of peat on the sub-Antarctic islands signifies a major landscape change which has previously been linked to the retreat of glaciers. Here we test this hypothesis by comparing previously published and new basal peat ages from Marion Island with cosmogenic isotope dates for deglaciation, and local and regional palaeo-environmental changes. Results show that, in common with other sub-Antarctic islands, peat initiation occurred after the Antarctic Cold Reversal (15–13 ka) and through the early Holocene climate optimum. This substantially post-dates cosmogenic isotope evidence for deglaciation from the basalts which shows that the areas where the peatlands dominate were ice-free from the start of Marine Isotope Stage (MIS) 2 (~31 ka). This suggests that environmental conditions controlled peat initiation rather than deglaciation. Regional climatic proxies show that during and after MIS 2, extremely low temperatures, extensive sea ice conditions and depressed sea surface temperatures together with lower sea levels at an island scale could have maintained conditions unfavourable for peat initiation at their current locations. On Marion Island, the significant gap of ~20 000 years between the timing of deglaciation and peat formation indicates that the use of peat basal ages as a proxy for the minimum age of deglaciation in the sub-Antarctic should be used with extreme caution.

KEYWORDS: ^{14}C; deglaciation; Marion Island; peat; sub-Antarctic

Introduction

Sub-Antarctic islands are small islands located in the vast Southern Ocean with unique terrestrial archives which can be used to investigate past changes in local ice extent and regional oceanic and atmospheric circulation patterns in the southern mid-latitudes (van der Putten, 2012). Age determination of basal peats (mostly through ^{14}C dating of peat cores) has been used to infer minimum ages for deglaciation (Hodgson et al., 2014) across the sub-Antarctic. Peat cores have also provided reconstructions of the post-glacial vegetation history (see van der Putten et al., 2012), landscape evolution (Yeloff et al., 2007; Whittle et al., 2019) and climate change (Yeloff et al., 2007; Van Der Putten, 2012; Hodgson et al., 2014; Whittle et al., 2019; Payne et al., 2019).

From a biogeographical perspective, the islands that constitute the 'core' of the sub-Antarctic region are South Georgia, Marion and Prince Edward Islands, the archipelagos of Crozet and Kerguelen, Heard and McDonald Islands, and Macquarie Island (Convey, 2020) (Fig. 1). Marion Island (46°54′S, 37°45′E) is 293 km^2 in size and like the other 'core' islands has a hyper-maritime climate and is located in the westerly wind belt of the Southern Hemisphere (Fig. 1). Marion Island is a 1240-m-high (a.s.l.) shield volcano that rises above a flat-topped submarine platform. The island is dotted by about 150 cinder cones, smaller scoria cones and coastal tuff cones. The island comprises basaltic 'grey' lavas dating from 50 to 450 ka overlain by 'black' lavas of the pahoehoe and aa type (McDougall et al., 2001). Peat bogs are dominant on the lowland plains of Marion Island with different mire complexes covering ~50% of the island below 300 m a.s.l. Plant communities of the mires form the *Juncus scheuchzerioides–Blepharidophyllum densifolium* complex while the graminoid species *Agrostis magellanica, Uncinia compacta* and *Juncus scheuchzerioides* form an important component of the peat-forming plants (Yeloff et al., 2007). Areas around the mires and at higher elevations on the island are dominated by the fellfield complex which consists primarily of the cushion plant *Azorella selago.* From the early 1970s, the post-glacial vegetation history of Marion Island has been determined from palynological assessment of peat cores. Schalke and van Zinderen Bakker (1971) published the first pollen diagrams for Marion Island and inferred that their peat core (at Macaroni Bay) covers the last 16 ka. From ^{14}C analysis, they reported an age of 9500 ± 140 BP at a depth of 175–185 cm in their Macaroni Bay core and a peat basal age of their core at Juniors Kop of 3180 ± 120 BP (Schalke and van Zinderen Bakker, 1971). Scott (1985) described the pollen assemblages of several samples and suggests a succession of barren fjaeldmark (fellfield) through *Azorella selago* peats to mire communities. Subsequently, basal dates from these peat cores, together with dates from lake sediments and open sections have been used to determine minimum ages for the deglaciation of Marion Island and other sub-Antarctic islands (e.g. Hodgson et al., 2014). Here we test the

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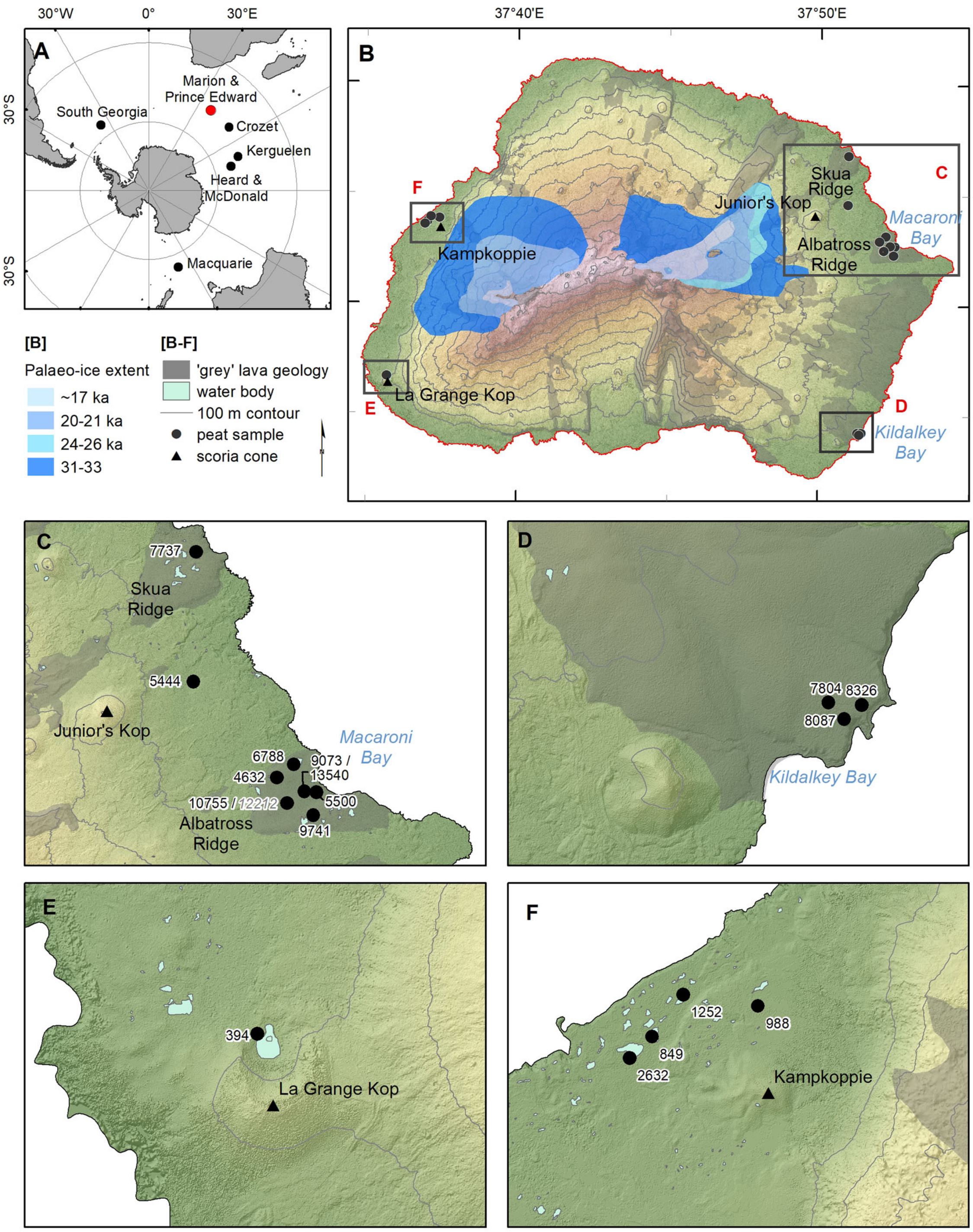

Figure 1. (A) The geographical context of Marion Island and other sub-Antarctic islands. (B) The sampling locations within the context of reconstructed palaeo-ice extent (Rudolph et al., 2024). (C–F) The recalibrated ^{14}C ages of peat and organic sediment from various published sources and new data from this study (see Table 1). Relevant peaks and place names are indicated and surficial 'grey' lava geological surfaces are demarcated. Spatial data are from Rudolph et al., (2021, 2022). [Color figure can be viewed at wileyonlinelibrary.com]

hypothesis that these are close minimum ages for deglaciation by comparing a synthesis and recalibration of previously published and new basal peat ages from Marion Island with cosmogenic isotope dates for deglaciation from the basalts. We then provide a critical assessment of the timing of peatland initiation against local and regional palaeo-environmental drivers.

Results and discussion

Previously published ^{14}C ages from peat cores on Marion Island (Schalke & van Zinderen Bakker, 1971; Scott, 1985; Yeloff et al., 2007) together with previous unpublished ages from seven peat cores are presented (Table 1). Ombrotrophic mires (from the different sectors of the island) were sampled to basal depth at Macaroni Bay, Albatross Ridge, Kildalkey Bay and the coastal plains at Kampkoppie (Fig. 1) using a Russian-pattern peat corer, or by sampling exposed sections. Radiocarbon (^{14}C) dates received from the various laboratories were (re)calibrated to calendar years BP (before 1950) using the SHCal20 calibration curve for the Southern Hemisphere (Hogg et al., 2020) in Calib 8.2 (Stuiver and Reimer, 1993) (Table 1). Furthermore, ^{14}C dates from basal organic sediment in lakes at Kampkoppie and La Grange Kop that were previously sampled

Table 1. Radiocarbon ages of peat and lake sediment deposits on Marion Island. Calibration was done using the SHCal20 calibration curve for the Southern Hemisphere (Hogg et., 2020) in Calib 8.2 (Stuiver and Reimer, 1993).

Site name	Sample ID	Lab identifier	Latitude	Longitude	Material dated/stratigraphic depth (cm)	Reported ^{14}C age (cal BP)	Calibrated age range 2 sigma	Median probability	Source publication
Northeast sector									
Albatross Lakes, Fourth boring		Pta-3231			Peat, 165–180	4140 ± 70	4502–4828	4632	Scott, 1985
Transvaal Cove	MARI 1 261.5 cm	GrA-30781	−46.8788	37.8486	Plant macros, peat, 261.5	4750 ± 40	5321–5422	5444	Yeloff et al. 2007
Macaroni Bay Site 2	MI 2 J 379-380	Beta-663733	−46.8944	37.8744	Peat basal, 379–380	4780 ± 30	5445–5584	5500	Unpublished
Albatross Lakes, Third boring		Pta-3232			Peat, 353–363	5990 ± 70	6627–6985	6788	Scott, 1985
Skua Ridge, First boring		Pta-3214			Peat, 130–140	6930 ± 90	7579–7873	7737	Scott, 1985
Macaroni Bay Site 1	MI 1 J 407-408	Beta-663732	−46.8943	37.8720	Peat–clay transition, 407–408	8170 ± 30	8995–9140	9073	Unpublished
Albatross Ridge	ALB200-250_49-50 cm	Beta-478311	−46.8977	37.8739	Peat, 250	8790 ± 40	9550–9906	9741	Unpublished
Macaroni Bay		K-1064			Peat, 175–185	9500 ± 140	10 375–11 180	10 755	Schalke & van Zinderen Bakker, 1971
Macaroni Bay		I-2278			Peat, 275–295	10600 ± 700	10 257–13 798	12212	Schalke & van Zinderen Bakker, 1971[R]
Macaroni Bay Site 1	MI 1 K 442-443	Beta-663731	−46.8943	37.8720	Clay organics basal, 442–443	11710 ± 40	13440–13607	13 540	Unpublished
Southeast sector									
Kildakey Bay peat section		Pta-3208			Peat, basal, 600	7300 ± 70	7936–8203	8087	Scott, 1985
Kildakey Bay peat section	Kildalkey 2023 basal	Beta-675290	−46.9648	37.8548	Peat, basal	7010 ± 30	7695–7868	7804	Unpublished
Kildalkey Bay penguin colony	MI 3 L2 476-477	Beta-663735	−46.9649	37.8568	Peat basal, 476–477	7540 ± 30	8281–8386	8326	Unpublished
West sector									
La Grange Kop Lake basal	LGK 43.5 cm	SUERC-63990	−46.9444	37.5946	Organic sediment basal, 43.5	371 ± 35	313–472	394	Perren et al., 2020
Kampkoppie Lake 2	KK2 L2 68-69	SUERC-55253	−46.8859	37.6167	Organic sediment basal, 68–69	977 ± 38	766–926	849	Unpublished
Kampkoppie higher coastal plain	MI 5D 158-159	Beta-663734	−46.8845	37.6233	Peat basal, 158–159	1130 ± 30	1007–1057	988	Unpublished
Kampkoppie lower coastal plain	MI 7 C 94-95	Beta-663736	−46.8841	37.6186	Peat, 94–95	1380 ± 30	1260–1304	1252	Unpublished
Kampkoppie Lake 1	KK1 L1 57.5	SUERC-55249	−46.8868	37.6153	Organic sediment basal, 57.5	2596 ± 36	2672–2758	2632	Unpublished

[R] Rejected age is the age 12212 presented by Schalke & van Zinderen Bakker, 1971.

(see Perren et al., 2020 for sampling procedure and ^{14}C age determination) are also presented here (Table 1). The Kampkoppie lake is on a black lava flow west of Kampkoppie cone while the La Grange Kop lake is within the scoria cone with the same name on the west coast of Marion Island (Fig. 1). The lakes are ideally positioned to accumulate sea salt and minerogenic inputs from the prevailing westerly winds, whilst receiving minimal inputs from elsewhere on the island (Perren et al., 2020).

The mires at Skua Ridge, Macaroni Bay, Albatross Ridge and Kildalkey Bay are in areas underlain by Pleistocene grey lavas in the eastern sector of the island (Fig. 1). These mires are expected to be the oldest on the island since the area has not been influenced by the most recent volcanic activity (Rudolph et al., 2021). Peat basal dates range from ~5500 to 9073 cal a BP with the core at Macaroni Bay site 1 being the oldest core ever dated on Marion Island (Table 1). Here the base consists of a grey lava clay layer with the organics dated to 13540 cal a BP and the transition from clay to peat at 9073 cal a BP. This grey lava clay layer is considered to be the base that made the site habitable for plant life as described by Schalke and van Zinderen Bakker (1971) while the transition layer age is the age of peat initiation (Quik et al., 2022). It is noteworthy that the original dates presented by Schalke and van Zinderen Bakker (1971) for their core at Macaroni Bay (Table 1) fit with the new core dates for the area even though their basal date of 12 212 cal a BP was rejected by the original authors due to 'contamination'. Therefore, the subsequent inference by the original authors (Schalke and van Zinderen Bakker, 1971) and presented elsewhere (see Van der Putten et al., 2010) that the base is ~17 000 years old is rejected. The mires that were cored on the western coastal plain at Kampkoppie (Fig. 1) are underlain by Holocene black lava (Verwoerd, 1971; Rudolph et al., 2021). It is in the area on Marion Island that has some of the youngest black lavas, as it is situated near the zone of the most recent outflow in 1980 (Rudolph et al., 2021). The peats are young and shallow with a peat basal age of ~1200 years which is younger than the basal age of the lake sediment at Kampkoppie lake 1 (2632 cal a BP).

Recent advancements in cosmogenic nuclide exposure dating techniques and ^{36}Cl analytics allow for the exposure dating of oceanic island basalts (Nel et al., 2021). Exposure ages of glacial features in the basalts on the northeast coast of Marion Island show that the last deglaciation began before 34 ka, and continued until ~17 ka, by which time the ice had retreated up to ~900 m a.s.l. (Rudolph et al., 2020). However, new exposure ages (Rudolph et al., 2024) indicate that the local Last Glacial Maximum was reached prior to ~56 ka and that by using a conceptual model of island-scale deglaciation across time scales, it can be seen that all the areas on Marion Island where peat is found were essentially ice free from ~31 ka (Rudolph et al., 2024, their fig. 5). Furthermore, a boulder in a moraine at Macaroni Bay (MB1) (in the vicinity of our own Macaroni Bay site 1) returned an exposure age of ~37 ka which was accepted in the context of its geomorphic association (Rudolph et al., 2024). Additionally, the exposure age for the moraine is more likely to be under-estimated due to erosion that is potentially unaccounted for, rather than overestimated due to unaccounted inheritance (Rudolph et al., 2024). The reasons for this early deglaciation on Marion Island are described by Rudolph et al. (2024) and all indications are that the grey lava ice-free landscape on Marion Island is thus significantly older than previously considered (Nel et al., 2021) but the bases of the peats are all essentially Holocene in age. This shows a significant lag (of at least 20 ka) between the timing of deglaciation and peat formation. This implies that the use of peat basal ages as a proxy for the minimum age of deglaciation for Marion Island (Hodgson et al., 2014) is not pragmatic.

The sub-Antarctic is considered a data-poor region in terms of palaeo-climatic sites but there has been renewed palaeo-ecological and climatological interest in the peat archives of sub-Antarctic islands (van der Putten et al., 2012; Hodgson et al., 2014; Whittle et al., 2019; Payne et al., 2019). A review of ^{14}C peat dates from the 'core' sub-Antarctic islands (Convey, 2020) adapted from Hodgson et al. (2014) is presented in Table 2. Except for one radiocarbon date of ~15 600 cal a BP (Van Der Putten, 2010) from near the base of a peat core on the eastern side of the Kerguelen archipelago, minimum ages for peat development on these islands are essentially confined to after the Antarctic Cold Reversal (15–13 ka) with most occurring during the early Holocene climate optimum (11 500 and 9000 years BP) (Masson et al., 2000; Parrenin et al., 2013) (Table 2). When peat development on Marion Island is juxtaposed next to several palaeo-environmental proxies (Fig. 2) it can be seen that after deglaciation of the coastal areas during Marine Isotope Stage (MIS) 2 (~31 ka), temperatures remained extremely low (about −8°C below present at sea level) (Parrenin et al., 2013) and sea levels were also 100–120 m lower than present (Miller et al., 2020). This local state (during MIS 2), together with extensive sea ice conditions and depressed sea surface temperatures (SSTs) in the Southern Ocean (Chadwick et al., 2022), lasted into MIS 1 (~18 ka) (Fig. 2). The low air temperatures and extensive sea ice conditions are likely to have starved Marion Island of moisture while a 100- to 120-m drop in sea level would effectively have meant the position of the current peat bogs on Marion Island would have been higher in elevation and much further from the coast. If the dry adiabatic lapse rate is also taken in consideration a 100-m rise in altitude would have resulted in a further decrease in mean air temperature of about −1°C. Even though most of the island was not in a glaciated state during the global Last Glacial Maximum (gLGM) (Rudolph et al., 2024), it is suggested here that the climatic conditions would still have been unfavourable for peat initiation. From 18 to 13 ka sea levels started to rise, SSTs started to increase, sea ice diminished and air temperatures increased (Fig. 2). The effect of the Antarctic Cold Reversal (ACR) (~15–13 ka BP) on the landscape and climate of Marion Island is currently unknown but it is possible that the northward shift in the Southern Westerly Winds (Fletcher et al., 2021) and decreasing temperatures during the ACR could have further delayed large-scale peat formation. From the Early Holocene (~12 ka BP) the local sea levels and regional SSTs, sea ice and air temperatures stabilized to essentially current levels (Fig. 2). This coincides with the basal ages of the oldest known peat on Marion Island and the deepest peat ages across the 'core' sub-Antarctic islands (Tables 1 and 2). Growing evidence suggests that sub-Antarctic islands experienced more extensive glacial maxima during their MIS 3/4 advances than during MIS 2 (gLGM) or subsequent glaciations such as the ACR (see Darvill et al., 2016; Schaefer et al., 2015; Shulmeister et al., 2019). Even though exotic pollen grains, which have been transported by the prevailing westerly winds, make up ~1.2% of all pollen recorded, it is suggested that wind dispersal did not play a major role in the establishment of the present biota on Marion Island (Scott and van Zinderen Bakker, 1985). Irrespective of the timing and extent of the glaciations on the individual islands, or the local and regional temperature and moisture regimes throughout MIS 1 and 2, the native subantarctic phanerogamic flora survived through local refugia since the plant species are present at the onset of accumulation of the organic sediment and there is no evidence for the natural

Table 2. Selected radiocarbon ages of peat (adapted from Hodgson et al., 2014) on the ‘core’ sub-Antarctic islands (Convey, 2020). Calibration of radiocarbon ages was undertaken using the CALIB 6.01 and the SHcal04 Southern Hemisphere data set (McCormac et al., 2004).

Site name	Sample ID	Latitude	Longitude	Material dated, depth (cm)	Reported ^{14}C age	Calibrated age range 2 sigma	Source publication
South Georgia							
Tønsberg Point	UtC-4179	54°10′S	36°39′W	Peat, 308	9520 ± 80	10 512–10 893	Van der Putten et al., 2004
Dartmouth Point	SRR-1165	54°19′S	36°26′W	Peat	9433 ± 120	10 264–10 869	Smith, 1981
Gun Hut Valley, Site 4	SRR-736			Peat, 258	9493 ± 370	12 150–9650	Barrow, 1978
Gun Hut Valley′	SRR-1979			Peat, 350	9700 ± 50	11 600–10 550	Van der Putten and Verbruggen, 2005
Husdal, Sink Hole sequence	UtC-3307			Peat, 460	9160 ± 110	10 113–10 570	Van der Putten et al., 2012
Grytrviken	SRR-1168			Peat, 460	8737 ± 50	9536–9795	Smith, 1981
Maiviken	SRR-1162	54°15′S	36°29′W	Peat, 180	8657 ± 45	9495–9680	Smith, 1981
Gun Hut Valley, Site 3				Peat, 160	8537 ± 65	9396–9553	Barrow, 1978
Kanin Point	UtC-6866	54°11′09″S	36°41′44″W	Peat, 312	8225 ± 45	9009–9270	Van der Putten et al., 2009
Black Head bog	Beta-271303	54°04′07″S	37°08′41″W	Peat, 373	8110 ± 50	8723–9123	Hodgson et al., 2014
Husdal River site	UtC-6869			Peat, 300	6840 ± 40	7571–7690	Van der Putten et al., 2013
Husdal	UtC-6867			Peat, 290	6415 ± 40	7174–7418	Van der Putten et al., 2013
Crozet - Ile de la Possession							
Base A. Faure, V. De Branloires	KIA-19231	46°25′49″S	51°51′31″E	Peat, 402	9655 ± 60	10 750–[11 000*]	Van der Putten et al., 2010
Morne Rouge Volcano flank	KIA-31355	46°23′35.45″S	51°48′28.85″E	Peat, 197	6110 ± 40	6779–7020	Ooms et al., 2011
Morne Rouge peat sequence	NZA-11509	46°23′26″S	51°48′45″E	Peat, 532	5480 ± 60	6000–6316	Van der Putten et al., 2008
Kerguelen Islands							
Estacade	SacA 7753	49°16′03″S	70°32′29″E	Peat, 468	13 190 ± 50	15396–16624*	Van der Putten et al., 2010
Golfe du Moribihan, Core 2				Peat 525	11 010 ± 160	12 765–13241*	Young and Schofield, 1973
Ampère Glacier	2	49°23′50″S	69°10′14″E	Peat, sample 2	10 120 ± 90	11 336–12 054*	Frenot et al., 1997
Ampère Glacier	1	49°23′50″S	69°10′14″E	Peat, sample 1	10 140 ± 120	11 264–12 151*	Frenot et al., 1997
Ampère Glacier	3	49°23′42″S	69°10′55″E	Peat, sample 3	9930 ± 70	11 212–11 629*	Frenot et al., 1997
Golfe du Moribihan, Core 1				Peat, 260	8595 ± 125	9141–9912	Young and Schofield, 1973
Ampère Glacier	4	49°23′47″S	69°09′55″E	Peat, sample 4	4590 ± 60	5054–5188	Frenot et al., 1997
Ampère Glacier	5	49°24′15″S	69°10′23″E	Peat, sample 5	2220 ± 80	2098–2208	Frenot et al., 1997
Ampère Glacier	6	49°24′15″S	69°10′23″E	Peat, sample 6	1960 ± 80	1732–1928	Frenot et al., 1997
Ampère Glacier	7	49°23′47″S	69°09′55″E	Peat, sample 7	1670 ± 50	1384–1621	Frenot et al., 1997
Ampère Glacier	8	49°24′15″S	69°10′23″E	Peat, sample 8	1320 ± 70	1166–1282	Frenot et al., 1997
Ampère Glacier	9	49°24′17″S	69°10′23″E	Peat, sample 9	900 ± 70	716–804	Frenot et al., 1997
Macquarie Island							
Finch Creek Ridge	Beta-1386	54°34′S	158°54′E	Peat	10 275 ± 230	11 284–12 581*	Selkirk et al., 1988
Green Gorge Ridge	SUA-1461	54°38′S,	158°54′E	Peat, 130	7200 ± 130	7682–8203	Selkirk et al., 1988
Wireless Hill	Beta-1387			Sandy peat, 360	5960 ± 360	5986–7476	Selkirk et al., 1988
Finch Creek valley	SUA-1845X	54°34′S,	158° 55′E	Peat, 190	5930 ± 240	6206–7272	Selkirk et al., 1988

*See stratigraphic comment in Selkirk et al. (1988).

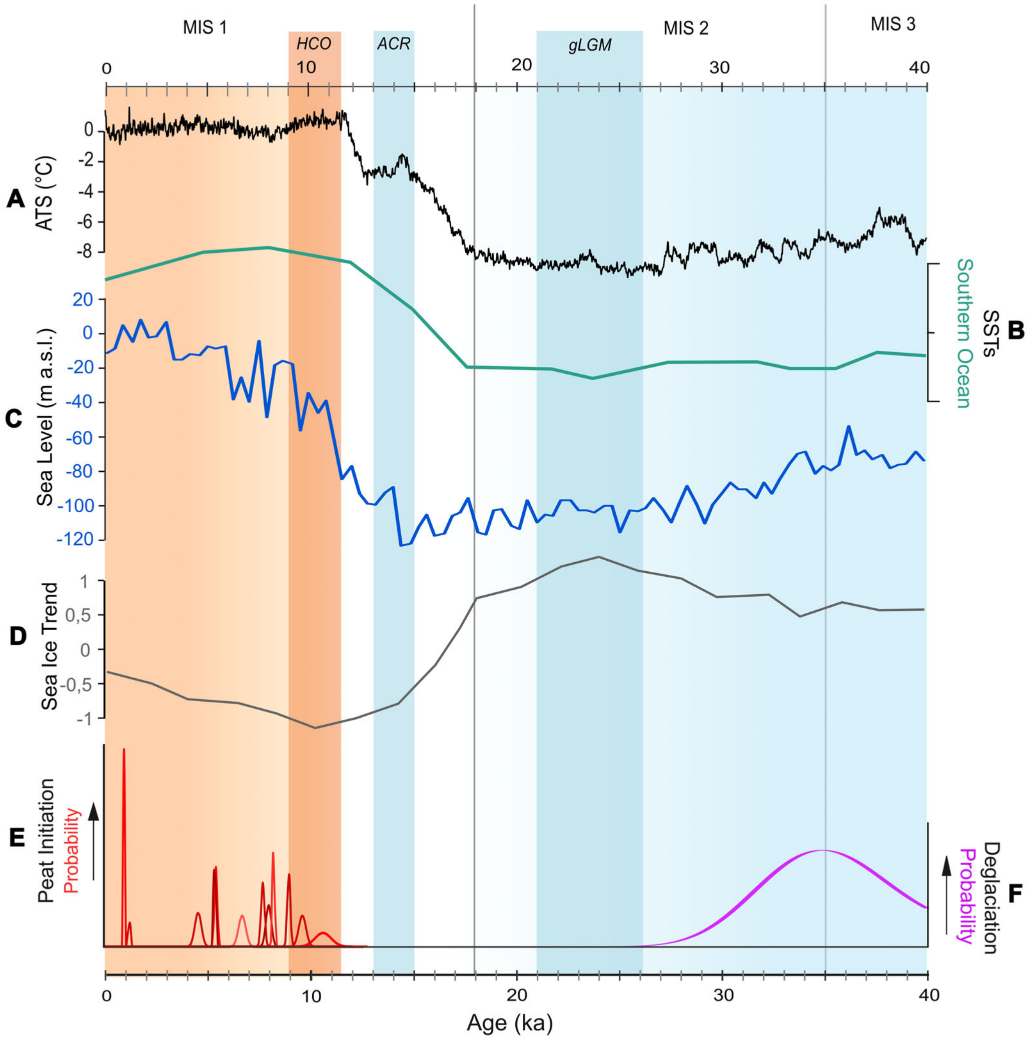

Figure 2. Southern Hemisphere palaeo-climate proxies juxtaposed alongside Marion Island's peat development timeline: (A) the Antarctic Temperature Stack (ATS) relative to present-day temperatures (Parrenin et al., 2013); (B) Southern Ocean sea surface temperatures (SSTs); (C) changes in global mean sea level relative to present-day sea level (Miller et al., 2020); (D) the dominant trend in Southern Ocean sea ice extent, modified from Chadwick et al. (2022). Probability plots of (E) peat development constructed from ^{14}C ages of peat sediments and (F) deglaciation inferred from ^{36}Cl exposure ages of moraine boulders (Rudolph et al., 2024). The chronostratigraphic units indicate Marine oxygen Isotope Stages (MIS) (Railsback et al., 2015), the global Last Glacial Maximum (gLGM) (Clark et al., 2009) and the Antarctic Cold Reversal (ACR) (Putnam et al., 2010). [Color figure can be viewed at wileyonlinelibrary.com]

arrival of new immigrants (Van Der Putten, 2010). On Marion Island, the Feldmark Plateau and the middle of Long Ridge are potentially the oldest exposed surfaces (Rudolph et al., 2024). These areas, along with the coastal areas now inundated by post-glacial sea level rise, are probably the biological refugia which made the establishment of vegetation and peat initiation possible at their current locations during the Holocene.

Conclusion

Peat basal dates in the mires underlain by pre-glacial grey lavas on Marion Island range from ~5500 to 9073 cal a BP. In the oldest peat core ever dated on the island, the material that made this site habitable for plant life is dated to 13540 cal a BP and peat initiation is dated at 9073 cal a BP. Recent cosmogenic nuclide exposure ages of the grey lavas indicate that the areas where the mires dominate were ice-free from ~31 ka but the base of the peats underlain by these pre-glacial lavas are Holocene in age. There is a gap of at least 20 ka between the timing of deglaciation and peat formation which suggests that the use of peat basal ages as a close proxy for the minimum age of deglaciation is not realistic.

Absolute and minimum ages for peat development on sub-Antarctic islands are essentially confined to after the ACR (15–13 ka). When peat development is juxtaposed to regional climatic proxies, it is proposed that after MIS 2 a combination of regional environmental conditions (low temperatures, extensive sea ice conditions and depressed sea surface temperatures) together with lower sea levels at an island scale would have made conditions unfavourable for peat initiation at their current locations on the island. Peat initiation only became possible once the local sea levels and regional SSTs, sea ice and air temperatures reached favourable levels during and after the Early Holocene climate optimum.

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Data availability statement

The data that support the findings of this study are available in Tables 1 and 2.

Conflict of Interest Statement—The authors declare no conflict of interest.

Abbreviations. ACR, Antarctic Cold Reversal; gLGM, global Last Glacial Maximum; MIS, Marine Isotope Stage; SST, sea surface temperature.

References

Barrow, C.J. (1978) Postglacial pollen diagrams from South Georgia (sub-Antarctic) and West Falkland Island (South Atlantic). *Journal of Biogeography*, 5, 251–274.

Chadwick, M., Crosta, X., Esper, O., Thöle, L. & Kohfeld, K.E. (2022) Compilation of Southern Ocean sea-ice records covering the last glacial-interglacial cycle (12–130 ka). *Climate of the Past*, 18(8), 1815–1829. Available at: https://doi.org/10.5194/cp-18-1815-2022

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B. et al. (2009) The Last Glacial Maximum. *Science*, 325(5941), 710–714. Available at: https://doi.org/10.1126/science.1172873

Convey, P. (2020) Current changes in Antarctic ecosystems. In: Goldstein, M.I. & Dellasala, D.A., (Eds.) *Encyclopedia of the World's Biomes*. Elsevier. pp. 666–685.

Darvill, C.M., Bentley, M.J., Stokes, C.R. & Shulmeister, J. (2016) The timing and cause of glacial advances in the southern mid-latitudes during the last glacial cycle based on a synthesis of exposure ages from Patagonia and New Zealand. *Quaternary Science Reviews*, 149, 200–214. Available at: https://doi.org/10.1016/j.quascirev.2016.07.024

Fletcher, M.-S., Pedro, J., Hall, T., Mariani, M., Alexander, J.A., Beck, K. et al. (2021) Northward shift of the southern westerlies during the Antarctic Cold Reversal. *Quaternary Science Reviews*, 271, 107189.

Frenot, Y., Gloaguen, J.C. & Tréhen, P. (1997) Climate change in Kerguelen islands and colonization of recently deglaciated areas by Poa kerguelensis and Poa annua. In: Battaglia, F., Valencia, J. & Walton, D.W.H., (Eds.) *Antarctic Communities: Species, Structure and Survival*. Cambridge University Press. pp. 358–366.

Hodgson, D.A., Graham, A.G.C., Roberts, S.J., Bentley, M.J., Cofaigh, C.Ó., Verleyen, E. et al. (2014) Terrestrial and submarine evidence for the extent and timing of the Last Glacial Maximum and the onset of deglaciation on the maritime-Antarctic and sub-Antarctic islands. *Quaternary Science Reviews*, 100, 137–158. Available at: https://doi.org/10.1016/j.quascirev.2013.12.001

Hogg, A.G., Heaton, T.J., Hua, Q., Palmer, J.G., Turney, C.S., Southon, J. et al. (2020) SHCal20 Southern Hemisphere Calibration, 0-55,000 Years cal BP. *Radiocarbon*, 62(4), 759–778. Available at: https://doi.org/10.1017/RDC.2020.59

Masson, V., Vimeux, F., Jouzel, J., Morgan, V., Delmotte, M., Ciais, P. et al. (2000) Holocene Climate Variability in Antarctica Based on 11 Ice-Core Isotopic Records. *Quaternary Research*, 54(3), 348–358. Available at: https://doi.org/10.1006/qres.2000.2172

McCormac, F., Hogg, A., Blackwell, P., Buck, C., Higham, T. & Reimer, P. (2004) Shcal04 southern hemisphere calibration 0-11.0 cal Kyr BP. *Radiocarbon*, 46, 1087e1092.

McDougall, I., Verwoerd, W. & Chevallier, L. (2001) K–Ar geochronology of Marion Island, Southern Ocean. *Geological Magazine*, 138(1), 1–17. http://geolmag.geoscienceworld.org/content/138/1/1.abstract

Miller, K.G., Browning, J.V., Schmelz, W.J., Kopp, R.E., Mountain, G.S. & Wright, J.D. (2020) Cenozoic sea-level and cryospheric evolution from deep-sea geochemical and continental margin records. *Science Advances*, 6(20), eaaz1346. Available at: https://doi.org/10.1126/sciadv.aaz1346

Nel, W., Boelhouwers, J.C., Borg, C.-J., Cotrina, J.H., Hansen, C.D., Haussmann, N.S. et al. (2021) Earth science research on Marion Island (1996–2020): a synthesis and new findings. *South African Geographical Journal*, 103(1), 22–42. Available at: https://doi.org/10.1080/03736245.2020.1786445

Ooms, M., Van de Vijver, B., Temmerman, S. & Beyens, L. (2011) A Holocene palaeoenviromental study of a sediment core from Ile de la Possession, Iles Crozet, sub-Antarctica. *Antarctic Science*, 23(5), 431–441.

Parrenin, F., Masson-Delmotte, V., Köhler, P., Raynaud, D., Paillard, D., Schwander, J. et al. (2013) Synchronous change of atmospheric CO2 and Antarctic temperature during the last deglacial warming. *Science*, 339(March), 1060–1063. Available at: https://doi.org/10.1126/science.1226368

Payne, R.J., Ring-Hrubesh, F., Rush, G., Sloan, T.J., Evans, C.D. & Mauquoy, D. (2019) Peatland initiation and carbon accumulation in the Falkland Islands. *Quaternary Science Reviews*, 212, 213–218. Available at: https://doi.org/10.1016/j.quascirev.2019.03.022

Perren, B.B., Hodgson, D.A., Roberts, S.J., Sime, L., Van Nieuwenhuyze, W., Verleyen, E. et al. (2020) Southward migration of the Southern Hemisphere westerly winds corresponds with warming climate over centennial timescales. *Communications Earth & Environment*, 1(1), 58. Available at: https://doi.org/10.1038/s43247-020-00059-6

Putnam, A.E., Schaefer, J.M., Barrell, D.J.A., Vandergoes, M., Denton, G.H., Kaplan, M.R. et al. (2010) In situ cosmogenic 10Be production-rate calibration from the Southern Alps, New Zealand. *Quaternary Geochronology*, 5(4), 392–409. Available at: https://doi.org/10.1016/j.quageo.2009.12.001

Quik, C., Palstra, S.W.L., van Beek, R., van der Velde, Y., Candel, J.H.J., van der Linden, M. et al. (2022) Dating basal peat: The geochronology of peat initiation revisited. *Quaternary Geochronology*, 72(November 2021), 101278. Available at: https://doi.org/10.1016/j.quageo.2022.101278

Railsback, L.B., Gibbard, P.L., Head, M.J., Voarintsoa, N.R.G. & Toucanne, S. (2015) An optimized scheme of lettered marine isotope substages for the last 1.0 million years, and the climatostratigraphic nature of isotope stages and substages. *Quaternary Science Reviews*, 111, 94–106. Available at: https://doi.org/10.1016/j.quascirev.2015.01.012

Rudolph, E.M., Hedding, D.W., de Bruyn, P.J.N. & Nel, W. (2022) An open access geospatial database for the sub-Antarctic Prince Edward Islands. *South African Journal of Science*, 118(9/10), 12302.

Rudolph, E.M., Hedding, D.W., Fabel, D., Hodgson, D.A., Gheorghiu, D.M., Shanks, R. et al. (2020) Early glacial maximum and deglaciation at sub-Antarctic Marion Island from cosmogenic 36Cl exposure dating. *Quaternary Science Reviews*, 231, 106208.

Rudolph, E.M., Hedding, D.W., Hodgson, D.A., Fabel, D., Gheorghiu, D.M., Shanks, R. et al. (2024) A glacial chronology for sub-Antarctic Marion Island from MIS 2 and MIS 3. *Quaternary Science Reviews*, 325, 108485.

Rudolph, E.M., Hedding, D.W. & Nel, W. (2021) The surface geology of the Prince Edward Islands: refined spatial data and call for geoconservation. *South African Journal of Geology*, 124(3), 627–638. Available at: https://doi.org/10.25131/sajg.124.0014

Schaefer, J.M., Putnam, A.E., Denton, G.H., Kaplan, M.R., Birkel, S., Doughty, A.M. et al. (2015) The Southern Glacial Maximum 65,000 years ago and its Unfinished Termination. *Quaternary Science Reviews*, 114, 52–60. Available at: https://doi.org/10.1016/j.quascirev.2015.02.009

Schalke, H. & van Zinderen Bakker Sr., E. (1971) History of Vegetation. In: van Zinderen Bakker, Sr., E., Winterbottom, J.M. & Dyer, R., (Eds.) *Marion and Prince Edward Islands: report on the South African biological and geological research expedition 1965-1966*. A.A. Balkema. pp. 89–97.

Scott, L. (1985) Palynological indications of the Quaternary vegetation history of Marion Island (Sub-Antarctic. *Journal of Biogeography*, 12(5), 413–431. Available at: https://doi.org/10.2307/2844951

Scott, L. & Van Zinderen Barker, E.M. (1985) Exotic pollen and long-distance wind dispersal at a sub-Antarctic Island. *Grana*, 24(1), 45–54. Available at: https://doi.org/10.1080/00173138509427422

Selkirk, D.R., Selkirk, P.M., Bergstrom, D.M. & Adamson, D.A. (1988) Ridge top peats and palaeolake deposits on Macquarie Island. *Proceedings of the Royal Society of Tasmania*, 122(1), 83–90.

Shulmeister, J., Thackray, G.D., Rittenour, T.M., Fink, D. & Patton, N.R. (2019) The timing and nature of the last glacial cycle in New Zealand. *Quaternary Science Reviews*, 206, 1–20. Available at: https://doi.org/10.1016/j.quascirev.2018.12.020

Stuiver, M. & Reimer, P.J. (1993) Extended14C Data Base and Revised CALIB 3.014C Age Calibration Program. *Radiocarbon*, 35, 215–230.

Smith, R.I.L. (1981) Types of peat and peat-forming vegetation on South Georgia. *British Antarctic Survey Bulletin*, 53, 119–139.

Van der Putten, N., Hébrard, J.P., Verbruggen, C., Van de Vijver, B., Disnar, J.R., Spassov, S. et al. (2008) An integrated palaeo environmental investigation of a 6200 year old peat sequence from Ile de la Possession, Iles Crozet, sub-Antarctica. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 270, 179–185.

Van der Putten, N. & Verbruggen, C. (2005) The onset of deglaciation of Cumberland Bay and Stromness Bay, South Georgia. *Antarctic Science*, 17(1), 29–32.

Van der Putten, N., Verbruggen, C., Alexanderson, H., Björck, S. & Van de Vijver, B. (2013) Postglacial sedimentary and geomorphological evolution of a small sub-Antarctic fjord landscape, Stromness Bay, South Georgia. *Antarctic Science*, 25(03), 409–419.

Van der Putten, N., Verbruggen, C., Ochyra, R., Spassov, S., de Beaulieu, J.-L., Dapper, M.D. et al. (2009) Peat bank growth, Holocene palaeoecology and climate history of South Georgia (sub-Antarctica), based on a botanical macrofossil record. *Quaternary Science Reviews*, 28, 65–79.

Van der Putten, N., Stieperaere, H., Verbruggen, C. & Ochyra, R. (2004) Holocene palaeoecology and climate history of South Georgia (sub-Antarctic) based on a macrofossil record of bryophytes and seeds. *The Holocene*, 14(3), 382–392.

Van der Putten, N., Mauquoy, D., Verbruggen, C. & Björck, S. (2012) Subantarctic peatlands and their potential as palaeoenvironmental and palaeoclimatic archives. *Quaternary International*, 268, 65–76. Available at: https://doi.org/10.1016/j.quaint.2011.07.032

Van der Putten, N., Verbruggen, C., Ochyra, R., Verleyen, E. & Frenot, Y. (2010) Subantarctic flowering plants: Pre-glacial survivors or post-glacial immigrants? *Journal of Biogeography*, 37(3), 582–592. Available at: https://doi.org/10.1111/j.1365-2699.2009.02217.x

Verwoerd, W.J. (1971) Geology. In: Van Zinderen Bakker, E., Sr., Winterbottom, J.M. & Dyer, R., (Eds.) *Marion and Prince Edward Islands: report on the South African biological and geological research expedition 1965-1966*. A.A. Balkema. pp. 40–62.

Whittle, A., Amesbury, M.J., Charman, D.J., Hodgson, D.A., Perren, B.B., Roberts, S.J. et al. (2019) Salt-Enrichment Impact on Biomass Production in a Natural Population of Peatland Dwelling Arcellinida and Euglyphida (Testate Amoebae). *Microbial Ecology*, 78(2), 534–538. Available at: https://doi.org/10.1007/s00248-018-1296-8

Yeloff, D., Mauquoy, D., Barber, K., Way, S., van Geel, B. & Turney, C.S.M. (2007) Volcanic Ash Deposition and Long-Term Vegetation Change on Subantarctic Marion Island. *Arctic, Antarctic, and Alpine Research*, 39(3), 500–511.

Young, S.B. & Schofield, E.K. (1973) Pollen evidence for Late Quaternary Climate Changes on Kerguelen Islands. *Nature*, 245, 311–312.