

RADIOCARBON RESERVOIR AGES FROM FRESHWATER LAKES, SOUTH GEORGIA, SUB-ANTARCTIC: MODERN ANALOGUES FROM PARTICULATE ORGANIC MATTER AND SURFACE SEDIMENTS

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ABSTRACT. Lake sediments have the potential to preserve proxy records of past climate change. Organic material suitable for radiocarbon dating often provides age control of such proxy records. Six shallow freshwater lakes on the sub-Antarctic island of South Georgia were investigated for carbon reservoir effects that may influence age-depth profiles from lake sediment records in this important region. Paired samples of particulate organic matter (POM) from the water column and surface sediment (bulk organic carbon) were analyzed by accelerator mass spectrometry ¹⁴C. POM in 4 lakes was found to be in equilibrium with the atmosphere (~107% modern), whereas 2 lakes showed significant depletion of ¹⁴C. In each lake, the surface sediment ages were older than the paired POM age. Surface sediment ages showed a much greater range of ages compared to the equivalent POM ages, even for lakes located in close proximity. We conclude that sediment disturbance during coring, bioturbation, and periodic resuspension of sediments are likely factors causing the difference in the apparent age of surface sediments.

INTRODUCTION

Radiocarbon dating is a useful tool for providing a chronological framework for Late Pleistocene–Holocene paleoenvironmental studies. However, the application of ¹⁴C dating to Antarctic sediments is complicated by the difficulty of establishing the temporal and spatial variability of the carbon reservoir effect in that region. Gordon and Harkness (1992) produced an invaluable review and summary of Antarctic marine reservoir corrections, but as yet, no equivalent review exists for Antarctic freshwater environments. Many studies of sediments from freshwater lakes in Antarctica have yielded older than expected ¹⁴C ages (Zale and Karlén 1989; Björck et al. 1991a; Ingólfsson et al. 1992; Hjort et al. 1997; Doran et al. 1999; Takahashi et al. 1999; Hall and Henderson 2001). Explanations for the “old” ages depend on sample type and lake location, although the erroneous ages are most commonly attributed to the input of ¹⁴C-depleted glacial meltwater, contamination by marine water or marine sediment, restricted gaseous exchange due to ice cover, and disturbance of sediments by ice. Other factors that may influence the apparent age of core top sediments are mixing of sediment due to bioturbation, resuspension of sediments by wind-driven circulation, and possible loss of surface material during core recovery.

None of the previous investigations of lake sediments from South Georgia produced ¹⁴C ages for lake water, microbial mats, water-borne particulate organic matter (POM), or surface sediments. Ages from core-top sediments were not reported due to disturbance of the poorly consolidated upper sediment during core recovery or due to insufficient carbon for radiometric dating (Birnle 1990; Rosqvist et al. 1999; Rosqvist and Schuber 2003). The aim of our study is, therefore, to provide an estimate of the potential local carbon reservoir effect influencing age determinations on lake sediments from South Georgia.

Here, we report contemporary ¹⁴C ages from POM and surface sediments from 6 freshwater lakes on South Georgia ahead of a more detailed chronology and multi-disciplinary paleoenvironmental

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investigation of sediment cores recovered from those lakes. All samples were collected in the austral summer 2002–2003.

The sub-Antarctic island of South Georgia is ideally situated to investigate the chronology of climate change as it lies between the current maximum extent of winter sea ice and the Antarctic Convergence Zone, where warm temperate and cold Antarctic waters meet (Figure 1). Climatically induced changes in the position of these boundaries profoundly impact the environment and are recorded in the sediment by proxy signals (e.g. diatom and pollen assemblage, oxygen isotopes of biogenic silica, carbon and nitrogen isotope ratios of the organic material, and physical parameters, such as grey-scale density, grain size, and magnetic susceptibility). Recent paleolimnological evidence from South Georgia indicates that substantial parts of the island were ice-free by 18,600 calendar BP (Rosqvist et al. 1999), strongly suggesting that deglaciation commenced there much earlier than had been previously thought. Many paleoenvironmental records from other Antarctic and sub-Antarctic islands do not extend beyond the Holocene (e.g. Wasell and Håkansson 1992; Björck et al. 1991a, 1991b, 1996; Jones et al. 2000), which emphasizes the importance of South Georgia in providing long terrestrial paleoclimatic records for the Antarctic region.

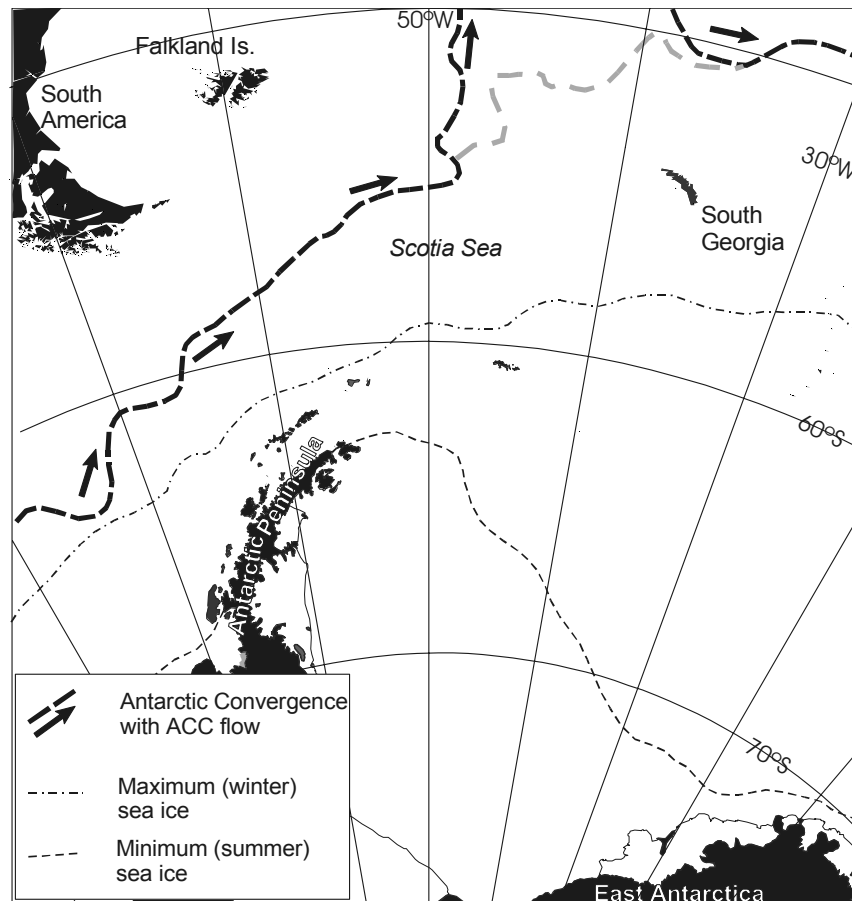


Figure 1 South Atlantic sector of the Southern Ocean showing current positions of the Antarctic Convergence and sea-ice limits. Migrations of these boundaries in response to climatic changes profoundly affect the environment and glacier extent on sub-Antarctic islands.

Site Locations

Six freshwater lakes in a range of geographical and topographical settings on the relatively ice-free eastern side of the island were sampled as part of a sediment coring program which aims to investigate the timing and spatial continuity of the glacier retreat after the Last Glacial Maximum (LGM) and the paleoenvironmental history of South Georgia since the LGM (Figure 2). All lakes are small with surface areas between 3000 m² and 60,000 m² and a maximum depth of 6.0 m. The presence of overflow channels and low embankments around one or more sides of each lake means that the lakes were close to, or at, their maximum depth at the time of sample collection. In situ roots of terrestrial plants were not observed in recovered sediment cores, indicating that the lakes have not been prone to prolonged desiccation. The lakes are ice-covered for 4–5 months per year but thoroughly mixed when ice-free. Restricted gaseous exchange is not thought to be a major problem for causing ¹⁴CO₂ disequilibrium. Salinity, temperature, and pH profiles indicate that at the time of sampling, all of the lakes were thoroughly mixed (S Davies, unpublished data). Only 1 lake, Block Lake (BLC), is fed by glacial meltwater and receives substantial inputs of mineral material. The steep gradient and length (~1.5 km) of the meltwater stream flowing into Block Lake is sufficient to allow thorough mixing of the water and ¹⁴CO₂ equilibration with the atmosphere (Stuiver et al. 1981). Because all of the POM samples consist of primary or secondary productivity, we expected ¹⁴C concentrations close to modern atmospheric ¹⁴CO₂ levels.

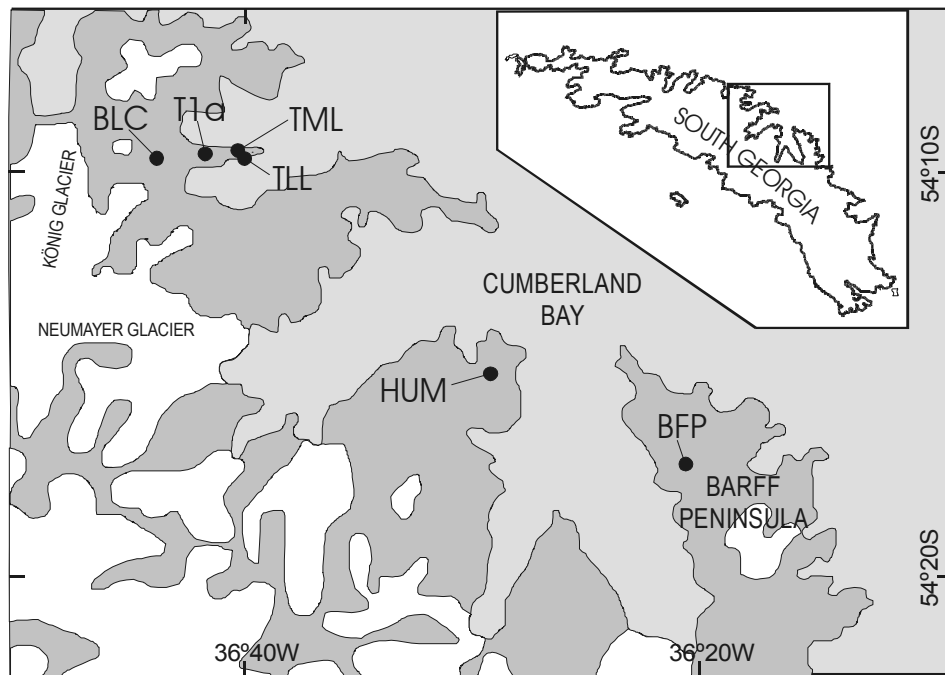


Figure 2 Map showing the location of the 6 freshwater lakes sampled for this study. There is no discernible spatial trend in the ages of either the POM or surface sediments in these lakes.

Most lake names presented are unofficial names and the following codes have been used for brevity: Tønsberg Lake T1 (T1a), Tønsberg Middle Lake (TML), Tønsberg Lower Lake (TLL), Block Lake (BLC), Barff Peninsula Lake (BFP), Humic Lake (HUM).

Sample Collection

The POM was collected from the water column by trawling with a hand-held 30- μm mesh plankton net. Most of the organic material collected was zooplankton, with lesser amounts of phytoplankton, aquatic insects, and insect larvae.

Samples of the uppermost 1 cm of sediment were sampled to compare with the ages of core-top sediment (which will be analyzed in the near future). The poorly consolidated nature of the sediment leads to suspicions that some core-top material might be lost during core recovery and direct comparison between surface sediment and core-top ages will allow the amount of sediment lost to be quantified. A plastic scoop on a 1.5-m pole was used to collect the surface sediment. Direct observation of the sampling operation in clear water ensured that only the topmost 1 cm of sediment was sampled. One lake (TML) was too deep for this method and a core-top sample from a “mini Kullenberg corer” was dated instead.

Particulate organic matter samples were acid washed in 1M HCl for 2 hr at 80 °C, surface sediment samples were acid washed in 2M HCl for 2 hr at 80 °C. All samples were rinsed free from mineral acid with de-ionized water, dried, and homogenized. The total organic carbon in a known weight of pretreated sample was recovered as CO₂ by heating with CuO in a sealed quartz tube. The CO₂ was converted to graphite by stepped Fe/Zn reduction. Sample pretreatment was completed at the Natural Environment Research Council Radiocarbon Laboratory, East Kilbride, UK. Graphite targets were analyzed at the Scottish Universities Environmental Research Centre (SUERC) accelerator mass spectrometry facility, East Kilbride, UK.

RESULTS AND DISCUSSION

Particulate Organic Matter

Four of the 6 POM samples (TML, TLL, BFP, HUM) show ¹⁴C enrichment of >100% modern (106.71–109.04 absolute percent modern carbon [pMC]; Table 1). The ¹⁴C enrichment values for these 4 lakes lie close to a current (2002–2003) atmospheric ¹⁴C concentration of ~107 pMC, extrapolated from the Northern Hemisphere atmospheric ¹⁴CO₂ trend of Levin and Kromer (1997). This indicates that the dissolved ¹⁴CO₂ in these lakes is in equilibrium with the atmosphere and there is no carbon reservoir effect influencing the age of the autochthonous sediments in these 4 lakes.

Two lakes (T1a and BLC) produced POM ¹⁴C values <100 pMC, indicating that the lake water is not in equilibrium with the atmosphere. In order to acquire a conventional ¹⁴C age, the POM must be diluted with enough “old” carbon to swamp the enriched atmospheric ¹⁴CO₂ signal. With the limited data currently available, it is not possible to definitively calculate the magnitude of the reservoir age for these lakes. However, based on the POM pMC values of 96.60 ± 0.47 (T1a) and 93.76 ± 36 (BLC), we estimate the age offset to be approximately ~850 and ~1100 ¹⁴C yr too old, respectively. It is not known at this stage what is producing these age offsets, nor whether the offset has remained constant over time. Hardwater error has been discounted, as the Cumberland Bay region comprises mainly quartzose greywackes, volcanic greywackes, slates, and igneous intrusions in which calcite is absent or present at very low quantities (Skidmore 1972). Contamination by marine water can also be ruled out as the lakes are fresh, conductivity in each is <100 $\mu\text{S cm}^{-1}$ (S Davies, unpublished data), and analyses of $\delta^{18}\text{O}$ and δD of the lake and through flow water indicate the lakes are replenished by local precipitation, and isotopic enrichment due to evaporation is insignificant (Rosqvist et al. 1999; unpublished data). Relict ¹⁴CO₂ in glacial meltwater has been discounted for the reasons outlined above. At this stage, not enough is known about the hydrology of South Georgia to be able

Table 1 ¹⁴C concentrations and conventional ¹⁴C ages for POM and surface sediment in 6 freshwater lakes, South Georgia, sub-Antarctic.

Publication Code	Lake code	Absolute % modern ± 1 σ	Conventional ¹⁴ C age (BP ± 1 σ)	δ ¹³ C _{PDB} ‰ ± 0.1 σ	Carbon content (% by wt)
Particulate Organic Matter					
SUERC-592	T1a	96.60 ± 0.47	226 ± 39	-30.1	27.3
SUERC-593	TML	109.05 ± 0.49	> modern	-27.1	65.2
SUERC-594	TLL	106.64 ± 0.33	> modern	-28.4	59.2
SUERC-595	BLC	93.76 ± 0.36	466 ± 30	-23.7	29.4
SUERC-596	BFP	108.30 ± 0.38	> modern	-25.7	21.6
SUERC-597	HUM	107.66 ± 0.40	> modern	-23.7	54.0
Surface Sediment					
SUERC-598	T1a	85.62 ± 0.27	1196 ± 26	-22.5	14.4
SUERC-603	TML	83.42 ± 0.52	1405 ± 50 ^a	-25.5	28.2
SUERC-600	TLL	105.37 ± 0.70	> modern	-25.7	34.4
—	BLC ^b	—	—	—	—
SUERC-604	BFP	94.34 ± 0.84	417 ± 71	-20.6	13.3
SUERC-605	HUM	96.63 ± 0.50	224 ± 41	-27.7	39.2

^aCore top sample.
^bNo data available.

to establish whether groundwater might play a part in introducing ¹⁴C-depleted water in to the lakes. One possible source of old ¹⁴C in the POM samples is resuspended sediment. We consider this to be the most likely source given the poorly consolidated nature of the sediments and the shallowness of these lakes.

Surface Sediments

In all lakes, the pMC is greater in the POM than in the surface sediment. However, there was considerable variation in the surface sediment ages between lakes. The 2 lakes in closest proximity to each other (TML and TLL) showed the greatest difference in surface age. One possible cause of this discrepancy might be the need to use a core-top sample from TML rather than directly sampled surface sediment. The sediments in all the lakes are poorly consolidated and the deployment of the trigger operated “mini Kullenberg corer” in TML might have been sufficient to dislodge the uppermost sediment, leaving an incomplete sediment record. Further investigation of down-core ¹⁴C and ²¹⁰Pb profiles will help to clarify this issue. The apparent older surface sediment ages in the other lakes is most likely due to a combination of bioturbation and periodic resuspension and settling of sediment.

CONCLUSIONS

For the majority of lakes studied, POM in the water column is in equilibrium with the atmosphere, indicating that no carbon reservoir effect influences the age of these autochthonous sediments. However, 2 lakes (T1a and BLC) yield reservoir ages. Therefore, the previous chronology produced for sediments from Tønsberg Lake T1 (Rosqvist et al. 1999) might have over estimated the age of deglaciation by about 850 ¹⁴C yr, assuming that present-day conditions also existed in the past, as no carbon reservoir/dilution effect was taken into account when producing the age model. Likewise, the age model used in the Block Lake record showing millennial-scale climate change (Rosqvist and Schuber 2003) might also need correction by about 1100 ¹⁴C yr.

We have shown that surface sediment ages are highly variable, even from lakes in close proximity. Therefore, studies of modern analogues from POM and surface sediments are necessary before presenting climate change chronologies based on ^{14}C results. The choice of coring method is critical to obtain an undisturbed sediment-water interface of unconsolidated surface sediments.

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REFERENCES

- Birnie J. 1990. Holocene environmental change in South Georgia: evidence from lake sediments. *Journal of Quaternary Science* 5:171–87.
- Björck S, Håkansson H, Zale R, Karlén W, Jönsson BL. 1991b. A Late Holocene lake sediment sequence from Livingston Island, South Shetland Islands, with palaeoclimatic implications. *Antarctic Science* 3(1):61–72.
- Björck S, Hjort C, Ingólfsson Ó, Skog G. 1991a. Radiocarbon dates from the Antarctic Peninsula region—problems and potential. *Quaternary Proceedings* 1:55–65.
- Björck S, Olsson S, Ellis-Evans C, Håkansson H, Humlum O, de Lirio JM. 1996. Late Holocene palaeoclimatic records from lake sediments on James Ross Island, Antarctica. *Palaeogeography, Palaeoclimatology, Palaeoecology* 121:195–220.
- Doran PT, Berger GW, Lyons WB, Wharton Jr RA, Davisson ML, Southon J, Dibb JE. 1999. Dating Quaternary lacustrine sediments in the McMurdo Dry Valleys, Antarctica. *Palaeogeography, Palaeoclimatology, Palaeoecology* 147:223–39.
- Gordon JE, Harkness DD. 1992. Magnitude and geographic variation of the radiocarbon content in Antarctic marine life: implications for reservoir corrections in radiocarbon dating. *Quaternary Science Reviews* 11:697–708.
- Hall BL, Henderson GM. 2001. Use of uranium-thorium dating to determine past ^{14}C reservoir effects in lakes: examples from Antarctica. *Earth and Planetary Science Letters* 193:565–77.
- Hjort C, Ingólfsson Ó, Möller P, Lirio JM. 1997. Holocene glacial history sea-level changes on James Ross Island, Antarctic Peninsula. *Journal of Quaternary Science* 12(4):259–73.
- Ingólfsson Ó, Hjort C, Björck S, Smith RIL. 1992. Late Pleistocene and Holocene glacial history of James Ross Island, Antarctic Peninsula. *Boreas* 21:209–22.
- Jones VJ, Hodgson DA, Chepstow-Lusty A. 2000. Palaeolimnological evidence for marked Holocene environmental changes on Signy Island, Antarctica. *The Holocene* 10(2):43–60.
- Levin I, Kromer B. 1997. Twenty years of atmospheric $^{14}\text{CO}_2$ observations at Schauinsland Station, Germany. *Radiocarbon* 39(2):205–18.
- Rosqvist GC, Rietti-Shati M, Shemesh A. 1999. Late glacial to middle Holocene climatic record of lacustrine biogenic silica isotopes from a Southern Ocean island. *Geology* 27:967–70.
- Rosqvist G, Schuber P. 2003. Millennial-scale climate changes on South Georgia, Southern Ocean. *Quaternary Research* 59(3):470–75.
- Skidmore MJ. 1972. The geology of South Georgia: 3. Prince Olav Harbour and Stromness Bay areas. *British Antarctic Survey Scientific Reports* 73:50.
- Stuiver M, Denton GH, Hughes TJ, Fastook JL. 1981. History of the marine ice sheet in west Antarctica during the last glaciation, a working hypothesis. In: Denton GH, Hughes TH, editors. *The Last Great Ice Sheets*. New York: Wiley-Interscience. p 319–436.
- Takahashi HA, Wada H, Nakamura T, Miura H. 1999. ^{14}C anomaly of freshwater algae in Antarctic coastal ponds and lakes. *Polar Science* 12:248–57.
- Wasell A, Håkansson H. 1992. Diatom stratigraphy in a lake on Horseshoe Island, Antarctica: a marine-brackish-freshwater transition with comments on the systematics and ecology of the most common diatoms. *Diatom Research* 7:157–94.
- Zale R, Karlén W. 1989. Lake sediment cores from the Antarctic Peninsula and surrounding islands. *Geografiska Annaler* 71(A):211–20.