RADIOCARBON DATES FROM ANTARCTICA

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ABSTRACT. The radiocarbon time-scale is based on what is now known to be an oversimplification of carbon geochemistry. A realistic interpretation of ^{14}C dates therefore demands an appreciation of those limitations which, although subject to continuing research, are as yet inherent in the conventional chronology. Parameters, which influence the radiometric age evaluation but which are at proven variance with past and present environmental conditions, are discussed with particular reference to ^{14}C ages measured for organic materials from Antarctica. A list of the ^{14}C ages measured in the course of several studies by British Antarctic Survey personnel is appended in *Radiocarbon* format.

THE award of the 1960 Nobel Prize for Chemistry to W. F. Libby, in recognition of his conception and development of radiocarbon dating, underlined the potential value of the method particularly in respect of the degree of accuracy achieved for materials of known age, the range of the time-scale and its apparent global application. During the 25 years which have elapsed since Libby published his first confirmatory dates, many thousands of natural ^{14}C measurements have been reported from a world-wide and ever increasing network of specialized laboratories, and the radiocarbon time-scale is currently applied in most areas of the earth sciences which seek to establish and explain the sequences of environmental change which have occurred over the past 50 millenia. As might be expected, however, the development and acceptance of radiocarbon dating as the premier chronological method for the late Quaternary has been far from straightforward. Improvements in the analytical precision of the method together with its widening application tended, from time to time, to produce results which conflicted with those of alternative dating methods and/or pre-conceived archaeological chronologies. Such apparent discrepancies in the radiocarbon time-scale stimulated research into those geophysical/geochemical parameters likely to determine or influence the natural distribution of the carbon isotopes and it has now been proved beyond doubt that several assumptions fundamental to the conventional dating theory are less than strictly valid. Hence it must be accepted that conventional radiocarbon ages, as calculated and quoted in accordance with the format of the journal *Radiocarbon*, do not correspond exactly with the solar time-scale and their interpretation must be tempered by an appreciation of the limitations inherent in the dating method.

Since its inception in July 1971, the N.E.R.C. Radiocarbon Laboratory at the Scottish Universities Research and Reactor Centre has provided ^{14}C measurements in collaboration with several research programmes initiated by British Antarctic Survey personnel, and a comprehensive list of these data is appended. It would then seem pertinent to review at this time the current state of knowledge regarding the sources of deviation between radiocarbon and solar years and in particular the magnitude to which these may be reflected in the ^{14}C record of sample materials from Antarctica.

CONVENTIONAL THEORY

Radiocarbon dating is made possible by the assimilation of a small concentration of the radioactive isotope ^{14}C into the carbonaceous tissues of all living plants and animals. This naturally occurring ^{14}C is formed in the upper atmosphere by the interaction of cosmic ray induced neutrons with the nitrogen atoms in air, viz. $^{14}N+n \rightarrow {}^{14}C+p$. Once formed, the radioactive atoms are rapidly oxidized to $^{14}CO_2$ and thus introduced into the dynamic carbon cycle (Fig. 1), wherein the total inventory of ^{14}C is determined and maintained by the balance between cosmic ray production and subsequent radioactive decay. If the parameters which

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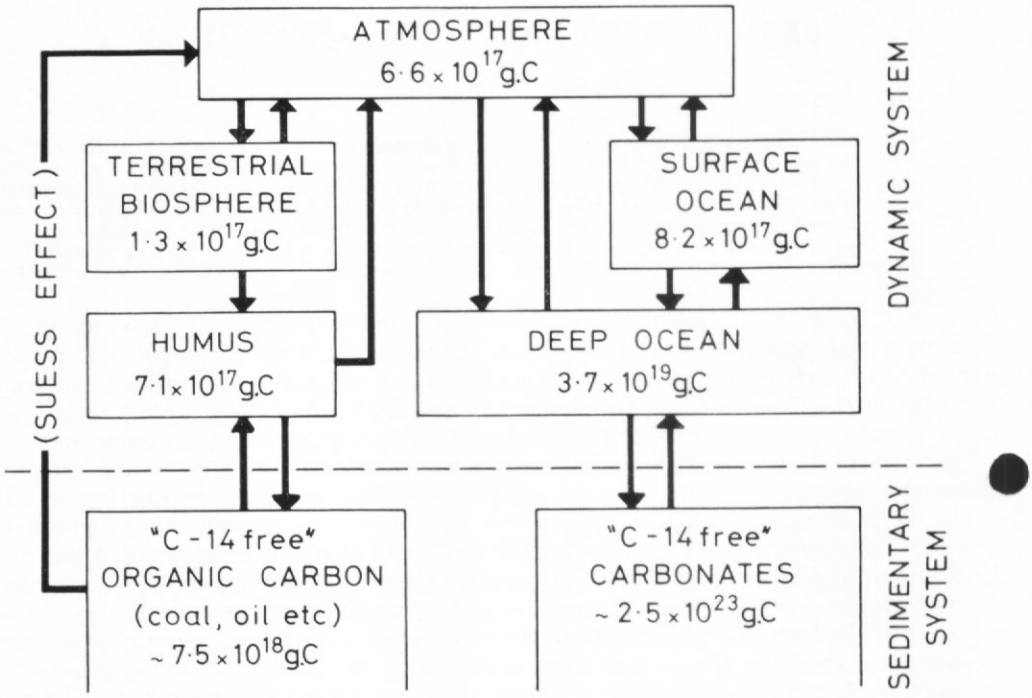

Fig. 1. Distribution of carbon in nature. The dynamic system need only be considered in ^{14}C dating, since the rate of natural exchange with sedimentary carbon is too slow to have a significant influence on the relative isotopic abundancies in living material, viz. $^{12}C : {}^{13}C : {}^{14}C = 1 : 10^{-2} : 10^{-12}$.

control the production and distribution of ^{14}C have remained constant throughout the time span of the chronology, then the major carbon reservoirs will have exhibited a constant concentration of the radioisotope. This situation of isotopic equilibrium would, of course, encompass all living organisms via the agencies of photosynthesis or feeding and respiration. At death, however, the assimilation of carbon ceases and the ratio of radioactive to stable carbon ($^{14}C/^{12}C$) in the detrital material proceeds to decrease exponentially in accordance with the *c.* 5,700 year half-life for ^{14}C. Thus a comparison of the residual $^{14}C/^{12}C$ in the sample (A) with that for recently grown material (A_o) should provide a measure of the time (t) elapsed since sample death via the relationship

$$A = A_o e^{-\lambda t},$$

where λ is the radioactive decay constant for ^{14}C, viz. $\log_e 2$/half-life.

Discussion

As mentioned above, Libby (1955) found good agreement, within the then limits of experimental error, between the known age of selected samples and their residual ^{14}C activity. Clearly, however, the precision of the chronology in absolute terms and its universal application are dependent on several questionable assumptions, viz.

i. That the half-life value for ^{14}C is determined accurately.
ii. That the specific activity of ^{14}C in the major carbon reservoirs has remained constant over the chronological span.
iii. That no geographical variations have existed in the specific activity of ^{14}C in contemporaneous living material.

iv. That isotopic fractionation effects are negligible in the natural exchange processes for carbon.

^{14}C Half-life

From Equation (1) it is apparent that the half-life value ascribed to the radioactive decay process ($^{14}C \rightarrow {}^{14}N + \beta$) defines in the first instance the relationship between radiocarbon and solar years. Libby used the value of 5,568 ± 30 years on the basis of its being the mean of the most precise determinations then available. More recent determinations (Hughes and Mann, 1964) suggest that the true value is some 3 per cent greater, viz. 5,730 years, and there is now general acceptance that this is the more accurate evaluation. By international convention, however, laboratories continue to calculate and report dates on the basis of the "Libby half-life". This policy agreed at the 1962 Cambridge Radiocarbon Conference (Godwin, 1962), and reaffirmed at the 1972 Radiocarbon Conference held in New Zealand, is designed to avoid confusion and the possible need for future multiple corrections to published data. It is also recommended that such conventional ages are expressed as years B.P. (before present), which relates to A.D. 1950, and defined as "radiocarbon" as opposed to "calibrated", "calendar" or "solar" years.

Adjustment of conventional ages so that they comply with the more recent half-life value is simply a matter of multiplication by 1·03.

Constancy of ^{14}C specific activity

Without doubt this has proved to be the most controversial assumption. Direct comparison of the radiocarbon time-scale with precise dendrochronological sequences indicates that the atmospheric burden of ^{14}C has varied appreciably at least during the last seven millenia. Fig. 2 shows the general trend of secular variations in atmospheric ^{14}C as reflected in ring-dated wood from the redwood (*Sequoia gigantea*) and the longest known living species the bristlecone pine (*Pinus aristata*). Superimposed on the long-term variation, which indicates that back beyond Christian times ^{14}C ages become progressively too young, is a complex and as yet largely unresolved pattern of short-term variations in the order 1–2 per cent (1 per

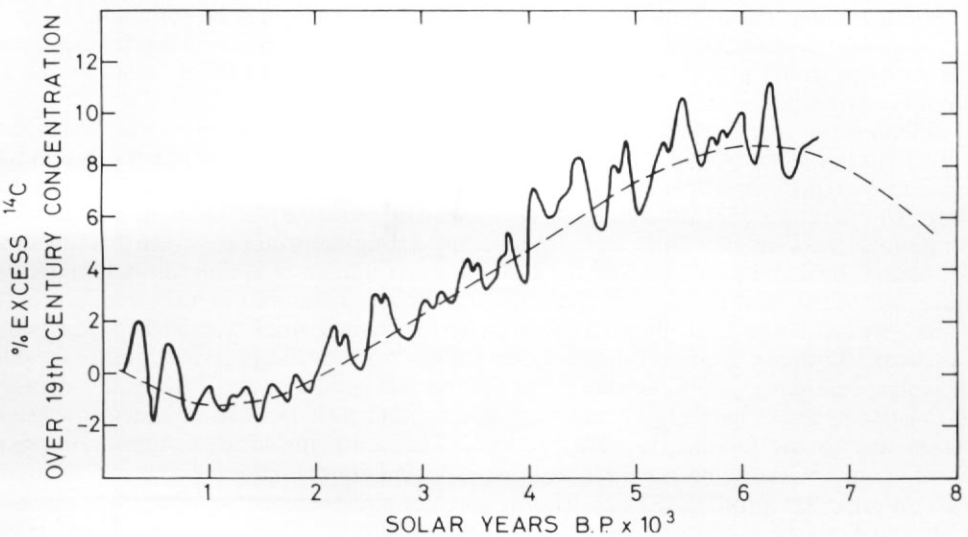

Fig. 2. Pattern of past variations in natural ^{14}C concentration as indicated by dendrochronological comparison.

cent variation in ^{14}C activity is equivalent to 83 years). The behaviour of the radiocarbon time-scale beyond the limit of dendrochronological evidence remains speculative in the absence of a suitably precise chronology for comparison, although recent investigations using terrestrial organic debris embedded in varved marine sediments from western Canada (Yang and Fairhall, 1972) would suggest the continuation of a sinusoidal pattern with a gradual decrease in excess ^{14}C back to *c.* 11,000 years B.P.

The relative importance of the several mechanisms likely to have been responsible for secular variations in the concentration of natural radiocarbon remains the subject of continuing research. Changes in ^{14}C production rate and/or disturbance of the equilibrium distribution of carbon between the atmospheric and oceanic reservoirs are, however, recognized as the most probable causes. The effect of variations known to have occurred in both the geomagnetic field strength and solar activity on the rate of ^{14}C production have been postulated to explain respectively the long-term (Bucha, 1969) and short-term (Baxter and Walton, 1971) fluctuations. It seems likely, however, that changes in global climate may also have made a significant contribution (De Vries, 1958).

The dendro/^{14}C data so far available have been variously interpreted and presented, e.g. in graphical (Suess, 1969) or tabular (Damon and others, 1972) forms, as a tool whereby the last 7,000 years of the radiocarbon time-scale may be calibrated. It must, however, be appreciated that since there is a significant degree of uncertainty inherent in the calibration data itself, in particular the real occurrence of short-term variations as described above, this is reflected in the conversion of radiocarbon to solar years.

Since the mid-nineteenth century, naturally induced changes which may have occurred in the environmental concentration of ^{14}C are largely obscured by anthropogenic effects. First, since the onset of the industrial revolution, increasing quantities of ^{14}C-free carbon dioxide are being released to the atmosphere in the utilization of fossil fuels. The decrease in natural ^{14}C specific activity which has resulted from this dilution is commonly known as the "Suess effect". More recently, neutrons produced during the testing of nuclear devices in the atmosphere have caused a corresponding rise in the ^{14}C specific activity (bomb effect). The relative magnitude of these effects as measured in the lower atmosphere is presented in Fig. 3. The pre-1972 differences in the secular pattern for bomb ^{14}C between the Northern and Southern Hemispheres reflects the regional nature of its input and the finite time for subsequent atmospheric mixing. Latitudinal variations for the "Suess effect" may be considered as largely insignificant since, although the primary source areas for fossil carbon dioxide injection are North America and Europe, the rate of ^{14}C dilution has been small in terms of the time required for atmospheric dispersion.

In different respects these anthropogenic effects are both detrimental and beneficial to ^{14}C-based studies. Clearly, the ^{14}C concentration recorded in post-industrial revolution living material cannot provide a reliable modern reference activity for the radiocarbon time-scale. In order to overcome this problem and also to avoid possible variation in the activity of contemporary working standards used by different dating laboratories, a universal standard (oxalic acid) is held and distributed by the U.S. National Bureau of Standards. All radiocarbon ages are calculated relative to 95 per cent of the activity measured in this standard as this value has proved to be equivalent to the activity of pre-industrial wood when adjusted for hypothetical ^{14}C decay relative to A.D. 1950. Another disadvantage arising from the Suess effect is age ambiguity of ^{14}C activities for the period back to A.D. 1700, viz. a measured ^{14}C deficiency in the range 0–3 per cent may reflect either post-1850 Suess effect or a genuine reduction due to the radioactive decay process. The sharp injection of approximately 10^7 curies of bomb ^{14}C into the northern stratosphere and its continuing dispersal throughout the carbon cycle has afforded the opportunity to trace and evaluate the kinetics of intra- and inter-reservoir mixing for natural ^{14}C (Nydal, 1967; Walton and others, 1970). The particular value of such transport studies is discussed below.

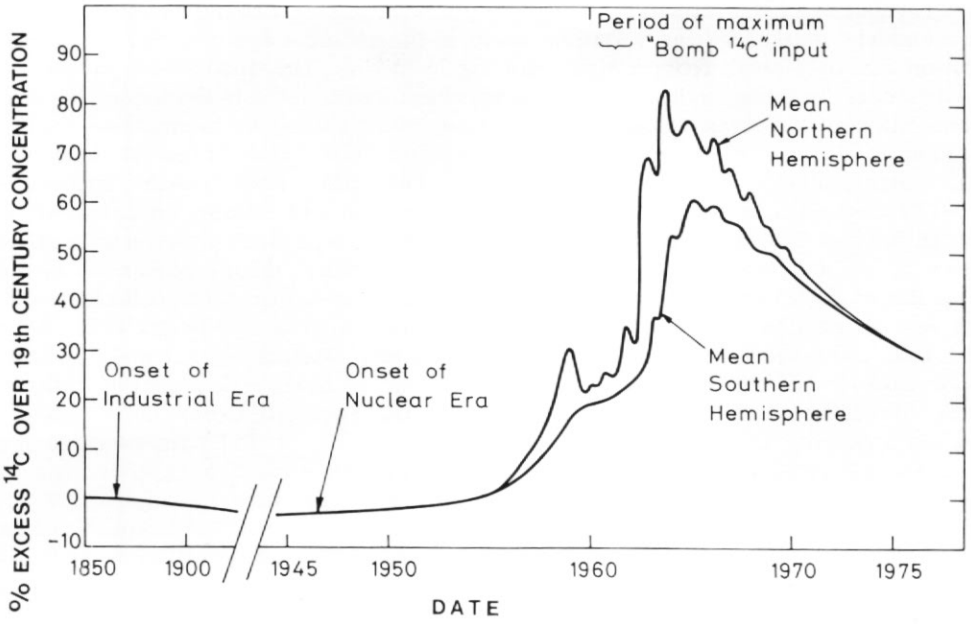

Fig. 3. Artificially induced changes in the concentration of atmospheric ^{14}C.

Global uniformity of ^{14}C specific activity

While ^{14}C is produced in the upper atmosphere, the relative mass distribution for carbon among the major exchange reservoirs (Fig. 1) implies that more than 90 per cent of the radioactive decay process occurs within the world's oceans. The assumption of global uniformity of ^{14}C concentration throughout the dynamic system therefore infers that the overall mixing rate for carbon is infinitely rapid in comparison with the 8,300 year mean-life of a ^{14}C atom.

The behaviour of bomb ^{14}C has shown that the atmosphere is indeed well mixed within a very short period, viz. less than 10 years. Further, it has been proved that terrestrial life accurately reflects changes in the ^{14}C concentration of atmospheric carbon dioxide (Baxter and Walton, 1971). Thus with a few rare exceptions, e.g. where limestone-derived carbon is incorporated directly into living tissue, there is little reason to suspect that at any time in the past the contemporaneous natural ^{14}C record of land-based plants and animals was other than globally uniform. Unfortunately, in respect of marine carbon the situation is much more complex and less well defined. The basic problems result from the relatively massive size of the oceanic reservoir allied with the appreciable time necessary for the circulation of water masses. As can be appreciated from the box-model representation (Fig. 1), the mean residence time for a carbon atom in any well-mixed reservoir is determined by (i) the total carbon content and (ii) the rate of inter-reservoir exchange, in this case passage of carbon dioxide across the air/sea interface. Evidence that the mean residence time for atmospheric carbon dioxide before transfer to the oceans, although finite is less than 20 years, has been provided both by the rate of fossil CO_2 build up in the atmosphere and by the post-1963 decrease in bomb ^{14}C concentrations. From the relative mass consideration, however, the mean residence time for oceanic carbon must be considerably greater (*c.* 95 times). Consequently, a significant amount of radioactive decay can proceed in the oceans and this is borne out by conventional ages of 1,200 years for the inorganic carbon (HCO_3^-, CO_3^{2-}) in Pacific Ocean water collected from 500 m. depth at mid latitudes (Bien and Suess, 1967). If the total water mass could be considered well mixed, the problem would be minimal in that a universal correction factor would apply

in the correlation of the "apparent ^{14}C age" of marine samples with the terrestrial time-scale. Unfortunately, marked spacial variations occur in the apparent age of ocean water and this situation can only result from a significant lag in mixing. The distribution pattern of ^{14}C activities does, however, indicate that it is feasible to consider sub-division of the oceanic carbon into (i) the ocean surface layer—defined as extending to thermocline depth and latitudinally restricted by the existence of this inversion layer, and (ii) the vast bulk of deep ocean water contained outwith these boundaries. The surface layer between approximately lat. 40°N. and 40°S. appears to be internally well mixed and exhibits an apparent age of between 300 and 500 years. Polewards of this region, however, a much more variable and older pattern of ^{14}C activities occurs due to the large-scale vertical mixing of surface and deep water. Rafter (1968) reported a ^{14}C age of 2,520 years for surface water collected from the Ross Sea during 1960 and more recent investigations (Rafter and O'Brien, 1972; Williams and Linick, 1975) show that, while in 1971–72 the "stable" surface layer at mid latitudes had a slight positive ^{14}C enrichment due to the dissolution of bomb ^{14}C, inorganic carbon and marine life collected at comparable depths from the Southern Ocean and Weddell Sea exhibited apparent ^{14}C ages in excess of 1,000 years due to the predominant influence of deep water. Shallow coastal waters outwith the stable mid-latitude band can also be regarded in some cases as relatively stable and hence the concept of an apparent age adjustment may be applied, and the specific activities of ^{14}C in marine shells collected live and at known pre-bomb dates have been monitored in attempts to establish such factors. Samples from the fjords of western Norway (Mangerud, 1972) and the estuarine systems of Scotland (Harkness, in press) indicate that 450 ± 50 years must be subtracted from the conventional ^{14}C age of marine samples from these regions. The coastal waters off New Zealand are taken to exhibit a natural ^{14}C deficiency equivalent to 300 years (Rafter, 1972) and modern shell ages of 240 ± 80 years have been reported by Taylor and Berger (1967) for the western coast of Central and South America.

The results of an exercise designed to assess the apparent age of marine samples from the coastline of South Georgia are reported, viz. SRR-740 to SRR-744, and the inherent uncertainty as to the correction factor for Antarctic marine life may be appreciated from these and respective results included in the Appendix. The presence of bomb ^{14}C in those materials collected live from the intertidal zone (SRR-741 and 743) points to the lack of appreciable deep-water influence and hence reinforces the possibility that the natural ^{14}C record of sub-Antarctic inshore waters may be regarded as at least semi-stable. The *c.* 650–800 year correction factor, as indicated by SRR-740, is however considerably greater than those described for lower latitudes. The 971 ± 35 year age (SRR-744) obtained for the modern but pre-bomb whalebone is ominous and most probably reflects the fact that these animals feed over an area variously influenced by upwelling. Thus an apparent age uncertainty comparable with the 2,500 year old value for deep water could well occur in the case of samples derived from such migratory species. On the other hand, comparison of the presumably contemporaneous peat (SRR-738) and whalebone (SRR-737) dates provides an "apparent age" estimate for the latter material which is in excellent agreement with the inshore value as does the modern elephant seal sample SRR-742, although here the influence of bomb ^{14}C cannot be discounted.

Isotopic fractionation

As was first pointed out by Craig (1953), fractionation during the geochemical transfer of carbon produces non-uniformities in the equilibrium distribution of the isotopes ^{12}C, ^{13}C and ^{14}C and, although small, this effect can be significant in terms of the dating precision now attainable. Due to the *c.* 1 per cent abundance of ^{13}C in nature, the magnitude of isotopic fractionation on the ratio of the stable isotopes ($^{13}C/^{12}C$) can be measured with a suitably designed mass spectrometer. It has been shown, for example, that on average the photosynthetic fixation of carbon results in a 1·8 per cent reduction in the heavier isotope and conversely

the inorganic carbon dissolved in ocean water is typically 0·7 per cent enriched in ^{13}C relative to atmospheric carbon dioxide. In addition to the naturally induced effects, a measurable degree of isotopic fractionation can also occur in the laboratory when less than 100 per cent yield is obtained in the essential conversion of sample carbon into a molecular form suitable for the radiometric assay of ^{14}C. As a consequence, it has become standard practice in most radiocarbon-dating laboratories to measure and where necessary correct for the isotopic fractionation effects associated with each sample prior to the calculation of its conventional radiocarbon age.

In practice the age adjustment hinges on the fact that the extent of isotopic enrichment, either positive or negative, on the $^{14}C/^{12}C$ ratio is essentially double that which may be directly monitored for $^{13}C/^{12}C$. Enrichment data as quoted in conjunction with radiocarbon ages are expressed relative to a primary standard which, unless stated otherwise, is PDB limestone (a Cretaceous belemnite, *Belemnitella americana*, from the Peedee Formation of South Carolina), thus

$$\delta^{13}C‰ = \left[\frac{^{13}C/^{12}C_{sample} - ^{13}C/^{12}C_{standard}}{^{13}C/^{12}C_{standard}}\right] \times 1{,}000.$$

The organic compounds which comprise the vast majority of sample materials to which radiocarbon dating may be applied exhibit a marked negative enrichment on the PDB scale, that is to say they are relatively depleted in the heavier carbon isotopes. It is therefore considered preferable to normalize ^{14}C activities so that they correspond to an enrichment value more representative than the primary carbonate zero. This norm value has been chosen as $-25‰$ with respect to PDB to represent the mean isotopic composition of wood.

As mentioned above, the age adjustment which must be applied to account for isotopic fractionation is generally small and may be appreciated as follows:

i. A quoted $\delta^{13}C = -25‰$ indicates that no adjustment to the radiometric age determination has proved necessary.

ii. $\delta^{13}C = -30‰$ implies a $5‰$ depletion in ^{13}C and consequently the measured ^{14}C activity has been increased by $10‰$ which is in turn equivalent to 83 years.

iii. Similarly, a value of $\delta^{13}C = -20‰$ has required a $10‰$ reduction in the measured ^{14}C activity prior to its interpretation in terms of radiocarbon years.

The carbon in land-based plants and the soft tissue of animals rarely exhibits $\delta^{13}C$ values outwith the -20 to $-30‰$ range and hence the age adjustment for this type of sample is more often than not less than the statistical uncertainty term associated with the particular age determination. Maximum age adjustments are most frequently encountered with shell dates where a preference for the heavier isotopes during carbonate formation results in a *c.* $50‰$ ^{14}C excess (equivalent to 415 years) in comparison with contemporaneous wood.

Conclusions

The modifications necessary to relate conventional radiocarbon ages to sidereal time, although important, detract little from the positive value of the dating method. It must be emphasized that the interpretation which may be put on any ^{14}C age is often limited in the first instance by the relationship between the sample and the event which it is proposed to date. The residual ^{14}C activity affords only a measure of when the organism died and not necessarily, for example, the time elapsed since it was buried or transported by a geological event. Apart from this general consideration, it would seem necessary, at least in respect of Antarctic samples, to draw a clear distinction between the degree of confidence which may be placed on ^{14}C ages for purely terrestrial materials as opposed to those associated with the marine environment. Where the sample carbon can be confidently assumed to have derived solely from photosynthesis by land-based plants there is little reason to suspect a significant deviation from the conventional radiocarbon time-scale, particularly where the radiometric age has

been normalized to account for isotopic fractionation. Correlation with the solar time-scale is of course governed by considerations of the radioactive half-life and the constancy of ^{14}C specific activity as discussed. On the other hand, the conventional ages obtained from materials linked with the primary fixation of oceanic carbon must be regarded as less reliable, and in most cases the overestimation of ^{14}C age inherent in this type of sample is not readily defined. The greatest degree of uncertainty occurs for marine life whose potential food chain extends beyond the coastal regime and at best the ^{14}C dates obtained from the detrital remains of such species should only be regarded as providing a maximum possible age for the event with which they are associated.

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APPENDIX

List of all S.U.R.R.C. radiocarbon age measurements so far reported to, and edited by, the appropriate British Antarctic Survey personnel. These data will be submitted for publication in *Radiocarbon* under "Scottish Universities Research and Reactor Centre Radiocarbon Measurements III".

SAMPLE DESCRIPTIONS

SRR-27. Signy Island, South Orkney Islands — **254±35**, **AD 1696**, $\delta^{13}C = -22{\cdot}5‰$

Moss peat from base of bank, ca 30 cm deep exposed by retreat of snow bank below Jane Peak, Signy Island (60° 40′ S, 45° 40′ W). Coll 1970 by N J Collins; subm by R J Adie, British Antarctic Survey.

SRR-28. Elephant Island, South Shetland Islands — **1515±36**, **AD 435**, $\delta^{13}C = -23{\cdot}2‰$

Moss peat from erroded bank on SE slope N of Walker Point, Elephant Island (61° 10′ S, 55° 14′ W). Coll 1970 by R M O'Brien, Joint Services Expedition; subm by R J Adie, British Antarctic Survey.

SRR-29. Grytviken, South Georgia — **722±57**, **AD 1228**, $\delta^{13}C = -25{\cdot}0‰$

Polytrichum alpestre peat from base of vegetation hummock, ca 100 cm high, S of Grytviken whaling station, King Edward Cove, South Georgia (54° 17′ S, 36° 31′ W). Coll 1971 by R I L Smith; subm by R J Adie, British Antarctic Survey.

Cumberland East Bay series, South Georgia

Peat from profiles taken on plain below gun hut SW of King Edward Cove, Cumberland East Bay, South Georgia (54° 17′ S, 36° 29′ W). Site consists of a *Rostkovia magellanica* bog with scattered patches of *Sphagnum fimbriatum*; surface slopes to the sea where it is fringed by a narrow zone of *Poa flabellata*. Samples coll 1961 by S W Greene; subm by R J Adie, British Antarctic Survey.

SRR-30. Cumberland East Bay, 38 cm depth — **391±70**, **AD 1559**, $\delta^{13}C = -22{\cdot}7‰$

Base of *Sphagnum* peat layer, profile No. 3 (Greene 3616).

SRR-31. Cumberland East Bay, 102 cm depth — **2335±50**, **385 BC**, $\delta^{13}C = -19{\cdot}2‰$

Rostkovia moss peat, profile No. 3 (Greene 3620).

SRR-32. Cumberland East Bay, 38 cm depth **227±25**
AD 1723
$\delta^{13}C = -26{\cdot}2‰$

Base of *Sphagnum* peat layer, profile No. 6 (Greene 3633).
General comment (SWG): see Sphagnum Valley, Cumberland West Bay series.

Husvik series, South Georgia

Sphagnum peat from profiles taken within a single patch of living *Sphagnum fimbriatum* (ca 12·2×21 m area) in an area of *Rostkovia magellanica* bog W of graveyard in valley running SW from Husvik whaling station, Stromness Bay, South Georgia (54° 10′ S, 36° 42′ W). Sample coll 1961 by S W Greene; subm by R J Adie, British Antarctic Survey.

SRR-33. Husvik, 51 cm depth **657±72**
AD 1293
$\delta^{13}C = -26{\cdot}3‰$

Base of *Sphagnum* layer in profile No. 15 (Greene 3676).

SRR-34. Husvik, 76 cm depth **1092±55**
AD 858
$\delta^{13}C = -25{\cdot}8‰$

Rostkovia moss peat in profile No. 15 (Greene 3674).

SRR-35. Husvik, 38 cm depth **564±70**
AD 1386
$\delta^{13}C = -24{\cdot}3‰$

Base of *Sphagnum* peat layer in profile No. 16 (Greene 3682).

SRR-36. Stromness Bay, 51 cm depth **1084±65**
AD 866
$\delta^{13}C = -25{\cdot}5‰$

Base of *Sphagnum* peat layer in profile No. 17 (Greene 3686).
General comment (SWG): see Sphagnum Valley, Cumberland West Bay series.

Stromness Harbour series, South Georgia

Peat from profile (No. 18) taken in centre of carpet of living *Sphagnum fimbriatum* (ca 22·9×25·9 m area) in *Rostkovia magellanica* bog N of whaling station on W shore of Stromness Harbour, Stromness Bay, South Georgia (54° 08′ S, 36° 42′ W). Coll 1961 by S W Greene; subm by R J Adie, British Antarctic Survey.

SRR-37. Stromness Harbour, 38 cm depth **300±50**
AD 1650
$\delta^{13}C = -24{\cdot}1‰$

Base of *Sphagnum* peat layer (Greene 3692).

SRR-38. Stromness Harbour, 64 cm depth **584±50**
AD 1366
$\delta^{13}C = -24{\cdot}2‰$

General comment (SWG): see Sphagnum Valley, Cumberland West Bay series.

Sphagnum Valley, Cumberland West Bay series, South Georgia

Peat from profiles taken in *Rostkovia magellanica* bog in Sphagnum Valley sited behind shore at Low Point SE of Cumberland West Bay, South Georgia (54° 16′ S, 36° 35′ W).

Profiles Nos. 19 and 21 overlain by a surface layer of *Sphagnum fimbriatum*, profile No. 20 lacked such a layer. Coll 1961 by S W Greene; subm by R J Adie, British Antarctic Survey.

SRR-39. Sphagnum Valley, 38 cm depth **435±50**
AD 1515
$\delta^{13}C = -24{\cdot}8‰$

Base of uppermost *Sphagnum* peat layer in profile No. 19 (Greene 3698).

SRR-40. Sphagnum Valley, 64 cm depth **869±50**
AD 1081
$\delta^{13}C = -25{\cdot}8‰$

Base of a buried *Sphagnum* peat layer in profile No. 19 (Greene 3696).

SRR-41. Sphagnum Valley, 89 cm depth **1547±50**
AD 403
$\delta^{13}C = -27{\cdot}4‰$

Top of a buried *Sphagnum* peat layer in profile No. 19 (Greene 3706).

SRR-42. Sphagnum Valley, 102 cm depth **1759±50**
AD 191
$\delta^{13}C = -28{\cdot}8‰$

Base of a buried *Sphagnum* peat layer in profile No. 19 (Greene 3705).

SRR-43. Sphagnum Valley, 152 cm depth **2380±50**
430 BC
$\delta^{13}C = -29{\cdot}0‰$

Rostkovia-moss peat in profile No. 19 (Greene 3701). Sample from 140 to 152 cm (Greene 3701 plus 3702) previously dated 2500±800 (UCLA-658C).

SRR-44. Sphagnum Valley, 38 cm depth **718±60**
AD 1232
$\delta^{13}C = -25{\cdot}2‰$

Base of a buried *Sphagnum* peat layer in profile No. 20 (Greene 3712).

SRR-45. Sphagnum Valley, 64 cm depth **1563±60**
AD 387
$\delta^{13}C = -29{\cdot}9‰$

Rostkovia-moss peat overlying a layer of buried *Sphagnum* peat in profile No. 20 (Greene 3710).

SRR-46. Sphagnum Valley, 76 cm depth **1962±60**
12 BC
$\delta^{13}C = -26{\cdot}0‰$

Base of a buried *Sphagnum* peat layer in profile No. 20 (Greene 3709).

SRR-47. Sphagnum Valley, 64 cm depth **1886±65**
AD 64
$\delta^{13}C = -24{\cdot}8‰$

Base of a buried *Sphagnum* peat layer in profile No. 21 (Greene 3720).

SRR-48. Sphagnum Valley, 127 cm depth **5191±100 3241 BC**

$\delta^{13}C = -22{\cdot}9‰$

Rostkovia-moss peat in profile No. 21 (Greene 3715). Sample from 102 to 115 cm depth in this profile (Greene 3716 and 3717) previously dated 6500±500 (UCLA-658B).
General comment (SWG): while none of the dates is for the base of the whole peat layer, it appears that South Georgia has been in part well vegetated for at least 6,500 years. The dates for the most complete profiles provide a clear picture of the steady accumulation of peat on South Georgia, with little evidence of further compression below a depth of about 50 cm.

SRR-49. Nordenskjöld Glacier, South Georgia **1541±65 AD 409**

$\delta^{13}C = -18{\cdot}4‰$

Collagen isolated from whalebone embedded in surface near crest of 4 m high moraine, 400 m in front of Nordenskjöld Glacier and 80 m landward of present beach, on W side of Cumberland East Bay, South Georgia (54° 17′ S, 36° 29′ W). Coll 1971 by C M Clapperton; subm by R J Adie, British Antarctic Survey.

SRR-512. Cape Hansen, Coronation Island, South Orkney Islands **168±60 Modern (AD 1782)**

$\delta^{13}C = -23{\cdot}1‰$

Moss peat (*Chorisodontium aciphyllum*) from base of 10 cm thick bank re-exposed by retreat of snow cover at Cape Hansen, Coronation Island, South Orkney Islands (60° 39′ S, 45° 32′ W). Sample represents basal 3·5 cm of peat overlying mineral soil. Coll 1974 by J H C Fenton; subm by N J Collins, British Antarctic Survey.
Comment (NJC): see general comment for SRR-513 to SRR-515.

Signy Island series, South Orkney Islands

Moss peat (mainly *Chorisodontium aciphyllum* with some *Polytrichum alpestre*) from persistent snowfield, an extension of the main ice cap, E of Rusty Bluff, Signy Island, South Orkney Islands (60° 40′ S, 45° 40′ W). Coll 1974 by J H C Fenton; subm by N J Collins, British Antarctic Survey.

SRR-513. Signy Island **162±55 Modern (AD 1788)**

$\delta^{13}C = -27{\cdot}2‰$

Upper layer of ca 70 cm thick deposit buried under 65 cm of ice.

SRR-514. Signy Island **71±65 Modern (AD 1879)**

$\delta^{13}C = -23{\cdot}6‰$

Base of deposit (cf SRR-513) but may not be *in situ* since all moss shoots in this layer point downwards.

SRR-515. Signy Island **110±70 Modern (AD 1840)**

$\delta^{13}C = -25{\cdot}1‰$

Sample from bank of peat wedged between ice at margin of snowfield and a rock outcrop.
General comment (NJC): taken in conjunction with the age of 254±35 BP (SRR-27) for a re-exposed bank below Jane Peak, Signy Island, it appears that a number of moss-peat banks developed prior to the period of deterioration in climate in the Southern Hemisphere (Little

Ice Age) from the middle to the end of the nineteenth century. Some banks have been re-exposed in recent years whilst others are still buried at the margins of snowfields.

Cooper Bay series, South Georgia

Peat from low ground between moraine ridges at Cooper Bay, South Georgia (54° 47′ S, 35° 48′ W). Coll 1974 by P Stone; subm by R J Adie, British Antarctic Survey.

SRR-516. Cooper Bay (M671P.1) — **349±50**, **AD 1601**, $\delta^{13}C = -27{\cdot}8‰$

SRR-517. Cooper Bay (M671P.7) — **105·9±0·7% Modern**, $\delta^{13}C = -27{\cdot}8‰$

SRR-518. Cooper Bay (M671P.10) — **100·4±0·6% Modern**, $\delta^{13}C = -28{\cdot}3‰$

General comment (PS): SRR-517 and SRR-518 clearly post-date AD 1954 from presence of "bomb ^{14}C". All specimens were collected from moraine ridges believed to be about 6,000 years old. No significance therefore relative to the absolute age of the glacial advance. However, the deepest peat was always collected, so why was there no peat formation prior to 1600? Possible climatic change or even introduction into that area of peat-forming mosses.

SRR-519. Wirik Bay, South Georgia — **877±40**, **AD 1073**, $\delta^{13}C = -20{\cdot}5‰$

Collagen isolated from bone of elephant seal buried in moraine at Wirik Bay, South Georgia (54° 45′ S, 35° 51′ W). Coll 1974 by P Stone; subm by R J Adie, British Antarctic Survey.

Comment (PS): rather too young a date to avoid a large degree of error due to a falsely old reading. Certainly very much older than expected. Reflects "apparent age" of marine carbon sources in this geographical region?

SRR-520. Will Point, Royal Bay, South Georgia — **2369±40**, **419 BC**, $\delta^{13}C = -26{\cdot}1‰$

Unidentified animal remains from floor of sea cave associated with raised beach at Will Point, Royal Bay, South Georgia (54° 33′ S, 36° 01′ W). Coll 1973 by P Stone; subm by R J Adie, British Antarctic Survey.

Comment (PS): the sea cave is about 8 m asl and associated with a raised beach at 7·5 m asl. This date is therefore useful in an attempt to measure the rate of sea-level change.

Sphagnum Valley series, South Georgia

Peat from two bog sites, ca 500 m apart, with layered stratigraphy overlying glacial till in Sphagnum Valley, Cumberland West Bay, South Georgia (54° 16′ S, 36° 35′ W). Coll 1973 by C J Barrow; subm by R I L Smith, British Antarctic Survey.

SRR-578. Sphagnum Valley, 222·5 cm depth — **6647±120**, **4697 BC**, $\delta^{13}C = -27{\cdot}9‰$

Clay-rich peat, with remains of *Juncus*, bryophytes, grasses, from freshly cut section.

SRR-579. Sphagnum Valley, 232·5 cm depth — **3997±85 / 2047 BC** — $\delta^{13}C = -28{\cdot}8‰$

Clay-rich peat, origins of plant remains obscure, from section of bedded peats exposed by stream erosion.

General comment (JCB/RILS): Sphagnum Valley is a broad well-vegetated valley with extensive bogs (dominated by *Rostkovia magellanica*, *Juncus Scheuchzerioides* and bryophytes) and overlying deep deposits of peat. Sample SRR-578 was taken from the base of the continuous layer of organic material in a *Rostkovia*–bryophyte bog at ca 50 m alt. A palynological analysis of this level revealed an abundance of pollen of *Acaena* spp. (predominantly *Acaena magellanica*) and Gramineae and lesser quantities of *Gallium antarcticum*, *Colobanthus* spp. and spores of *Conostomum pentastichum* and an ascomycetous fungus believed to be parasitic on the rush. Grains of *Nothofagus* sp., of South American origin, were also isolated. The absence of juncaceous pollen is attributed to its poor preservation qualities. Small quantities of organic matter occurred in the clay at 317·5 cm in the same profile, while organic inclusions were visible in the clay deposits at 377 cm in another profile ca 15 m away. Sample SRR-579 came from the base of the continuous layer of peat in a wet bog dominated by *Acaena magellanica* with some *Rostkovia* and bryophytes ca 500 m from SRR-578. It lay nearer the shore close to the upper raised beach system of the Cumberland West Bay coastline, at ca 6 m alt. A palynological analysis of this level provided an abundance of pollen of *Acaena* spp. and Gramineae, and smaller amounts of *Gallium antarcticum*, *Colobanthus* spp. and spores of *Conostomum pentastichum*.

The discrepancy in age between the two samples from approximately the same depth may result from the fact that the raised beach area of SRR-579 was still unvegetated shoreline for a long time after the SRR-578 bog complex had been established. Thus samples from corresponding levels at these sites are likely to be much younger at the site where peat accumulation commenced much later.

"Gun Hut Valley" series, South Georgia

Clayey peat from valley floor deposit at ca 25 to 30 m alt in "Gun Hut Valley", South Georgia (54° 33′ S, 36° 28′ W). "Gun Hut Valley" is given in inverted commas as it is not an official place-name but a term in common usage. An ex-wartime gun hut is situated at the seaward end of the valley. Coll 1973 by C J Barrow; subm by R I L Smith, British Antarctic Survey.

SRR-580. "Gun Hut Valley", 50 cm depth — **4852±21[illegible] / 2902 BC** — $\delta^{13}C = -28{\cdot}8‰$

Peat in section exposed by melt-water stream erosion.

SRR-581. "Gun Hut Valley", 105 cm depth — **2935±85 / 985 BC** — $\delta^{13}C = -28{\cdot}2‰$

Peat in section exposed by stream erosion.

SRR-582. "Gun Hut Valley", 160 cm depth — **8537±65 / 6587 BC** — $\delta^{13}C = -29{\cdot}9‰$

Peat from base of deposit overlying glacial debris, section exposed by subsidence.

SRR-736. "Gun Hut Valley", 255 to 260 cm depth **9493±370**
7543 BC
$\delta^{13}C = -29{\cdot}7‰$

Clayey peat at base of compacted profile, exposed by stream erosion, and overlying stone/clay deposit at 265 cm depth.

General comment (CJB/RILS): "Gun Hut Valley" is a small broad valley with extensive bogs dominated by *Rostkovia magellanica*, *Juncus scheuchzerioides* and bryophytes and overlying deep deposits of peat. The sites lay between 300 and 500 m from the sea at an alt of ca 25–30 m. SRR-580 and SRR-582 were ca 15 m apart and SRR-581 was ca 200 m up-valley from these. SRR-736 was from the base of the same section as SRR-580; samples from the other two sites were from the lowest level of organic matter in their profiles.

Sites SRR-580 and SRR-582 appeared similar both in the composition and structure of the peat and the depth–age relationship. These sites were well drained in comparison with SRR-581. The peat at the former two sites is composed of *Rostkovia* and the tall turf-forming mosses *Chorisodontium aciphyllum*, *Dicranoloma* spp. and the *Polytrichum* spp. all of which accumulate peat relatively rapidly, whereas the deposit at SRR-581 is formed mainly by *Juncus*, *Tortula robusta* and some *Acaena magellanica*, species which develop peat much more slowly. Thus samples taken from corresponding levels at each site are likely to be much older at the latter site. Peat at the level SRR-736 is rich in fine plant material, particularly bryophyte remains. Pollen is sparse and well preserved, but not so sparse that it is likely to have come from South America. A preliminary palynological analysis of this level has revealed relatively abundant grains of *Acaena* (probably mainly *Acaena magellanica*, although *Acaena tenera* has been tentatively identified also) and small quantities of Gramineae, *Callitriche antarctica* and the moss *Conostomum pentastichum;* fungal material, one species of desmid and the remains of mites and possibly copepods have also been identified. This is the deepest and oldest sample yet analysed from South Georgia and the date ties in well with the estimated retreat of the last major glaciation on the island about 10,000 years ago.

SRR-583. Snipe Flats Camp, East Falkland Islands **9163±110**
7213 BC
$\delta^{13}C = -28{\cdot}6‰$

Clay-rich peat containing remains of *Juncus*, grasses and bryophytes from ca 28 cm above base of ca 2·6 m thick deposit overlying bedrock on floor of upland valley, alt 183 m OD, at Snipe Flats Camp, East Falkland Islands (51° 00′ S, 59° 05′ W). Coll 1973 by C J Barrow; subm by R I L Smith, British Antarctic Survey.

Comment (CJB/RILS): this site is typical of the undisturbed upland peats of the Falkland Islands. Slightly deeper deposits may occur in some valley bogs. The present vegetation at the site comprised dwarf shrubs, grasses, rushes, sedges and bryophytes.

SRR-584. Ocean Harbour, South Georgia **3591±100**
1641 BC
$\delta^{13}C = -28{\cdot}8‰$

Clay-rich peat containing *Sphagnum fimbriatum*, other bryophytes and *Juncus scheuchzerioides*, from 143 cm depth in valley-side deposit at ca 6 m alt Ocean Harbour, South Georgia (54° 20′ S, 36° 16′ W). Coll 1973 by C J Barrow; subm by R I L Smith, British Antarctic Survey.

Comment (CJB/RILS): this sample was from the lowest level of peat in a bog complex of similar floristic composition and altitude to that from which SRR-579 was derived. The age–depth relationship of the two sites is also comparable.

SRR-585. South Annenkov Island, South Georgia **1007±160 AD 943**

$\delta^{13}C = -27{\cdot}4‰$

Peat of grass origin (*Poa flabellata*) from base of ca 150 cm high tussock overlying rounded pebbles on bank of stream close to 1972–73 geology field camp, at ca 20 m alt, south Annenkov Island, South Georgia (54° 29′ S, 37° 05′ W). Coll 1972 by C J Barrow; subm by R I L Smith, British Antarctic Survey.

Comment (CJB/RILS): this sample was taken from the base of a tall organic "pedestal" formed by the accumulation of dead foliage, litter and living and dead roots of the tall tussock grass *Poa flabellata*. In comparison with peat accumulation in bogs, *Poa flabellata* forms relatively deep deposits of loose fibrous organic matter more rapidly than the rushes and bryophytes. Consequently, the comparatively young age of this deep sample should not be compared with samples from similar depths taken from valley bogs.

SRR-737. St. Andrew's Bay, South Georgia **846±50 AD 1104**

$\delta^{13}C = -20{\cdot}5‰$

Collagen isolated from striated whalebone exposed by stream erosion of re-advance moraine at St. Andrew's Bay, South Georgia (54° 28′ S, 36° 10′ W). Coll 1975 by D E Sugden and C M Clapperton, Univ of Aberdeen; subm on behalf of the British Antarctic Survey.

Comment (CMC): in conjunction with SRR-738 this material should date episode of glacial advance which is thought to relate to "Little Ice Age" of the Northern Hemisphere. Therefore, the ^{14}C age appears to be 650 to 800 years too old.

SRR-738. Heaney Glacier, South Georgia **155±45 AD 1795**

$\delta^{13}C = -33{\cdot}4‰$

Top 1 cm thickness of peat layer overlain by ca 60 cm till at 60 m inside re-advance limit of Heaney Glacier, South Georgia (54° 26′ S, 36° 11′ W). Coll 1975 and subm by D E Sugden and C M Clapperton, Univ of Aberdeen.

Comment (CMC): fits well with date of proposed glacial advance, viz. AD 1750 to AD 1890.

SRR-739. Doris Bay, South Georgia **2012±45 62 BC**

$\delta^{13}C = -21{\cdot}3‰$

Peat from basal deposit in kettle hole at Doris Bay, South Georgia (54° 29′ S, 36° 09′ W). Coll 1975 and subm by D E Sugden and C M Clapperton, Univ of Aberdeen.

Comment (CMC): kettle hole is in a complex system of recessional moraines which relate to a much more extensive glacial–climatic event than the "Little Ice Age". The date provides a useful minimum age for the event.

Sub-Antarctic (Modern) series

Twentieth century materials collected from various locations in South Georgia in an attempt to assess the "apparent age" as determined by the marine food chain in this region of the sub-Antarctic (Rafter and O'Brien, 1972). Sample coll 1975 by C M Clapperton and D E Sugden, Univ of Aberdeen; subm on behalf of the British Antarctic Survey.

SRR-740. Hound Bay, South Georgia

(a) "outer" fraction **687±40 AD 1263**

$\delta^{13}C = +1{\cdot}1‰$

(b) "inner" fraction **756±40**
AD 1194
$\delta^{13}C = +0{\cdot}8‰$

Shell, ca 0 to 20 years old, from high water mark on shingle beach at Hound Bay, South Georgia (54° 23′ S, 36° 15′ W). Prior to ^{14}C assay, the outermost 25% by weight of the shells was discarded by scrubbing and acid leaching. "Outer" and "inner" fractions of the leached shells were isolated via controlled hydrolysis using 2M HCl.

SRR-741. St. Andrew's Bay, South Georgia **113·5±0·5% Modern**
$\delta^{13}C = -14{\cdot}0‰$

Kelp growing in intertidal zone at St. Andrew's Bay, South Georgia (54° 28′ S, 36° 09′ W).

SRR-742. St. Andrew's Bay, South Georgia **786±35**
AD 1164
$\delta^{13}C = -19{\cdot}5‰$

Collagen isolated from bone of decomposing elephant seal carcass on beach at St. Andrew's Bay, South Georgia (54° 28′ S, 36° 10′ W).

SRR-743. St. Andrew's Bay, South Georgia
(a)"outer" fraction **107·6±0·5% Modern**
$\delta^{13}C = +2{\cdot}2‰$

(b) "inner" fraction **106·0±0·5% Modern**
$\delta^{13}C = +1{\cdot}9‰$

Limpet shells collected live from intertidal zone at St. Andrew's Bay, South Georgia (54° 28′ S, 36° 09′ W). Flesh discarded on collection, shells pre-treated as for SRR-740.

SRR-744. Grytviken whaling station, South Georgia **971±35**
AD 979
$\delta^{13}C = -19{\cdot}0‰$

Collagen isolated from whale rib in factory dump above high water mark and S of former Grytviken whaling station, South Georgia (54° 16′ S, 36° 30′ W). Bone ca 12 to 50 years old on basis of operations at Grytviken.