the recently erected powershack. At the very least it should redirect the engine exhaust to the north-eastern wall of the shack (the side away from the screen) and thoroughly examine its influence on temperatures being recorded in the screen.

The South African Weather Bureau supplied the temperature data for the Island from 1949 to 1991. The temperature measurements for the comparison of the two screens were made by Clive McMahon, meteorologist of the 1991/92 expedition team to the Island. The work reported on here forms part of a project on the biological effects of climate change at Marion and Prince Edward Islands and was sponsored by the South African Department of Environment Affairs.

V.R. SMITH

*Department of Botany and Genetics,*
*University of the Orange Free State,*
*Bloemfontein, 9301 South Africa.*

Received 6 May; accepted 11 August 1992.

1. Adamson D.A., Whetton P. and Selkirk P.M. (1988). An analysis of air temperature records for Macquarie Island: decadal warming, ENSO cooling and Southern Hemisphere circulation patterns. *Pap. Proc. R. Soc. Tasm.* **122**, 107–112.
2. Allison F. and Keague P.L. (1986). Recent changes in the glaciers of Heard Island. *Polar Rec.* **23**, 255–271.
3. Jacka T.H., Christou L. and Cook B.J. (1984). Data bank of mean monthly and annual surface temperatures for Antarctica, the Southern Ocean and South Pacific Ocean. *A.N.A.R.E. Res. Notes* **22**, 1–97.
4. Jones P.D. and Wigley T.M.L. (1990). Global warming trends. *Scient. Am.* 66–73.
5. Jones P.D., Raper S.C.B. and Wigley T.M.L. (1986). Southern Hemisphere surface air temperature variations: 1851–1984. *J. Clim. Appl. Met.* **25**, 1213–1230.
6. Lewis Smith R.I. (1990). Signy Island as a paradigm of biological and environmental change in Antarctica terrestrial ecosystems. In *Ecological Change and the Conservation of Antarctica Ecosystems*, eds. E. Hengel and K.R. Kerry, pp. 32–50. Springer-Verlag, Heidelberg.
7. Raper S.C.B., Wigley T.M.L., Mayes P.R., Jones P.D. and Salinger M.J. (1984). Variations in surface air temperatures, Part 3: The Antarctic, 1957–82. *Mon. Weath. Rev.* **112**, 1341–1353.
8. Salinger M.J. and Gunn J.M. (1975). Recent climatic warming around New Zealand. *Nature* **256**, 396–398.
9. Schulze B.R. (1971). The climate of Marion Island. In *Marion and Prince Edward Islands*, eds. E.M. van Zinderen Bakker, J.M. Winterbottom and R.A. Dyer, pp. 16–31. A.A. Balkema, Cape Town.
10. Smith V.R. and Steenkamp M. (1990). Climatic change and its ecological implications at a sub-Antarctic Island. *Oecologia* **85**, 14–24.

# Radiocarbon dates of snow petrel regurgitations can reveal exposure periods for nunataks in Antarctica

Nunataks are exposed areas of rock protruding through the polar ice sheets. Away from the coastline, life in Antarctica is largely restricted to nunataks and other ice-free oases.[1] Nunataks support simple biotas, consisting predominantly of bacteria, fungi, lichens, mosses and such invertebrates as tardigrades, mites and collembolans. In addition, some nunataks support breeding colonies of petrels (Procellariiformes). Conceivably, the nutrient input of these birds, in the form of guano, carcasses and regurgitated proventricular oil, is of great importance to the nunatak ecosystem as a whole.[1,2] However, nunatak ecosystems have been relatively little studied to date.

Many petrels regurgitate proventricular oil as a means of defence against potential predators, such as skuas (*Catharacta* spp.). Microbial activity is reduced at nunataks, because of low ambient temperatures, allowing these proventricular oils to accumulate. Deposits of proventricular oil, mixed with some guano,[3] are known as 'mumiyo' after similar-looking deposits found in the mountains of central Asia.[4,5] Antarctic mumiyo generally has a stratified internal structure and sometimes occurs as large accumulations of several kilogrammes.[3] This provides an opportunity to use radiocarbon dating techniques to estimate the length of occupation of nunataks by petrel breeding colonies.[3] Samples of mumiyo and guano from a few sites in Antarctica have previously been radiocarbon dated.[3,6,7] If occupation by breeding seabirds is an important preliminary stage in the colonization of nunataks by some plant and invertebrate species, knowing the length of time a bird colony has been established should be of great value in studies on the colonization of nunataks by floral and faunal elements.

## Methods

During January 1988, two large pieces of mumiyo were collected from the vicinity of snow petrel *Pagodroma nivea* nests at the Robertskollen nunatak group (71°27′S; 3°15′W), northern Ahlmannryggen, Dronning Maud Land, Antarctica (Fig. 1).[8] The first was collected on 'Cairn Peak', some 20 m above the current ice-line. This piece was roughly hemispherical in shape with a radius of 100 mm and a mass of 3.0 kg. The second piece was a 150-mm-deep block with a mass of 1.6 kg, collected from the summit of 'Tumble Ice' nunatak, 40 m above the current ice-line. Following collection, the mumiyo pieces were sealed in plastic bags and kept deep-frozen for later analysis.

Antarctic krill (*Euphausia superba*) is thought to be the major prey of snow petrels off Dronning Maud Land (e.g. Griffiths[9]). Therefore, a specimen of Antarctic krill was collected from the Southern Ocean at 69°S, 2°W and used to obtain a radiocarbon date for present-day organic material within the Southern Ocean food web, from the vicinity of the Robertskollen snow petrel colony.

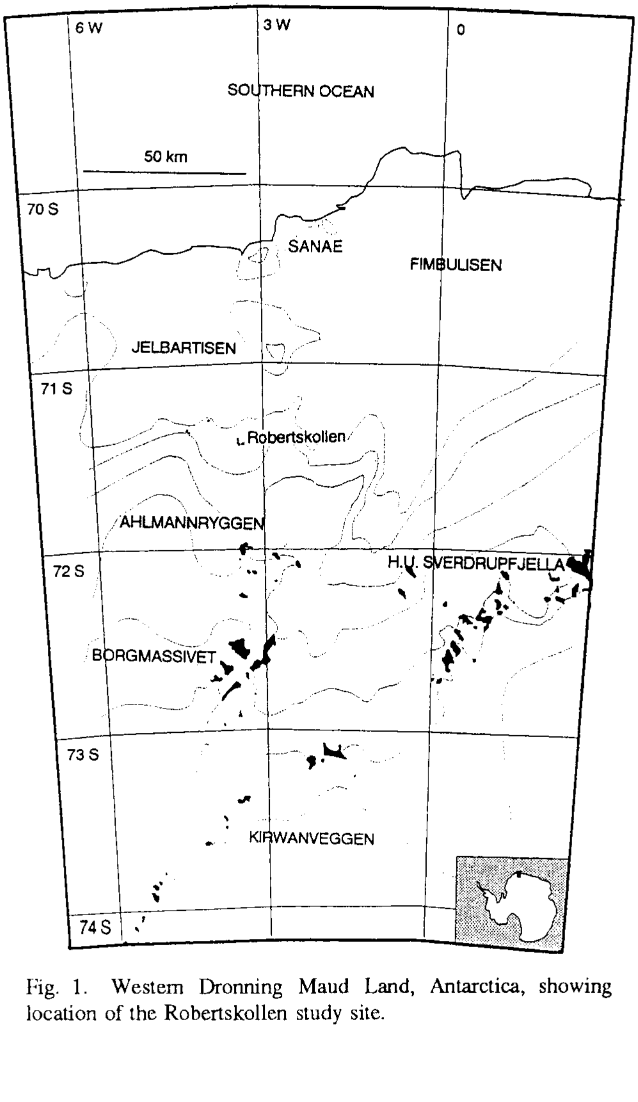


Fig. 1. Western Dronning Maud Land, Antarctica, showing location of the Robertskollen study site.

In the laboratory, the mumiyo pieces were sectioned and small samples of about 10 g extracted, from different stratified layers, along a transect between the base and the outer layer of each mumiyo piece. The surface layers of the mumiyo pieces were not sampled, to avoid the potential problem of surface contamination. The isotope analyses were done by one of us (J.V.C.) at the CSIR, Pretoria. All samples were treated with hot, dilute hydrochloric acid to remove the more mobile organic matter. Radiocarbon dates were calculated in conventional radiocarbon years before present (BP) based on a $^{14}C$ half-life of 5 568 years.

The ratio between the two stable isotopes of carbon, $^{13}C$ and $^{12}C$, in organic material, relative to that in a reference sample of Peedee Belemnite, is widely used as a standard measure, allowing comparison between samples (e.g. Harkness[10]). This value is generally expressed as $\delta^{13}C$, measured in parts per thousand. It is now standard practice to determine the $\delta^{13}C$ for all samples that are radiocarbon dated to determine the degree of fractionation that has occurred, and allow for correction of changes in relative $^{14}C$ abundance caused by this factor (e.g. Harkness[10] and Hiller *et al.*[3]). The $\delta^{13}C$ values of all samples were determined to estimate the degree of isotope fractionation to which they had been exposed.

## Results

The mean $\delta^{13}C$ value for the mumiyo samples was −30.6 ± 0.4‰ ($N$ = 10) (Table 1) compared to −28.4‰ for the Antarctic krill specimen. Radiocarbon-derived dates of the mumiyo samples indicate that the oldest date of occupation of Robertskollen by snow petrels was more than 7 000 years ago (Table 1). The conventional radiocarbon dates shown in Table 1 have been corrected for fractionation of the carbon isotopes. The modern krill sample analysed in this study had an apparent age of 830 ± 45 years BP.

The radiocarbon dates of the two mumiyo pieces show a general decrease in age from the base to the top (Fig. 2). Accumulation rates of mumiyo were very low. The Cairn Peak sample had 100 mm laid down over approximately 1 000 years (or 3 g $yr^{-1}$) and the average accumulation rate for the Tumble Ice sample was only 21 mm per 1 000 years (or 0.2 g $yr^{-1}$) (Table 1). However, there may have been discontinuous use of the Tumble Ice breeding site, causing a discontinuous accumulation of mumiyo (Fig. 2).

## Discussion

Due to isotopic effects causing fractionation, $\delta^{13}C$ values become less negative as carbon moves up the trophic levels.

Table 1. Radiocarbon-derived dates of subfossilized petrel proventricular oil regurgitations at Robertskollen.

| Sample no. | Sample depth (mm) | $\delta^{13}C$ (‰) | Conventional $^{14}C$ age (yr BP) | Corrected age (yr BP) |
|---|---|---|---|---|
| **Cairn Peak** | | | | |
| Pta-4791 | 2–3 | −30.2 | 1 690 ± 45 | 400 |
| Pta-4800 | 30 | −30.3 | 2 320 ± 50 | 1 000 |
| Pta-4832 | 60 | −30.0 | 2 610 ± 50 | 1 300 |
| Pta-4783 | 100 | −30.1 | 2 640 ± 60 | 1 300 |
| **Tumble Ice** | | | | |
| Pta-4795 | 1–2 | −30.7 | 1 540 ± 50 | 200 |
| Pta-4962 | 20 | −31.0 | 3 230 ± 60 | 1 900 |
| Pta-4957 | 50 | −31.0 | 3 760 ± 50 | 2 400 |
| Pta-4912 | 80 | −31.1 | 4 530 ± 60 | 3 200 |
| Pta-4907 | 125 | −30.9 | 7 910 ± 80 | 6 600 |
| Pta-4786 | 150 | −30.7 | 8 330 ± 70 | 7 000 |

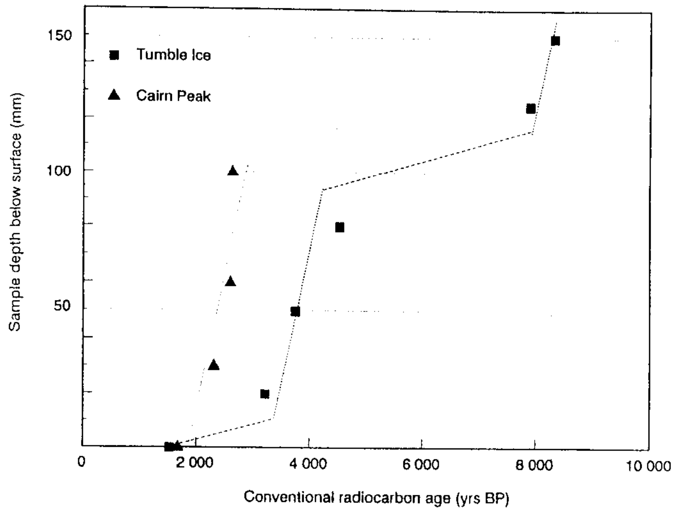


Fig. 2. Relationship between thickness of mumiyo and its radiocarbon age, showing possible discontinuous use of the Tumble Ice site.

Increases of 0.7 and 1.4‰ per trophic level have been measured in pelagic food chains.[11] Marine phytoplanktons generally exhibit $\delta^{13}C$ values of between −19 and −20‰.[11,12] However, $\delta^{13}C$ values of marine phytoplankton are directly related to water temperature,[13] although variation due to this influence is small. Furthermore, lipid fractions are $^{13}C$-depleted relative to other tissues,[6,14] and these facts may explain the very low $\delta^{13}C$ value (−28.4‰) exhibited by the lipid-rich Antarctic krill specimen analysed. Antarctic fishes analysed by Mizutani and Wada[15] were found to have a mean $\delta^{13}C$ of −26‰, the value expected for animals feeding predominantly on Antarctic krill or similar organisms. Tissue from animals feeding on these Antarctic fishes would have an expected $\delta^{13}C$ value in the order of −24.5‰.

The $\delta^{13}C$ values determined from the mumiyo samples at Robertskollen are in general agreement with $\delta^{13}C$ values determined for mumiyo, proventricular oil and tissue from snow petrels at Untersee Oasis (71°21′S; 13°28′E), Dronning Maud Land, reported by Hiller *et al.*[3] If snow petrels feed predominantly on Antarctic krill their body tissues would be expected to have $\delta^{13}C$ values of between −26 and −27‰, similar to those found for Antarctic fishes. In fact, snow petrel body tissue analysed by Hiller *et al.* exhibited a mean $\delta^{13}C$ value of −28‰.[3] Snow petrel mumiyo is even more negative at *ca.* −30‰ (Hiller *et al.*,[3] this study). This may be due to the fact that petrels concentrate the lipid fractions of their food in the form of proventricular oils,[16] making their diet $^{13}C$-depleted. Although fish is reported to be the most important prey of snow petrels from Adelie Land,[17,18] the $\delta^{13}C$ values determined for tissue and mumiyo of snow petrels from Dronning Maud Land (Hiller *et al.*,[3] this study) suggest that these birds are unlikely to have fed predominantly on fishes. However, until more $\delta^{13}C$ values are determined for fish species that are potential prey for snow petrels, this must remain a speculative conclusion.

There are several problems associated with determining radiocarbon dates, particularly for organic material from Antarctica.[10,19] The radiocarbon dates listed in Table 1 need to be adjusted for the apparent age of the surface seawater of the Southern Ocean. The exact number of years that needs to be subtracted from marine-related dates in order to obtain the true age is not well known. The krill specimen showed an apparent age of 830 years, but this value will have been influenced by post-bomb, $^{14}C$-enhanced, carbon uptake. Therefore, to obtain accurate ages for the mumiyo samples, a correction factor greater than 830 years should be subtracted from the conventional radiocarbon ages. Hiller *et al.* proposed a correction factor of 850 ± 300 years for the Antarctic nearshore oceanic region between 10°W and 40°E,[3] but this is probably too small. Stuiver *et al.* quote two measurements of marine specimens collected in 1912, which suggest a correction factor of 1 300 years.[20] The uncertainty in this value is probably in the region of ± 200 years. Due to fluctuations in the $^{14}C$ content of the atmosphere/ocean system, the correction factor to be applied is not constant but will vary over time by up to a few hundred years.

In the present context, the correction factor to be applied can be taken as 1 300 ± 200 years, indicating that the Tumble Ice nest was first occupied about 7 000 BP (Table 1). This conclusion is supported by the results of other studies of snow petrel breeding sites; on mumiyo from Untersee Oasis[3] and guano from Bunger Oasis (66°16′S; 100°45′E), Wilkes Land.[7] These results are not unexpected, because the start of the Holocene, some 10 000 years ago, was marked by relatively warm climatic conditions and glacial retreat. Only once ice had retreated sufficiently to expose a nunatak, would this become available as a breeding site for snow petrels. However, occupation of nunataks by breeding snow petrels may occur in cycles, coinciding with ice-level movements. Because ice cover is likely to obliterate all traces of occupation by snow petrels prior to the Holocene, it may be possible to obtain dates for the occupation of nunataks by breeding petrels only in the last 10 000 years.

The Tumble Ice sample was collected from a position some 20 m higher, above the current ice-line, than the Cairn Peak sample. Results indicate that the Tumble Ice mumiyo sample had been accumulating over 5 000 years before the Cairn Peak sample (Table 1). This may be attributed to the petrels' nesting lower down nunatak slopes as ice retreated.[3] Nest height above the ice-line is an important factor in the breeding success of snow petrels. Lower nests tend to become blocked by snow during storms, which leads to the death by starvation of the chick if the adults are not able to clear the nest entrance.[21]

The shape which mumiyo takes will depend on the topography of the ground at the nest entrance. If the ground is flat, the mumiyo deposits will be thin and flat, whereas if the regurgitations and defecations fall on a rock crevice, the mumiyo will form deeper deposits over the same period of time. Therefore, accumulation rates of mumiyo are expressed as mass accumulation as well as simply depth accumulation. Calculated accumulation rates for snow petrel mumiyo at Robertskollen are within the range found for mumiyo at Untersee Oasis. Hiller *et al.* calculated accumulation rates of between 9 and > 100 mm per 1 000 years at this site.[3] With the available data it is not possible to show conclusively that there was discontinuous occupation by snow petrels of the Tumble Ice breeding site.

Although there are several factors which are potential sources of error, radiocarbon dating of mumiyo from petrel colonies in the Antarctic can provide a relatively accurate measure of the length of time these colonies have been established since the last glacial period and, by inference, the length of time nunataks have been exposed. At present, radiocarbon dates are available for very few petrel breeding sites in Antarctica. Additional studies of this nature will be of potential biogeographical value and may provide information on ice-sheet dynamics. It is intended to undertake further radiocarbon dating of snow petrel breeding sites as part of the new South African Biological Antarctic Research Subprogramme (SABARSP), which commenced field work in Dronning Maud Land during the austral summer of 1991/92.[22]

We thank Dr P.R. Condy for his role in facilitating both the visit to Robertskollen and the radiocarbon dating. Financial and logistical support provided by the South African Committee for Antarctic Research and the South African Department of Environment Affairs is gratefully acknowledged.

P.G. RYAN, W.K. STEELE*, W.R. SIEGFRIED
and J.C. VOGEL[1]

**Percy FitzPatrick Institute,*
*University of Cape Town,*
*Rondebosch 7700, South Africa.*
*[1]Quaternary Dating Research Unit,*
*Ematek, CSIR, P.O. Box 395,*
*Pretoria 0001, South Africa.*

Received 12 November 1991; accepted 7 August 1992.


1. Smith R.I.L. (1985). Nutrient cycling in relation to biological activity in Antarctic and sub-Antarctic terrestrial and freshwater ecosystems. In *Antarctic Nutrient Cycles and Food Webs*, eds. W.R. Siegfried, P.R. Condy and R.M. Laws, pp. 138–155. Springer-Verlag, Berlin.
2. Ryan P.G. and Watkins B.P. (1989). The influence of physical factors and ornithogenic products on plant and arthropod abundance at an inland nunatak group in Antarctica. *Polar Biol.* **10**, 151–160.
3. Hiller A., Wand U., Kaempf H. and Stackebrandt W. (1988). Occupation of the Antarctic continent by petrels during the past 35 000 years: inferences from a carbon-14 study of stomach oil deposits. *Polar Biol.* **9**, 69–77.
4. Korotkevich E.S., Konovalov G.V. and Mikhailova T.A. (1967). Nachodki mumiyo v gorakh Antarktidy. *Inf. Byull. Sov. Antarkt. Eksped.* **66**, 58–63.
5. Winsnes T.S. (1969). What is 'mumiyo' from Antarctica? *Norsk Polatinst. Årbok* **1967**, 228.
6. Hiller A. and Wand U. (1984). Radiocarbon dating of breeding places of petrels in the Antarctic. *Zfi-Mitt.* **89**, 103–122.
7. Bolshiyonov D., Verkulich S., Klokov V., Makeev V. and Arslanov H. (1990). Radiocarbon dating of sediments from the Bunger Oasis (east Antarctica). In *Proceedings, 5th Working Meeting Isotopes in Nature*, Leipzig, September 1989, eds. U. Wand and G. Strauch, pp. 47–52. Leipzig, Zfi.
8. Ryan P.G., Watkins B.P., Lewis-Smith R.I., Dastych H., Eicker A., Foissner W., Heatwole H., Miller W.R. and Thompson G. (1989). Biological survey of Robertskollen, western Dronning Maud Land: area description and preliminary species lists. *S. Afr. J. Antarct. Res.* **19**, 10–20.
9. Griffiths A.M. (1983). Factors affecting the distribution of the Snow Petrel (*Pagodroma nivea*) and Antarctic Petrel (*Thalassoica antarctica*). *Ardea* **71**, 145–150.
10. Harkness D.D. (1979). Radiocarbon dates from Antarctica. *Br. Antarct. Surv. Bull.* **47**, 43–59.
11. Rau G.H., Mearns A.J., Young D.R., Olson R.J., Schafer H.A. and Kaplan I.R. (1983). Animal $^{13}C/^{12}C$ correlates with trophic level in pelagic food webs. *Ecology* **64**, 1314–1318.
12. Fontugne M.R. and Duplessy J.C. (1981). Organic carbon isotopic fractionation by marine phytoplankton in the temperature range –1 to 31°C. *Oceanologica Acta* **4**, 85–90.
13. Sackett W.M., Eckelmann W.R., Bender M.L. and Be A.W.H. (1965). Temperature dependence of carbon isotope composition in marine plankton and sediments. *Science* **148**, 235–237.
14. Peterson B.J. and Fry B. (1987). Stable isotopes in ecosystem studies. *A. Rev. Ecol. Syst.* **18**, 293–320.
15. Mizutani H. and Wada E. (1988). Nitrogen and carbon isotope ratios in seabird rookeries and their ecological implications. *Ecology* **69**, 340–349.
16. Warham J. (1976). The composition, energy content and function of the stomach oils of petrels (Order, Procellariiformes). *J. exp. Mar. Biol. Ecol.* **23**, 1–13.
17. Mougin J-L. (1968). Étude ecologique de quatre éspeces de petrels Antarctiques. *Oiseau* **38**, 1–51.
18. Ridoux V. and Offredo C. (1989). Tle diets of five summer breeding seabirds in Adelie Land, Antarctica. *Polar Biol.* **9**, 137–146.
19. Whitehouse I.E., Chinn T.J.H., von Hofle H.C. and McSaveney M.J. (1988). Radiocarbon contaminated penguin bones from Terra Nova Bay, Antarctica. *N.Z. Antarct. Rec.* **8** (3), 11–23.
20. Stuiver M., Pearson G.W. and Braziunas T. (1986). Radiocarbon age calibration of marine samples back to 9 000 cal yr BP. *Radiocarbon* **28**, 980–1021.
21. Brown D.A. (1966). Breeding biology of the Snow Petrel *Pagodroma nivea* (Forster). *A.N.A.R.E. Sci. Rep. Series B* **89**, 1–63.
22. Cooper J., Siegfried W.R., Ryan P.G., Crafford J.E. and Stock W.D. (1991). Effects of ornithogenic products on ecosystem structure and functioning: a new South African Biological Antarctic Research Subprogramme. *S. Afr. J. Sci.* **87**, 223–226.