Radiocarbon, Vol, Nr, 2019, p 1–19 DOI:10.1017/RDC.2019.54

INVESTIGATING SUBANTARCTIC ^{14}C AGES OF DIFFERENT PEAT COMPONENTS: SITE AND SAMPLE SELECTION FOR DEVELOPING ROBUST AGE MODELS IN DYNAMIC LANDSCAPES

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ABSTRACT. Precise radiocarbon (^{14}C) dating of sedimentary sequences is important for developing robust chronologies of environmental change, but sampling of suitable components can be challenging in highly dynamic landscapes. Here we investigate radiocarbon determinations of different peat size fractions from six peat sites, representing a range of geomorphological contexts on the South Atlantic subantarctic islands of the Falklands and South Georgia. To investigate the most suitable fraction for dating, 112 measurements were obtained from three components within selected horizons: a fine fraction <0.2 mm, a coarse fraction >0.2 mm, and bulk material. We find site selection is critical, with locations surrounded by high-ground and/or relatively slowly accumulating sites more susceptible to the translocation of older carbon. Importantly, in locations with reduced potential for redeposition of material, our results show that there is no significant or systematic difference between ages derived from bulk material, fine and coarse (plant macrofossil) material, providing confidence in the resulting age model. Crucially, in areas comprising complex terrain with extreme relief, we recommend dating macrofossils or bulk carbon rather than a fine fraction, or employing comprehensive dating of multiple sedimentary fractions to determine the most reliable fraction(s) for developing a robust chronological framework.

KEYWORDS: age modeling, climate change, reworking, Southern Ocean, terrestrial.

INTRODUCTION

Peat deposits are important natural archives for reconstructing past climate and environmental change. This is of particular significance in the mid to high-latitudes which are experiencing increasing climate variability and long-term warming but where there is a relative paucity of instrumental (observational) records (IPCC AR5 2013; Jones et al. 2016). Despite the importance of peat for reconstructing palaeo-ecological and -climate change (e.g. McGlone et al. 2010), its role as a major global carbon reservoir, including past changes in flux (Turney et al. 2016a; Amesbury et al. 2017; Gallego-Sala et al. 2018), and even defining geological epochs (Turney et al. 2018), there are a number of potential issues regarding precise dating of sequences in remote, highly dynamic locations. These include the suitability of available calibration curves (Scott et al. 2010; Reimer et al. 2013b), sedimentary material selection and pretreatment (Nilsson et al. 2001; Brock et al. 2010; Piotrowska et al. 2011), and site context for developing robust chronological frameworks.

A key consideration when selecting material for radiocarbon dating is whether the age assigned to a peat sample truly reflects the time that the associated sediments were deposited. It is well known that some sediments may incorporate carbon that is from the non-contemporaneous environment. Peat sediments can comprise both "older" and "younger" carbon, through the

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mobility of various size/chemical fractions, deposition of reworked material from upslope, and penetration of older peat by younger rootlets. The most important issue, therefore, is to identify the fraction that can provide a reliable radiocarbon determination (and is present in sufficient quantity). A key concern is the vertical penetration of roots, resulting in inclusion of "younger" carbon in the samples being dated (Kilian et al. 2000; Brock et al. 2011). When dating bulk peat samples, removal of visible roots can reduce the influence of this "younger" carbon, resulting in older ages. However, it should be noted that identification of these roots after decomposition might be challenging, particularly in sediments of greater antiquity. Another possibility is the downward vertical migration of microfossils by water movement/flow, however, this is generally limited to the relatively unconsolidated upper sediments, limiting the impact on age determinations (Ivanov 1981; Joosten and De Klerk 2007).

The dating of terrestrial plant macrofossils (e.g. seeds, wood, bark, leaves) has been suggested to improve the accuracy of chronologies as, providing they are *in situ* and have not been reworked, they are likely to be contemporaneous with the time of deposition and therefore reflect atmospheric ^{14}C, (Lowe and Walker 1997; Turney et al. 2000; Blockley et al. 2012). Dating short-lived terrestrial plant remains ensure that the assimilated atmospheric CO_2 is likely to be near-contemporaneous with the terrestrial environment. However, misidentification of root material for plant macrofossils can result in significant errors (Martin et al. 2018), so extreme caution must be taken. For highly humified peat, from which it is difficult to select specific macrofossils, or in the absence of visible macrofossils, it is possible to date either the whole peat sample (termed a "bulk" sample), or specific fractions of the peat, which may be separated physically or chemically. For rapidly accumulating peats in ombrotrophic bogs in particular, bulk ^{14}C ages can directly reflect atmospheric radiocarbon (Blaauw et al. 2004).

However, a potential source of older carbon being incorporated into a peat sequence, regardless of the material type, is the translocation of older carbon from higher adjacent ground as a result of erosion. A potentially important aspect on these islands is cryoturbation, which can distort the stratigraphic integrity of a sequence through movement/mixing of material of different coarseness in a profile. If the material is allogenic (i.e. transported from elsewhere) it is essential that it has not been reworked/redeposited from older geological strata or soils, as this could bias the ^{14}C age determination towards older values. For example, old soil humics and refractory soil organic material such as lignin can be several thousand years old at the point of redeposition (McGlone and Wilmshurst 1999). This is particularly problematic in organically lean sediments (Reimer et al. 2013a; Wilson et al. 2002). In addition, some organic components such as wood or charcoal may have inbuilt ages due to their persistence in a landscape on timescales of centuries or longer, before incorporation into a sediment unit (Oswald et al. 2005; Kershaw et al. 2007; Howarth et al. 2013).

Different sedimentary environments have been shown to have varying susceptibilities to the incorporation of non-contemporaneous carbon (McGlone and Wilmshurst 1999; Chu et al. 2016). As a result, there have been a number of studies investigating different size and chemical fractions for radiocarbon dating of peat. Two recent studies both found that the incorporation of bulk peat dates appeared to introduce no significant systematic biases into large datasets (Blaauw et al. 2004; Holmquist et al. 2016). A study from Australia found that ^{14}C dating of short-lived plant macrofossils resulted in consistently younger ages than from both pollen concentrate material and charcoal, with the macrofossils thought to be potentially closer to the age of the deposition of the sediment (Martin et al. 2018). In addition to separate size fractions, different chemical fractions may also provide divergent age determinations (Shore et al. 1995; Turetsky et al. 2004); vertical transport of humic acids in peat columns is potentially variable due to site-specific conditions, and may be arrested in acidic environments due to lower humic acid solubility (Wüst et al. 2008). While Brock et al. (2011) demonstrated that humic acid fractions are significantly younger than their humin counterparts at a site in northern Germany, it was difficult to conclude confidently that the date of one fraction was more reliable than any other. In contrast, Hill et al. (2019) found no statistical difference between humic and humin fractions in four out of five sample pairs derived from peat at Glastonbury, England—one sample pair showed an older humin fraction, probably as a result of site disturbance. Peat and macrofossils from bogs are thought to be least susceptible to older or younger carbon contamination, while lakes and swamps can be subject to redeposition of old carbon from the adjacent catchment, as well as hardwater effects (Olsson 1986). Some environments are more susceptible to the movement and redeposition of organic components. For example in some locations, root penetration can reach up to 2 m in depth and can therefore bias the radiocarbon determination of the peat unit by several thousand years (Martin et al. 2018).

The south Atlantic subantarctic islands of South Georgia and the Falklands are situated within the core latitude of the westerly wind belt (51–54°S). These islands have long been recognized for their potential for reconstructing regional and hemispheric climate and environmental changes (Barrow 1978), and have been the focus of several recent studies (van der Putten et al. 2009; Strother et al. 2015; Turney et al. 2016a, 2016b; Berg et al. 2019; Oppedal et al. 2018; Thomas et al. 2018a; White et al. 2018). The geochronological basis for these reconstructions has relied almost wholly on ^{14}C. While both islands experience a generally cool, maritime climate, the combination of extremes in altitude, climate, sea ice and glacial/periglacial conditions (the latter notably on South Georgia), and limited vegetation cover, has created landscapes that are highly dynamic across a range of timescales, with substantial potential for remobilization of sediments (and associated ^{14}C; Wilson et al. 2002; Oppedal et al. 2018).

This study compares ^{14}C determinations from different depositional environments on the highly dynamic subantarctic islands of the South Atlantic to investigate the most suitable fraction for ^{14}C dating, and to investigate the influence of local geomorphology on the ^{14}C inventory. We report a study of six sites from a range of different depositional terrestrial environments on two subantarctic islands in the South Atlantic: the Falkland Islands and South Georgia (Figure 1). To investigate the most reliable fraction(s), a total of 112 ^{14}C ages were obtained, comprising 24 pairs of bulk peat and macrofossils (coarse fraction, >0.2 mm), 21 pairs of fine fraction (<0.2 mm) and macrofossils, and two triplets of all three fractions. Here we explore different influences on the radiocarbon inventory in each sequence.

Study Area

The Falkland Islands and South Georgia lie in the South Atlantic at 52°S and 54°S, respectively. The Falklands are 540 km east of the coast of South America and 1500 km west of subantarctic South Georgia (Figure 1). Three sites were investigated on the Falkland Islands in the immediate area of Port Stanley (Figures 1 and 2). The first selected site was Canopus Hill, an Ericaceous-grass dominated peatland situated above Port Stanley Airport (51.691°S, 57.785°W, approximately 30 m above mean sea level (masl) (Figure 2A–E) from which a sediment sequence 1.6 m long was cored. In addition, we investigated peat sequences from Memorial Beach (51.70053°S, 57.78331°W, approximately 5 masl), and Silos (51.70224°S, 57.87939°W, approximately 83 masl) where we recovered 1.6 m and 0.7 m of sediment respectively. While

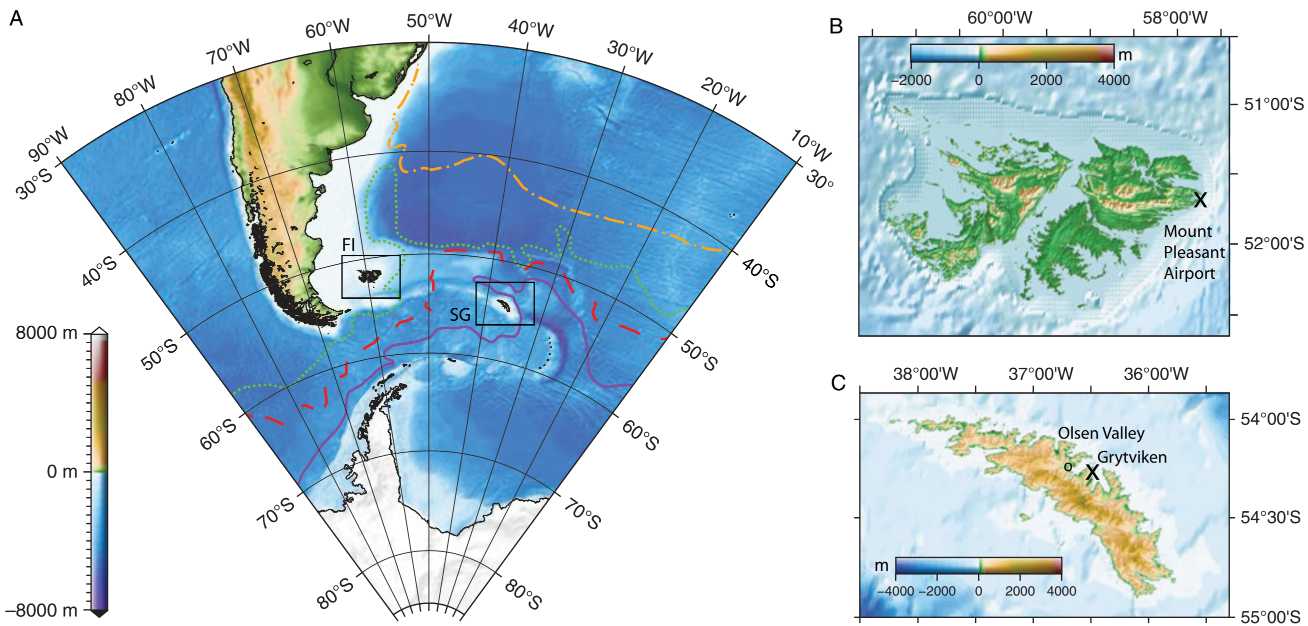

Figure 1 A) The South Atlantic sector of the Southern Ocean with the locations of the Falkland Islands (FI) and South Georgia (SG) (black boxes). Average positions of the southern limb of the Antarctic Circumpolar Current (purple, solid line), the polar front (red, dashed line), subantarctic front (green, dotted line) and the subtropical front (orange, dot-dash line) (Orsi et al. 1995). B) Falkland Islands (site locations at black X). C) South Georgia (site locations at black X, study discussed in text black circle). Maps produced with GMT (Wessel et al. 2013). (Please see electronic version for color figures.)

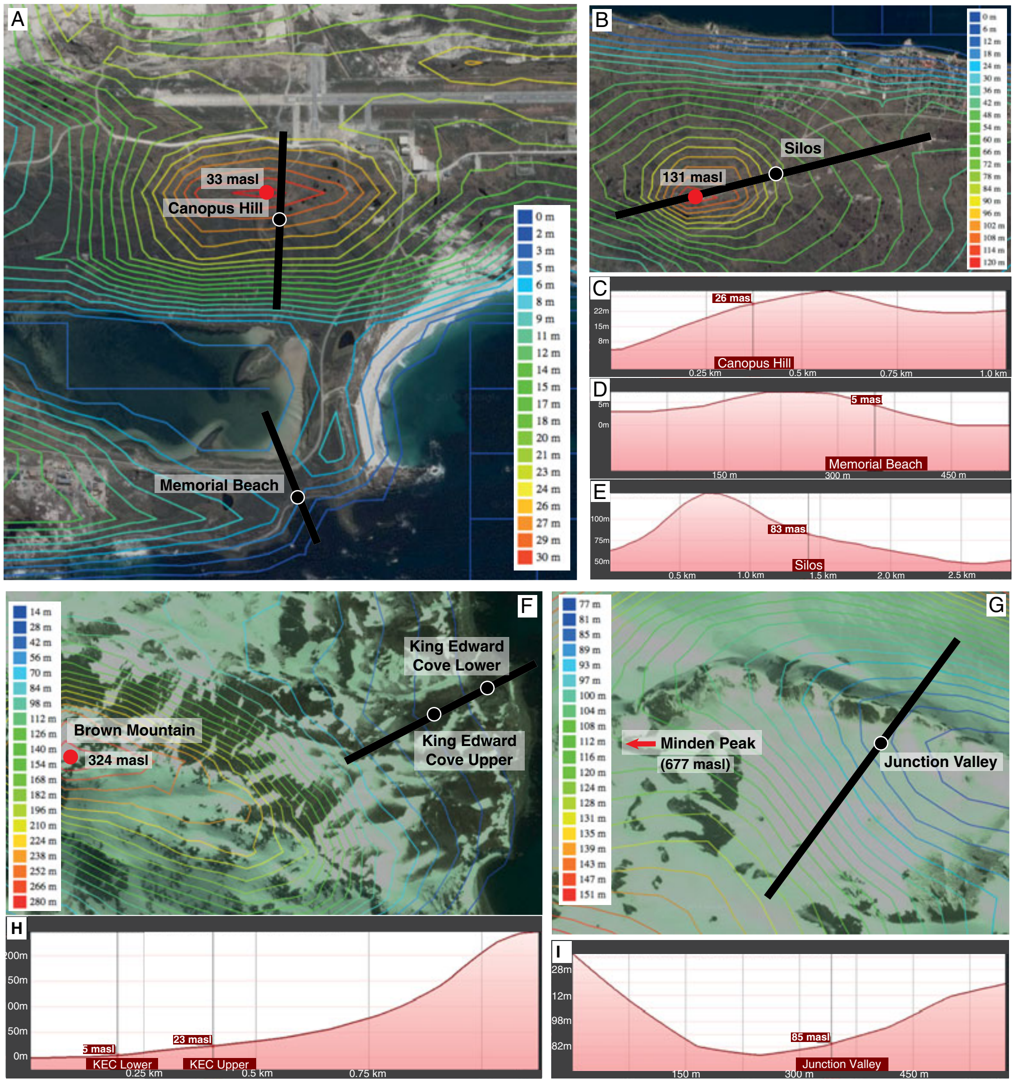

Figure 2 Site location maps with contours showing terrain, and elevation profiles: A) Canopus Hill and Memorial Beach contour map; B) Silos contour map; C, D, E) the respective elevation profiles of these 3 sites; F) King Edward Cove Lower and Upper contour map; G) Junction Valley contour map; H) the respective elevation profiles from these 3 sites. Black dots denote site locations.

the site at Silos is located on a gentle slope approximately 0.7 km from a local topographic peak, Memorial Beach is located on a narrow coastal isthmus, just above sea level (Figure 2A–E). On South Georgia, three moss-dominated (*Polytrichum strictum* and *Chorisodontium aciphyllum*) peat sites were investigated: a 0.8 m long record was obtained from King Edward Cove Lower (54.293°S, 36.494°W, approximately 5 masl); 0.9 m from King Edward Cove Upper (54.29396°S, 36.49642°W, approximately 23 masl) in Cumberland Bay; and a 0.7-m sequence was collected from Junction Valley (54.298°S, 36.524°W, approximately 80 masl, some 2 km farther inland from King Edward Cove). King Edward Cove Upper and Lower have similar depositional environments, located on the low gradient slopes, while the site at Junction

Valley is located on the toeslopes of the relatively wide valley (Figure 2F–I); all are surrounded by vegetated slopes and rocky peaks.

The subantarctic islands of the South Atlantic have been the focus of considerable work. Prior knowledge of radiocarbon chronologies from these regions can be extremely valuable when undertaking a dating campaign on a peat sequence, particularly for identifying potential accumulation rates. Following the Last Glacial Maximum, climate amelioration allowed the establishment of blanket peat across large parts of the Falkland Islands from 16,500 yr BP (Wilson et al. 2002). Today, the Falkland Islands are not glaciated, and are dominated by extensive undulating lowlands (though with several upland areas in excess of 500 m above sea level). The present climate of the Falkland Islands is characterized by a cool temperate, maritime climate, with low seasonality. The Mount Pleasant Airport weather station (Figure 1B), just a few hundred meters from the Canopus Hill site, records a mean annual temperature of 5.5°C (with a range of −5°C to 25°C), and annual precipitation of ~600 mm, which is distributed uniformly throughout the year (Lister and Jones 2014). Peat sequences across the islands have been used for studies of palaeovegetation (Barrow 1978; Clark et al. 1998), as well as past changes in the Southern Hemisphere westerly winds through the Holocene (Turney et al. 2016b; Thomas et al. 2018a).

South Georgia is a relatively small, mountainous island, down the axis of which are a series of icefields, many of which descend and terminate as tidewater glaciers that have experienced substantial retreat over recent decades (Bentley et al. 2007; Gordon et al. 2008; Cook et al. 2010; van der Bilt et al. 2017). At the Grytviken weather station (Figure 1C), a few km from the three peat sequences sampled, mean annual temperatures are ~2°C (with a range of −8°C to 20°C), with an annual precipitation over double that of the Falkland Islands at 1400 mm (mostly the result of orographic rainfall; Thomas et al. 2018b). In exceptional winters, sea ice can extend north of the island. Despite the large presence of ice over the island, the promontory of land around Grytviken is not currently directly influenced by glacial activity. However, recent work has suggested periods of glacial advance (and retreat) during the Holocene (van der Bilt et al. 2017; Berg et al. 2019; Oppedal et al. 2018), which would likely have directly impacted the higher ground around the sites investigated. Peat sequences dating to ~9000 yr BP have been analyzed for palaeovegetation and palaeoenvironmental reconstruction (van der Putten et al. 2004, 2009). The climate and environmental history of the islands will be considered when assessing the comparability of the radiocarbon inventory from each site.

METHODS

The peat sequences investigated in this study were collected by a combination of monolith tins (upper 50 cm) and at greater depth using a D-section corer with 8-cm diameter and 50-cm length. The sequences reported here comprise a uniform, humified, dark-brown peat. The material for radiocarbon dating was sampled at designated intervals, and a 1-cm section was extracted from the core using a scalpel. Where bulk peat samples were taken, any obvious woody rootlets were removed. To separate the fine and coarse fractions, the sample material was wet-sieved 0.2 mm. Sufficient micro- and macrofossil material for ^{14}C dating was obtained for each fraction after sieving.

The ^{14}C samples were pretreated, combusted, and graphitized at the University of Waikato Radiocarbon Laboratory. The $^{14}C/^{12}C$ measurement was undertaken at the University of

California at Irvine (UCI). All samples were pretreated using an acid-base-acid (ABA) protocol with multiple base extractions. Our routine procedure is 1M HCl at 80°C for 1 hr; 1M NaOH at 80°C for 30 min; 1M HCl at 80°C for 1 hr; 80°C, MilliQ^{TM} water for 5 min (pH>5), sonicated, then dried at 80°C. The supernatant is removed after each step by pipette. The chemical concentrations, number of NaOH treatments (which continues until the colour is no longer transferred from sample to the liquid), temperature and length of pretreatment will vary depending on the quantity and condition of the sample. The pretreated samples were converted to CO_2 by combustion in sealed pre-baked quartz tubes, containing Cu and Ag wire. The CO_2 was then converted to graphite using H_2 and an Fe catalyst, and loaded into aluminum target holders for measurement at UCI on a NEC compact (1.5SDH) AMS system (Southon et al. 2004).

A total of 112 ^{14}C ages were measured from 65 discrete depth horizons from six peat sequences (three on the Falkland Islands, and three from South Georgia). To better understand the radiocarbon inventory of the peat sequences, all sampled depths were measured for bulk peat, with more detailed study of 26 subsamples measured from the coarse fraction (macrofossils, identified here as >0.2 mm), and 23 samples from the fine fraction (<0.2 mm). Some of these dates have been previously published in studies reporting synoptic atmospheric circulation change and westerly wind periodicities (Turney et al. 2016a, 2016b; Thomas et al. 2018a). We report ^{14}C measurements as percent modern carbon (pMC), since some of the ages are younger CE 1950 (i.e. after the nuclear "bomb peak"), thus allowing systematic graphing and comparison (though uncalibrated radiocarbon ages are also presented in Table 1). We analyzed the uncalibrated pMC values to separate the effect of plateaus in the calibration curve in the distribution of calibrated ^{14}C dates. However, we also present a selection of probability density functions to show the effect of radiocarbon calibration using the Southern Hemisphere radiocarbon calibration curve (Hogg et al. 2013; SHCal13).

RESULTS AND DISCUSSION

The peat sequences from the two islands preserve a range of radiocarbon contents within different components of the host sediments. Canopus Hill provides the most coherent age-depth profile of the six sites investigated (Figure 3). The paired radiocarbon ages from the macrofossil, fine and bulk components are all within error, and fall on the 1:1 regression line in Figure 4, providing confidence that the age-depth relationship is robust, regardless of the fraction dated. There is therefore limited evidence of vertical movement of any fraction through the profile. Perhaps most importantly, the site is situated very near the top of a local topographic peak (Figure 2), with no surrounding higher slopes, limiting the input of older carbon into the site. Memorial Beach is situated on a short isthmus with no immediate surrounding steep slopes (Figure 2), suggesting little opportunity for redeposition of older carbon. While only bulk peat dating was undertaken, two duplicates were measured which dated within uncertainties (Figure 3). As the characteristics of Memorial Bay resemble that of Canopus Hill, we assume the age-depth profile also to be coherent.

In contrast to the above, the peat sequence at Silos has highly variable age components (Figure 3). Importantly, the 70 cm record captures most, if not all, of the Holocene (Table 1). The closest topographic high-point, only some 0.7 km distant, and the relatively steep slope (Figure 2) may have been the origin for reworked carbon, resulting in anomalously older ages for the fine fraction at any given depth (Figure 4). Here we find differences of up to 16 pMC from the upper part of the record (Wk 33414 for the coarse and

Table 1 Percent modern carbon and radiocarbon age and uncertainties for peat sequences on the Falkland Islands and South Georgia

Site and Laboratory number (Wk-)	Mid-depth (cm)	$\delta^{13}C$	Age BP	1σ	PMC	PMC-Error	Component
Canopus Hill, Falkland Islands							
34598	8.5	−25.2			116.965	0.328	Coarse
34598	8.5	−25.7			109.074	0.297	Fine
32994	11.5	−26.2			104.337	0.322	Bulk
32994	11.5	−25.1			107.824	0.329	Coarse
37007	18.5	−25.6			107.266	0.246	Coarse
33444	25.5	−26	204	25	97.494	0.305	Bulk
35146	25.5	−26.5	95	25	98.822	0.301	Coarse
32995	35.5	−26.6	648	25	92.253	0.285	Bulk
37008	35.5	−27.4	647	25	92.265	0.288	Coarse
33445	39.5	−26.4	900	25	89.401	0.272	Bulk
33445	39.5	−26	761	25	90.961	0.286	Coarse
32996	57.5	−26.5	1800	28	79.928	0.276	Bulk
32996	57.5	−26.5	1818	25	79.745	0.250	Coarse
32350	70.5	−25.4	2235	25	75.709	0.234	Coarse
32350	70.5	−26.4	2192	35	76.120	0.328	Fine
32997	97.5	−26.6	2771	30	70.825	0.267	Bulk
32997	97.5	−25.9	2749	25	71.022	0.222	Coarse
32998	107.5	−26.5	2889	29	69.789	0.245	Bulk
32998	107.5	−24.2	2914	26	69.573	0.220	Coarse
32351	141.5	−26.6	3955	32	61.115	0.239	Coarse
32351	141.5	−26.6	4054	35	60.373	0.262	Fine
Memorial Beach, Falkland Islands							
39909	2.5		106.8	0.3	106.771	0.263	Bulk
39910	10.5		100.6	0.3	100.628	0.249	Bulk
32352	30.5	−25.7	322	42	96.074	0.502	Bulk
33021	30.5	−25.4	410	26	95.023	0.311	Bulk
33417	65.5	−24.6	888	25	89.539	0.278	Bulk
33418	90.5	−25.4	1389	25	84.122	0.261	Bulk
33419	120.5	−25.1	2053	25	77.443	0.234	Bulk
32353	145.5	−24.9	2501	31	73.244	0.282	Bulk
33022	145.5	−26.5	2561	38	72.698	0.337	Bulk
Silos, Falkland Islands							
34841	5.5	−26.5			106.029	0.234	Coarse
33414	15.5	−24.4			108.924	0.317	Coarse
33414	15.5	−25.6	669	25	92.008	0.286	Fine
34838	15.5	−24.2			104.635	0.247	Coarse
32354	30.5	−26.1	2638	25	72.010	0.224	Coarse
32354	30.5	−25.7	6389	33	45.141	0.182	Fine
33019	30.5	−26.3	5471	28	50.606	0.175	Bulk
33415	40.5	−27.6	9644	34	30.104	0.129	Bulk
33415	40.5		1701	27	80.912	0.269	Coarse
34839	40.5	−24.6			101.757	0.240	Coarse

(*Continued*)

Table 1 (*Continued*)

Site and Laboratory number (Wk-)	Mid-depth (cm)	$\delta^{13}C$	Age BP	1σ	PMC	PMC-Error	Component
32355	48.5	−25.7	7775	34	37.987	0.159	Coarse
32355	48.5	−27.9	11930	45	22.647	0.126	Fine
33020	48.5	−26.4	9795	39	29.540	0.142	Bulk
33416	65.5	−25.8	10177	35	28.170	0.122	Coarse
33416	65.5	−27.6	12737	40	20.483	0.102	Fine
34840	65.5	−26.9	7879	45	37.498	0.207	Coarse
King Edward Cove Lower, South Georgia							
34599	8.5	−22.9			115.222	0.391	Coarse
34599	8.5	−24	136	25	98.315	0.297	Fine
32999	13.5	−23.6		0.4	101.254	0.327	Bulk
34600	16.5	−21.5			103.866	0.279	Coarse
34600	16.5	−23.8	287	25	96.484	0.296	Fine
33000	27.5	−24	337	26	95.890	0.308	Bulk
33000	27.5	−21.6			100.310	0.292	Coarse
33446	35.5	−23.5	574	25	93.100	0.288	Bulk
33446	35.5	−22.6	103	25	98.723	0.306	Coarse
34601	40.5	−21.2	251	25	96.921	0.295	Coarse
34601	40.5	−24.2	941	25	88.950	0.277	Fine
32358	45.5	−21.4	446	26	94.600	0.312	Coarse
32358	45.5	−23.1	1078	37	87.443	0.403	Fine
33001	57.5	−22.5	1012	25	88.166	0.276	Bulk
37009	57.5	−22.3	729	25	91.325	0.284	Coarse
34602	64.5	−23.9	1193	25	86.195	0.264	Coarse
34602	64.5	−24.6	1351	24	84.524	0.261	Fine
32359	70.5	−22.4	983	26	88.477	0.280	Coarse
32359	70.5	−23.7	1577	31	82.175	0.315	Fine
37010	75.5	−23.8	1015	25	88.132	0.271	Coarse
33002	78.5	−29.6	1692	29	81.006	0.295	Bulk
33447	80.5	−26.3	1513	25	82.830	0.253	Bulk
35149	81.5	−26.8	1373	30	84.294	0.319	Coarse
King Edward Cove Upper, South Georgia							
34603	8.5				103.479	0.396	Coarse
34603	8.5		521	25	93.716	0.287	Fine
33448	10.5	−25	526	25	93.658	0.289	Bulk
34604	11.5		539	26	93.505	0.300	Coarse
34604	11.5	−24.8	944	30	88.913	0.336	Fine
33003	13.5	−25.1	495	27	94.026	0.320	Bulk
33003	13.5	−23.3	82	25	98.990	0.317	Coarse
33449	20.5	−23.3	845	25	90.012	0.274	Bulk
33449	20.5	−23.5	113	26	98.601	0.315	Coarse
33450	25.5	−23.6	2002	25	77.936	0.240	Bulk
33450	25.5	−23.1	643	25	92.307	0.285	Coarse
33004	29.5	−27.3	2389	27	74.272	0.247	Bulk
34605	36.5	−25.3	3253	25	66.703	0.212	Coarse

Table 1 (*Continued*)

Site and Laboratory number (Wk-)	Mid-depth (cm)	$\delta^{13}C$	Age BP	1σ	PMC	PMC-Error	Component
34605	36.5	−25.1	3521	25	64.515	0.205	Fine
32360	45.5	−26.8	2821	27	70.388	0.237	Coarse
32360	45.5	−25.4	3958	33	61.098	0.252	Fine
33005	57.5	−27.7	3876	30	61.721	0.231	Bulk
33005	57.5		2133	28	76.678	0.267	Coarse
34606	64.5	−25.8	4224	25	59.104	0.180	Coarse
34606	64.5	−25.8	4472	27	57.307	0.190	Fine
33006	73.5	−26.5	4625	32	56.228	0.224	Bulk
33006	73.5	−24.6	2269	26	75.389	0.237	Coarse
32361	90.5	−27.5	6658	29	43.657	0.160	Coarse
32361	90.5	−26.6	7065	42	41.500	0.216	Fine
Junction Valley, South Georgia							
33451	7.25	−23.6		0.4	124.714	0.389	Bulk
35147	7.25	−27	Infinite		0.107	0.080	Coarse
37011	10.5	−26.5			121.690	0.377	Coarse
37012	12.5	−26.8			107.245	0.234	Coarse
33452	14.5	−25.5	240	25	97.052	0.292	Bulk
35148	14.5	−27.8	144	25	98.217	0.301	Coarse
32356	20.5	−27.4	737	25	91.233	0.286	Coarse
32356	20.5	−26.1	1374	31	84.273	0.321	Fine
37013	22.5	−29	545	25	93.435	0.289	Coarse
33007	33.5	−27.2	3229	33	66.902	0.279	Bulk
37014	33.5	−27.4	1821	25	79.716	0.247	Coarse
34607	36.5	−25.6	3714	25	62.981	0.198	Coarse
34607	36.5	−25.6	Infinite	—	0.024	0.053	Fine
33008	43.5	−26.4	4518	31	56.983	0.219	Bulk
33009	53.5	−27.1	4428	30	57.626	0.215	Bulk
34608	58.5	−25.7	4858	25	54.621	0.171	Coarse
34608	58.5	−25.7	5234	28	52.124	0.180	Fine
32357	64.5	−28	5071	30	53.193	0.198	Coarse
32357	64.5	−27.6	5692	33	49.235	0.202	Fine

fine fraction at 15–16 cm; Table 1); a duplicate coarse sample from the same depth indicates a 4 pMC difference (Wk 34838). At 65–66 cm depth, two duplicate coarse fractions indicate a difference of 11 pMC (Wk 33416 & 34840). Perhaps tellingly, the poor replication of duplicate samples demonstrates that developing a robust chronology from slowly accumulating sequences in areas surrounded by relatively steep slopes can be highly challenging.

To test the above interpretation, we sampled three sequences from South Georgia. Our immediate focus was on two sites near the coast at King Edward Cove. The “Upper” sequence was sampled from a peat-covered terrace towards the eastern base of Brown Mountain (324 masl), while the “Lower” record was obtained at lower elevation (i.e. below the terrace) closer to the coast (Figure 2). The two sites were selected to test whether the

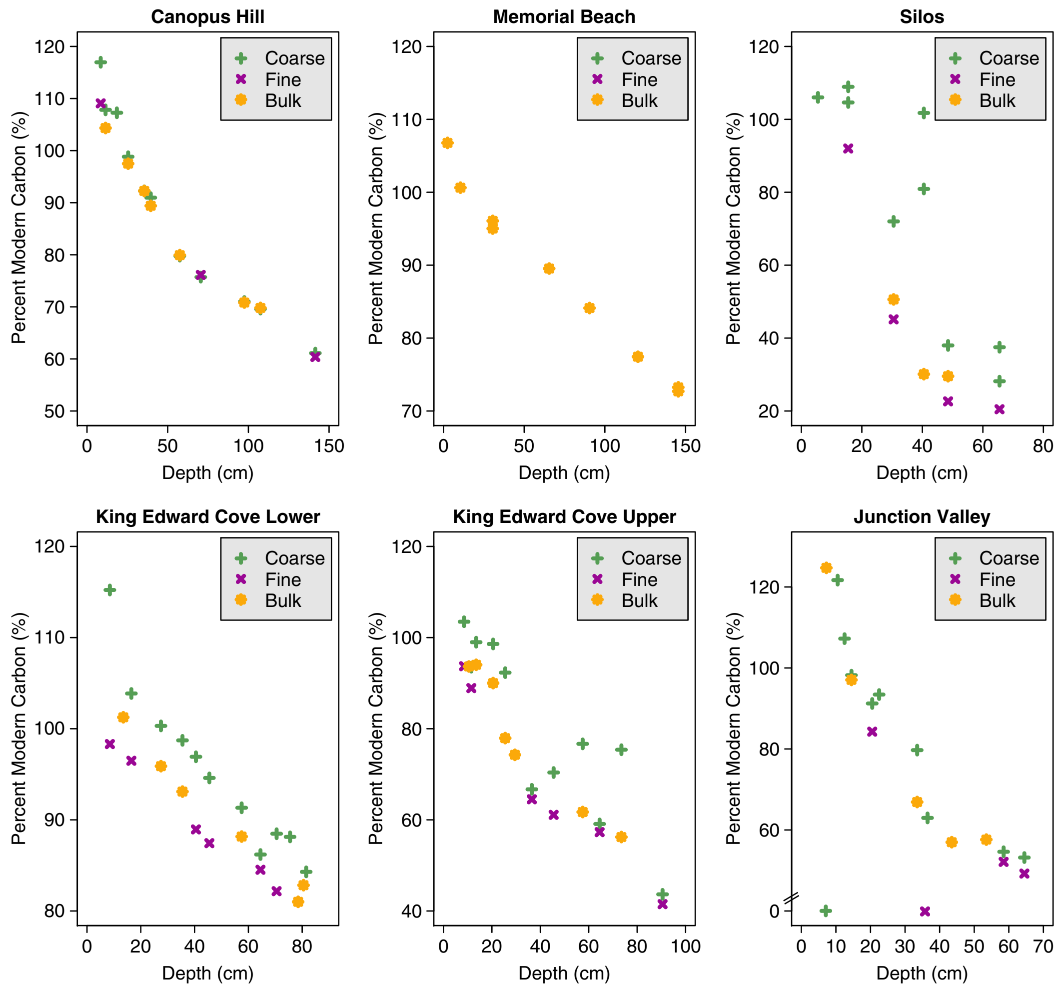

Figure 3 pMC vs. depth plot for each site on the Falkland Islands and South Georgia, with the coarse, fine, and bulk peat fraction pMC plotted. Note that two infinitely old ages (i.e. >50 ka) at 7–7.5 cm and 36–37 cm in the Junction Valley sediment core are not plotted.

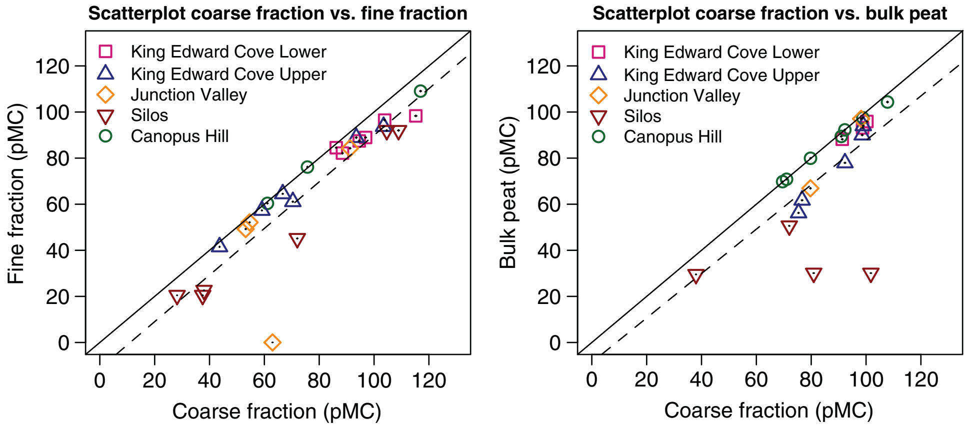

Figure 4 Scatterplot of pMC values for all sites with duplicate measurements, with the coarse, fine and bulk peat fraction separated. Solid line indicates a 1:1 regression, dashed line is a simple linear regression.

(upper) terrace site might be more vulnerable to the input of older carbon from Brown Mountain. In the Upper sequence we find that none of the components provide an internally coherent series of ages, although the coarse (macrofossil) samples are consistently younger than the other fractions (Figures 3 and 4). In contrast, the Lower sequence (farther from Brown Mountain) displays a striking consistent offset in ^{14}C measurements between the three fractions, with the coarse macrofossils the youngest component, and the fine the oldest. The implication of these two series is that close to mountain slopes, the coarse macrofossil fraction cannot necessarily be considered reliable, and that the fine fraction may be vertically mobile, resulting in older ages at depth.

Importantly, these findings do not preclude dating of sequences at relatively high elevations, as long as the site is surrounded by open, low gradient terrain as found at Junction Valley (Figure 2). The area is characterised by a succession of small peat terraces higher up that are stepped down through Junction Valley, allowing the opportunity to capture the (re) deposition of material from the upper slopes before it reaches the lower slopes. Here we sampled a peat sequence on the base of the hillslope, distant from the steeper upper slopes, that is relatively slowly accumulating (arguably similar to Silos on the Falkland Islands; Table 1). The sequence exhibits a surprising coherence between the different size fractions (Figure 3). However, two "infinitely-old" ages were measured from near the surface (macrofossils from 7–7.5 cm; Wk 35147) and at depth (the fine fraction at 36–37 cm; Wk 34607), suggesting that there is still potential for redeposition of significantly older carbon from eroding deposits upslope near Minden Peak (677 masl).

The calibration of ^{14}C ages relies on the construction of an appropriate calibration curve (e.g. IntCal13 (Reimer et al. 2013a) for Northern Hemisphere samples, and SHCal13 (Hogg et al. 2013) for Southern Hemisphere samples). However, a characteristic feature of calibration curves is that radiocarbon age is not precisely linear with calendar age, as evidenced by the presence of radiocarbon plateaux, where single ^{14}C ages correspond to multiple calendar ages, and "wiggles," where ^{14}C ages fluctuate rapidly. As a result, a single ^{14}C date may correspond to more than one calendar age, or a large time interval with a corresponding large uncertainty. Conversely, in periods containing ^{14}C "wiggles," a surprisingly precise chronology can be

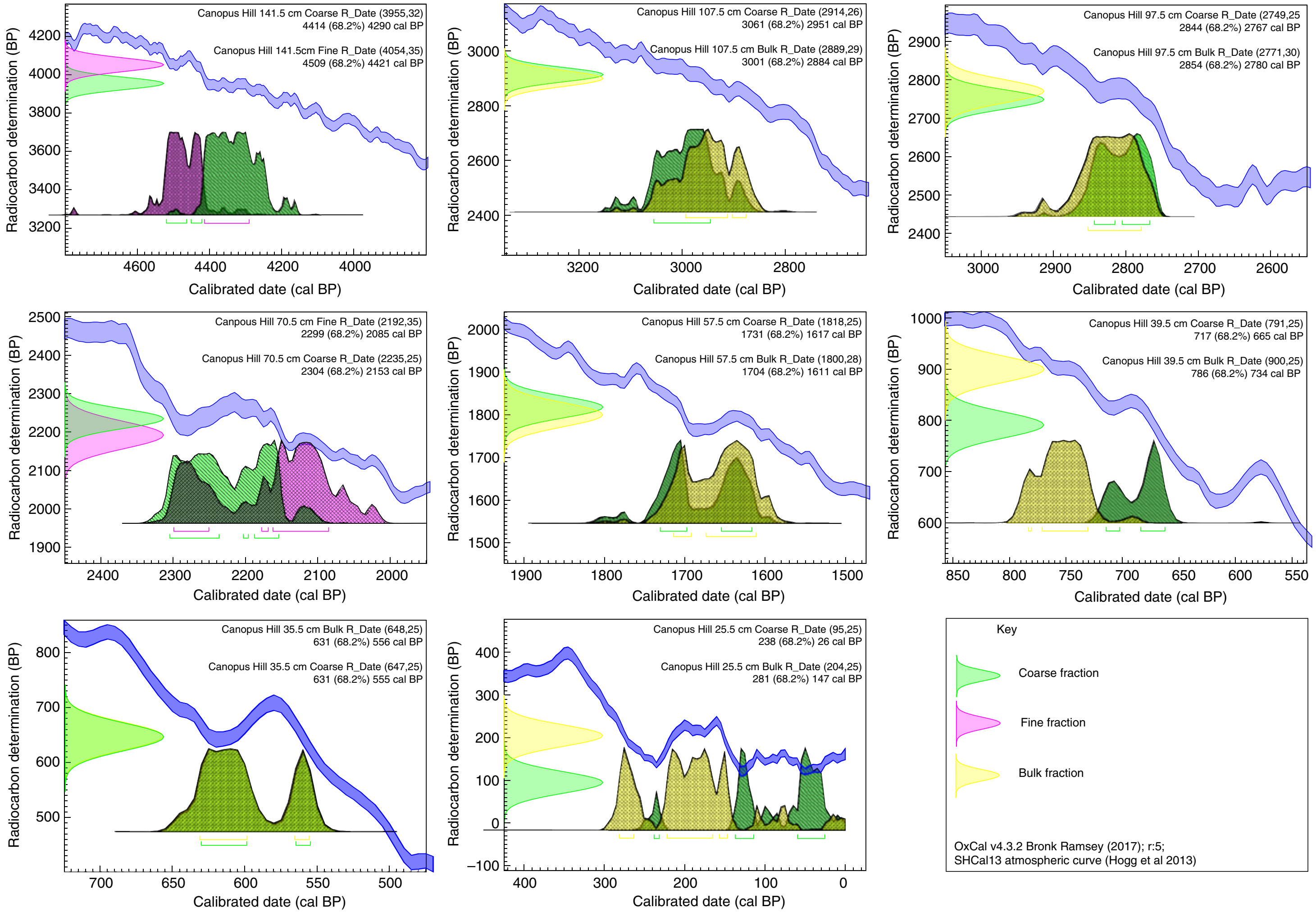

Figure 5 The calibrated age probability density distributions of paired fractions from Canopus Hill, Falkland Islands: coarse (green) and fine (purple), and coarse (green) and bulk (yellow) AMS ^{14}C ages. Calibrated with SHCal13 calibration curve (blue line) (Hogg et al. 2013), figure plotted with OxCal v4.3.2 (Bronk Ramsey 2017).

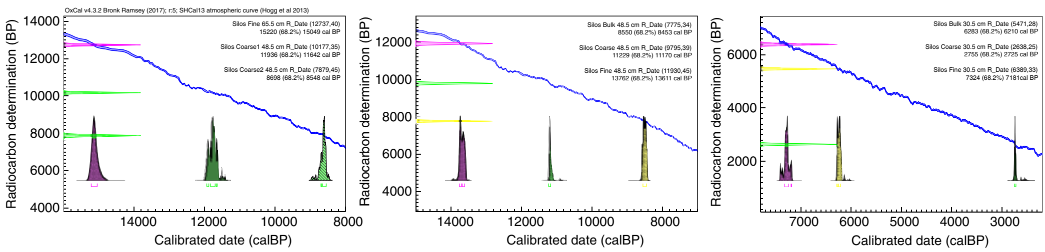

Figure 6 The calibrated age probability density distributions of three fractions from Silos, Falkland Islands: coarse (green), fine (purple), and bulk (yellow) AMS ^{14}C ages. Calibrated with SHCal13 calibration curve (blue line) (Hogg et al. 2013), figure plotted with OxCal v4.3.2 (Bronk Ramsey 2017).

determined, and Bayesian age-modeling software such as OxCal (Bronk Ramsey and Lee 2013) and Bacon (Blaauw and Christen 2011) can significantly reduce chronological uncertainties within a sequence.

In the Canopus Hill peat sequence, calibration of the paired ^{14}C ages from the different fractions results in virtually identical probability distribution functions for the calendar age ranges, although the exact degree of overlap depends somewhat on the structure of the calibration curve (Figure 5). Both the 57.5 cm and the 35.5 cm dated horizon in this sequence display a bimodal distribution as a result of the complex structure of the calibration curve, making the calendar age range estimation larger than a comparable unimodal distribution. However, in the Silos sequence, the difference in age determination between the three fractions is exacerbated when ages are calibrated, with individual horizons displaying a range of several millennia (Figure 6).

Certain climatic or environmental conditions may influence the radiocarbon inventory of different sizes and/or fractions. For example, cold environments (particularly those that are high latitude or high elevation) are generally characterized by low sedimentation rates. This increases the likelihood of higher proportions of redeposited older carbon being incorporated into the sediment sequence. In the Falkland Islands sites, both Canopus Hill and Memorial Beach have relatively high average sedimentation rates at 28.5 ^{14}C yr/cm and 17.5 ^{14}C yr/cm and display coherent age-depth profiles. Conversely, the site at Silos has a much lower sedimentation rate (119.4 ^{14}C yr/cm), with a less consistent age-depth profile, suggesting that the rates of sedimentation may play an important role in the comparability of different size fractions dated (Figure 3). However, this relationship does not hold in South Georgia, where average sedimentation rates range from 16.7 ^{14}C yr/cm (King Edward Cove Lower) to 77.6 ^{14}C yr/cm (King Edward Cover Upper) to 87.6 ^{14}C yr/cm (Junction Valley), and where Junction Valley displays the most coherent age-depth profile of the three sites, but with the slowest rate of sedimentation. This therefore suggests that while sedimentation rate is likely influential, it is not the most important factor affecting the reliability of ^{14}C dating of peat sequences. Another possible factor affecting the ^{14}C inventory is the contamination of marine carbon from bird droppings. Seabird colonies are common throughout the both islands though the site locations reported here were far from large colonies and beyond the direct influence of birds. While we found no physical or chemical evidence to suggest the incorporation of marine carbon, we cannot totally exclude this as a possibility.

To investigate any systematic differences in the sediment radiocarbon inventory arising from Holocene and Late Glacial environmental changes, we compared glacier and palaeoclimate

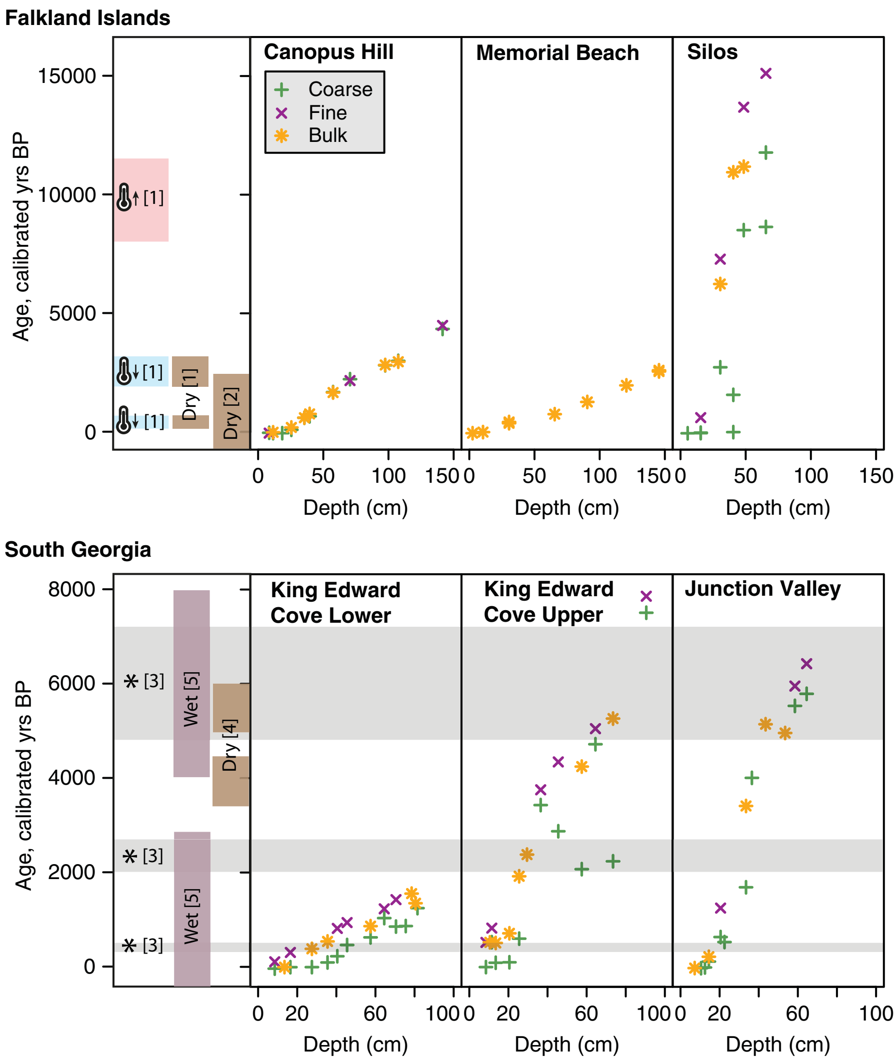

Figure 7 The calibrated age-depth relationship for each site, with a comparison of selected glacier and qualitative palaeoclimate reconstructions from the Falklands and South Georgia: [1] (Wilson et al. 2002); [2] (Thomas et al. 2018a); [3] (Oppedal et al. 2018); [4] (van der Putten et al. 2009); [5] (van der Putten et al. 2004). Thermometer symbols with arrows denote relative warm and cool periods (blue and red boxes). Asterisks denote glacial advances (grey band). Relative wet and dry periods are shown by the purple and brown boxes, respectively.

reconstructions from selected sites in the Falklands and South Georgia with ^{14}C profiles. Environmental changes, such as periods of glacier advance, seasonal snow-cover, and/or wetter conditions, can impact surface processes, potentially resulting in non-contemporaneous carbon being remobilized and incorporated into sedimentary sequences. The latter includes the migration of fine-sized material through sedimentary profiles. Although we found no evidence of cryoturbation in our sequences, it is possible that previously freezing period(s) may have impacted the stratigraphic record and left no visible evidence. For instance, several Holocene glacial advances have been recently identified in the Olsen Valley to the immediate west of Grytviken in South Georgia (Figures 1 and 7). These include an early Holocene advance (between 7200 ± 400 to 4800 ± 200 cal yr BP), a late Holocene advance (between 2700 ± 150 to 2000 ± 200 cal yr BP) and a more recent advance (500 ± 150 to 300 ± 100 cal yr BP) (Oppedal et al. 2018). Other reconstructions have suggested different periods of relatively wet and dry conditions throughout the Holocene (van der Putten et al. 2004, 2009). While the glacial advance between 2700 ± 150 to 2000 ± 200 cal yr BP coincides with a range of ^{14}C determinations over different fractions, similar ^{14}C distributions do not occur during other two reported glacial advances, suggesting there is limited support for strong environmental influence. In the Falkland Islands, there appears to have been a shift toward drier conditions over the last ~3000 years (Wilson et al. 2002; Thomas et al. 2018a). While Canopus Hill and Memorial Beach both display coherent age-depth profiles over this period, the site at Silos has a complex age-depth relationship, which does not appear to correlate with any published records of climate/environmental change (Figure 7). More detailed high-resolution climate reconstructions across the two islands are needed to clarify these relationships. Our results therefore suggest that while periods of environmental change can result in sediment (and ^{14}C) remobilization, site location remains a critical factor in what are inherently highly dynamic landscapes.

CONCLUSIONS

We conclude that site location is the primary factor for producing robust chronologies in highly dynamic landscapes. The most desirable situations are sites with limited opportunities for redeposition from higher adjacent areas, reducing the range of ^{14}C content within a sample. However, in situations where this is not possible, this study suggests that a coarse fraction (macrofossils) offers the best potential for ages that are more likely contemporaneous with the period of sediment accumulation. Bulk peat does not appear to introduce systematic bias and should not be excluded, a finding which supports previous studies (Blaauw et al. 2004; Holmquist et al. 2016). However, since most of the oldest ages were measured from the fine component, this fraction should be discouraged from use in the development of chronologies. Ideally, a large number of ^{14}C age determinations should be used to construct a robust chronology in highly dynamic landscapes, with dating of duplicate fractions to determine the extent of potential incorporation of non-contemporaneous carbon. However, the cost of such an approach is typically too expensive for most studies. It is therefore crucial that a thorough understanding of the depositional context and the potential for reworking is attained for radiocarbon dating of such deposits to be most successful. This is particularly important if natural archives in the mid to high latitudes are to be fully exploited for understanding past and future climate variability and impacts (Thomas 2016).

ACKNOWLEDGMENTS

CSMT and CF acknowledge the support of the Australian Research Council (FL100100195, FT120100004 and DP130104156). We thank the captain and crew of the Fishery Patrol Vessel The Pharos for travel to and from South Georgia, and the Government of South Georgia and the South Sandwich Islands, and the Falkland Islands Government for permission to undertake sampling on the island (permit numbers SGEP0110/11 and R07/2011, respectively), and Darren Christie for assisting with the fieldwork on the Falkland Islands. We would like to thank two anonymous reviewers and Associate Editor Pieter Grootes for their thorough reviews and helpful comments, which helped to improve the manuscript.

REFERENCES

Amesbury MJ, Roland TP, Royles J, Hodgson DA, Convey P, Griffiths H, Charman DJ. 2017. Widespread biological response to rapid warming on the Antarctic Peninsula. Current Biology 27(11):1616–1622.e2. doi: 10.1016/j.cub.2017.04.034.

Barrow C. 1978. Postglacial pollen diagrams from South Georgia (Sub-Antarctic) and West Falkland island (South Atlantic). Journal of Biogeography 5(3):251–274. doi: 10.2307/3038040.

Bentley MJ, Evans DJA, Fogwill CJ, Hansom JD, Sugden DE, Kubik PW. 2007. Glacial geomorphology and chronology of deglaciation, South Georgia, Sub-Antarctic. Quaternary Science Reviews 26(5-6):644–677. doi: 10.1016/j.quascirev.2006.11.019.

Berg S, White DA, Jivcov S, Melles M, Leng MJ, Rethemeyer J, Allen C, Perren B, Bennike O, Viehberg F. 2019. Holocene glacier fluctuations and environmental changes in subantarctic South Georgia inferred from a sediment record from a coastal inlet. Quaternary Research 91(1):132–148. doi: 10.1017/qua.2018.85.

Blaauw M, Christen JA. 2011. Flexible paleoclimate age-depth models using an autoregressive gamma process. Bayesian Analysis 6(3):457–474. doi: 10.1214/11-BA618.

Blaauw M, van der Plicht J, van Geel B. 2004. Radiocarbon dating of bulk peat samples from raised bogs: non-existence of a previously reported "reservoir effect"? Quaternary Science Reviews 23(14–15):1537–1542. doi: 10.1016/j.quascirev.2004.04.002.

Blockley SPE, Lane CS, Hardiman M, Rasmussen SO, Seierstad IK, Steffensen JP, Svensson A, Lotter AF, Turney CSM, Bronk Ramsey C. 2012. Synchronisation of palaeoenvironmental records over the last 60, 000 years, and an extended INTIMATE 1 event stratigraphy to 48, 000 b2k. Quaternary Science Reviews 36: 2–10. doi: 10.1016/j.quascirev.2011.09.017.

Brock F, Higham T, Ditchfield P, Bronk Ramsey C. 2010. Current pretreatment methods for ams radiocarbon dating at the oxford radiocarbon accelerator unit (ORAU). Radiocarbon 52(1):103–112. doi: 10.1017/S0033822200045069.

Brock F, Lee S, Housley RA, Bronk Ramsey C. 2011. Variation in the radiocarbon age of different fractions of peat: a case study from Ahrenshöft, Northern Germany. Quaternary Geochronology 6(6):550–555. doi: 10.1016/j.quageo.2011.08.003.

Bronk Ramsey C. 2017. OxCal program, version 4.3.

Bronk Ramsey C, Lee S. 2013. Recent and planned developments of the program OxCal. Radiocarbon 55(2-3):720–730. doi: 10.2458/azu_js_rc.55.16215.

Chu Z, Sun L, Huang W, Huang T, Zhou X. 2016. On selecting bulk fjord sediment samples for radiocarbon dating in Fildes Peninsula, Antarctica. Quaternary International 425: 173–182. doi: 10.1016/j.quaint.2015.10.118.

Clark R, Huber UM, Wilson P. 1998. Late Pleistocene sediments and environmental change at Plaza Creek, Falkland Islands, South Atlantic. Journal of Quaternary Science 13(2):95–105.

Cook AJ, Poncet S, Cooper APR, Herbert DJ, Christie D. 2010. Glacier retreat on South Georgia and implications for the spread of rats. Antarctic Science 22(3):255–263. doi: 10.1017/s0954102010000064.

Gallego-Sala AV, Charman DJ, Brewer S, Page SE, Prentice IC, Friedlingstein P, Moreton S, Amesbury MJ, Beilman DW,Björck S, Blyakharchuk T, Bochicchio C, Booth RK, Bunbury J, Camill P, Carless D, Chimner RA, Clifford M, Cressey E, Courtney-Mustaphi C, De Vleeschouwer F, de Jong R, Fialkiewicz-Koziel B, Finkelstein SA, Garneau M, Githumbi E, Hribjlan J, Holmquist J, Hughes PDM, Jones C, Jones MC, Karofeld E, Klein ES, Kokfelt U, Korhola A, Lacourse T, Le Roux G, Lamentowicz M, Large D, Lavoie M, Loisel J, Mackay H, MacDonald GM, Makila M, Magnan G, Marchant R, Marcisz K, Cortizas AM, Massa C, Mathijssen P, Mauquoy D, Mighall T, Mitchell FJG, Moss P, Nichols J, Oksanen PO, Orme L, Packalen MS, Robinson S, Roland TP, Sanderson NK, Sannel ABK, Silva-Sánchez N, Steinberg N, Swindles GT, Turner TE, Uglow J, Väliranta M, van Bellen S, van der Linden M, van Geel B, Wang G, Yu Z, Zaragoza-Castells J, Zhao Y. 2018. Latitudinal limits to the predicted increase of the Peatland carbon sink with warming. Nature Climate Change 8:907–913. doi: 10.1038/s41558-018-0271-1.

Gordon JE, Haynes VM, Hubbard A. 2008. Recent glacier changes and climate trends on South Georgia. Global Planetary Change 60(1-2): 72–84. doi: 10.1016/j.gloplacha.2006.07.037.

Hill TCB, Hill GE, Brunning R, Banerjea RY, Fyfe RM, Hogg AG, Jones J, Perez M, Smith DN. 2019. Glastonbury lake village revisited: a multi-proxy palaeoenvironmental investigation of an Iron Age wetland settlement. Journal of Wetland Archaeology 18(2):115–137. doi: 10.1080/14732971.2018.1560064.

Hogg AG, Hua Q, Blackwell PG, Niu M, Buck CE, Guilderson TP, Heaton TJ, Palmer JG, Reimer PJ, Reimer RW, Turney CSM, Zimmerman SRH. 2013. SHCAL13 Southern Hemisphere calibration, 0–50, 000 years cal BP. Radiocarbon 55(4):1889–1903.

Holmquist JR, Finkelstein SA, Garneau M, Massa C, Yu Z, MacDonald GM. 2016. A comparison of radiocarbon ages derived from bulk peat and selected plant macrofossils in basal peat cores from circum-arctic Peatlands. Quaternary

Geochronology 31:53–61. doi: 10.1016/j.quageo.2015.10.003.

Howarth JD, Fitzsimons SJ, Jacobsen GE, Vandergoes MJ, Norris RJ. 2013. Identifying a reliable target fraction for radiocarbon dating sedimentary records from lakes. Quaternary Geochronology 17:68–80. doi: 10.1016/j.quageo.2013.02.001.

IPCC AR5. 2013. Climate change 2013: the physical science basis. In: StockerTF, QinD, PlattnerG-K, TignorM, AllenSK, BoschungJ, NauelsA, XiaY, BexV, MidgleyPM, editors. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge and New York: Cambridge University Press.

Ivanov KE. 1981. Water movement in Mirelands. AQ3 Academic Press.

Jones JM, Gille ST, Goosse H, Abram NJ, Canziani PO, Charman DJ, Clem KR, Crosta X, de Lavergne C, Eisenman I, England MH, Fogt RL, Frankcombe LM, Marshall GJ, Masson-Delmotte V, Morrison AK, Orsi AJ, Raphael MN, Renwick JA, Schneider DP, Simpkins GR, Steig EJ, Stenni B, Swingedouw D, Vance TR. 2016. Assessing recent trends in high-latitude Southern Hemisphere surface climate. Nature Climate Change 6(10):917–926. doi: 10.1038/nclimate3103.

Joosten H, De Klerk P. 2007. In search of finiteness: the limits of fine-resolution palynology of Sphagnum peat. Holocene 17(7):1023–1031. doi: 10.1177/0959683607082416.

Kershaw PA, McKenzie G, Porch N, Roberts RG, Brown J, Heijnis H, Orr ML, Jacobson G, Newall PR. 2007. A high-resolution record of vegetation and climate through the last glacial cycle from Caledonia Fen, Southeastern highlands of Australia. Journal of Quaternary Science 22(8):481–500. doi: 10.1002/jqs.

Kilian MR, van Geel B, van der Plicht J. 2000. ^{14}C AMS wiggle matching of raised bog deposits and models of peat accumulation. Quaternary Science Reviews 19:1011–1033. doi: 10.1016/S0277-3791(99)00049-9.

Lister D, Jones P. 2014. Long-term temperature and precipitation records from the Falkland Islands. International Journal of Climatology 35(7):1224–1231. doi: 10.1002/joc.4049.

Lowe JJ, Walker MJC. 1997. Reconstructing quaternary environments. 2nd edition. Routledge.

Martin L, Goff J, Jacobsen G, Mooney S. 2018. The radiocarbon ages of different organic components in the Mires of Eastern Australia. Radiocarbon 61(1):1–12. doi: 10.1017/RDC.2018.118.

McGlone MS, Turney CSM, Wilmshurst JM, Renwick J,Pahnke K. 2010. Divergent trends in land and ocean temperature in the Southern Ocean over the past 18, 000 years. Nature Geoscience 3(9):622–626. doi: 10.1038/ngeo931.

McGlone MS, Wilmshurst JM. 1999. Dating initial Maori enviromental impact in New Zealand. Quaternary International 59:5–16.

Nilsson M, Klarqvist M, Bohlin E, Possnert G. 2001. Variation in ^{14}C age of macrofossils and different fractions of minute peat samples dated by AMS. Holocene 11(5):579–586. doi: 10.1191/095968301680223521.

Olsson IU. 1986. Study of errors in ^{14}C dates of peat and sediment. Radiocarbon 28(2):429–435.

Oppedal LT, Bakke J, Paasche Ø, Werner JP, van der Bilt WGM. 2018. Cirque glacier on South Georgia shows centennial variability over the last 7000 years. Frontiers of Earth Science 6(2). doi: 10.3389/feart.2018.00002. AQ4

Orsi AH, Whitworth T, Nowlin WD. 1995. On the meridional extent and fronts of the Antarctic circumpolar current. Deep-Sea Research Part I 42(5):641–673. doi: 10.1016/0967-0637(95)00021-W.

Oswald WW, Anderson PM, Brown TA, Brubaker LB, Feng SH, Lozhkin AV, Tinner W, Kaltenrieder P. 2005. Effects of sample mass and macrofossil type on radiocarbon dating of arctic and boreal lake sediments. The Holocene 15(5):758–767. doi: 10.1191/0959683605hl849rr.

Piotrowska N, Blaauw M, Mauquoy D, Chambers FM. 2011. Constructing deposition chronologies for peat deposits using radiocarbon dating. Mires and Peat 7(10):1–14. doi: 10.1111/j.1365-2486.2009.01920.x.

Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Ramsey CB. 2013a. IntCal13 and Marine13 radiocarbon age calibration curves 0-50, 000 years cal BP. Radiocarbon 55(4):1869–1887. doi: 10.2458/azu_js_rc.55.16947.

Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Ramsey CB, Brown DM, Buck CE, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Haflidason H, Hajdas I, Hatté C, Heaton TJ, Hogg AG, Hughen KA, Felix Kaiser K, Kromer B, Manning SW, Reimer RW, Richards DA, Marian Scott E, Southon JR, Turney CSM, van der Plicht J. 2013b. Selection and treatment of data for radiocarbon calibration: an update to the International Calibration (IntCal) criteria. Radiocarbon 55(4):1923–1945. doi: 10.2458/azu_js_rc.55.16955.

Scott EM, Cook GT, Naysmith P. 2010. The Fifth International Radiocarbon Intercomparison (VIRI): an assessment of laboratory performance in Stage 3. Radiocarbon 52(3):859–865.

Shore JS, Bartley DD, Harkness DD. 1995. Problems encountered with the ^{14}C dating of peat. Quaternary Science Reviews 14:373–383.

Southon J, Santos G, Druffel-Rodriguez K, Druffel E, Trumbore S, Xu X, Griffin S, Ali S, Mazon M. 2004. The Keck carbon cycle AMS laboratory, University of California, Irvine: initial operation and a background surprise. Radiocarbon 46(1):41–49.

Strother SL, Salzmann U, Roberts SJ, Hodgson DA, Woodward J, Van Nieuwenhuyze W, Verleyen E, Vyverman W, Moreton SG. 2015. Changes in Holocene climate and the intensity of Southern Hemisphere Westerly Winds based on a high-resolution palynological record from sub-Antarctic South Georgia. The Holocene 25(2):263–279. doi: 10.1177/0959683614557576.

Thomas ZA. 2016. Using natural archives to detect climate and environmental tipping points in the earth system. Quaternary Science Reviews 152:60–71. doi: 10.1016/j.quascirev.2016.09.026.

Thomas ZA, Jones RT, Fogwill CJ, Hatton J, Williams A, Hogg AG, Mooney SD, Jones PD, Lister D, Mayewski PA, Turney CSM. 2018a. Evidence for increased expression of the Amundsen Sea Low over the South Atlantic during the late Holocene. Climate of the Past 14:1727–1738. doi: 10.5194/cp-14-1727-2018.

Thomas Z, Turney C, Allan R, Colwell S, Kelly G, Lister D, Jones P, Beswick M, Alexander L, Lippmann T, Herold N, Jones R. 2018b. A new daily observational record from Grytviken, South Georgia: exploring 20th century extremes in the South Atlantic. Journal of Climate 31(5):1743–1755. doi: 10.1175/JCLI-D-17-0353.1.

Turetsky MR, Manning SW, Wieder RK. 2004. Dating recent peat deposits. Wetlands 24(2):324–356. doi: 10.1672/0277-5212(2004)024[0324:DRPD]2.0.CO;2.

Turney CSM, Coope GR, Harkness DD, Lowe JJ, Walker MJC. 2000. Implications for the dating of Wisconsinan (Weichselian) Late-glacial events of systematic radiocarbon age differences between terrestrial plant macrofossils from a site in SW Ireland. Quaternary Research 53(1):114–121. doi: 10.1006/qres.1999.2087.

Turney CSM, Jones RT, Lister D, Jones P, Williams AN, Hogg A, Thomas ZA, Compo GP, Yin X, Fogwill CJ, Palmer J, Colwell S, Allan R, Visbeck M. 2016a. Anomalous mid-twentieth century atmospheric circulation change over the South Atlantic compared to the last 6000 years. Environmental Research Letters 11(6):064009. doi: 10.1088/1748-9326/11/6/064009.

Turney CSM, Jones R, Fogwill C, Hatton J, Williams AN, Hogg A, Thomas Z, Palmer J, Mooney S. 2016b. A 250 year periodicity in Southern Hemisphere westerly winds over the last 2600 years. Climate of the Past 12:189–200. doi: 10.5194/cpd-11-2159-2015.

Turney CSM, Palmer J, Maslin MA, Hogg A, Fogwill CJ, Southon J, Fenwick P, Helle G. 2018. **AQ5**

Wilmshurst JM, McGlone M, Bronk Ramsey C, Thomas Z, Lipson M, Beaven B, Jones RT, Andrews O, Hua Q. 2018. Global peak in atmospheric radiocarbon provides a potential definition for the onset of the Anthropocene Epoch in 1965. Scientific Reports 8(1):3293. doi: 10.1038/s41598-018-20970-5. **AQ6**

van der Bilt WGM, Bakke J, Werner JP, Paasche Ø, Rosqvist G, Vatle SS. 2017. Late Holocene glacier reconstruction reveals retreat behind present limits and two-stage little Ice Age on Subantarctic South Georgia. Journal of Quaternary Science 32(6):888–901. doi: 10.1002/jqs.2937.

van der Putten N, Stieperaere H, Verbruggen C, Ochyra R. 2004. Holocene palaeoecology and climate history of South Georgia (sub-Antarctica) based on a macrofossil record of bryophytes and seeds. The Holocene 14(3): 382–392. doi: 10.1016/j.quascirev.2008.09.023.

van der Putten N, Verbruggen C, Ochyra R, Spassov S, de Beaulieu JL, De Dapper M, Hus J, Thouveny N. 2009. Peat bank growth, Holocene palaeoecology and climate history of South Georgia (sub-Antarctica): based on a botanical macrofossil record. Quaternary Science Reviews 28(1-2):65–79. doi: 10.1016/j.quascirev.2008.09.023.

Wessel P, Smith WHF, Scharroo R, Luis J, Wobbe F. 2013. Generic mapping tools: improved version released, Eos, Transactions. American Geophysical Union 94(45):409–410. doi: 10.1002/2013EO450001.

White DA, Bennike O, Melles M, Berg S, Binnie SA. 2018. Was South Georgia covered by an ice cap during the Last Glacial Maximum? Geological Society, London, Special Publications 461(1):49–59. doi: 10.1144/SP461.4.

Wilson P, Clark R, Birnie J, Moore DM. 2002. Late Pleistocene and Holocene landscape evolution and environmental change in the Lake Sulivan area, Falkland Islands, South Atlantic. Quaternary Science Reviews 21(16–17): 1821–1840. doi: 10.1016/S0277-3791(02)00008-2.

Wüst RAJ, Jacobsen GE, van der Gaast H, Smith AM. 2008. Comparison of radiocarbon ages from different organic fractions in tropical peat cores: insights from Kalimantan, Indonesia. Radiocarbon 50(3):359–372. doi: 10.1017/S0033822200053492.