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A decade of in situ cosmogenic 14C in Antarctica

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Title: A decade of in situ cosmogenic ^{14}C in Antarctica

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ABSTRACT

This letter reviews the contributions of the cosmogenic nuclide in situ ^{14}C to our knowledge of deglaciation in Antarctica. In situ ^{14}C is useful for studying glacier chronologies because its short half-life means exposure ages are less sensitive to nuclide inheritance when compared with more commonly measured long-lived nuclides. An increasing number of laboratories capable of extracting carbon from quartz and automation of the extraction process have led to in situ ^{14}C being measured in Antarctic samples at an increasing rate over the last decade. The nuclide has had the greatest impact in the Weddell Sea Embayment, where previous inferences on the thickness of ice and timing of deglaciation were limited by inheritance. Along with other future research priorities described, subglacial measurements of the nuclide hold much potential as they can provide direct evidence of proposed Holocene thinning and subsequent re-thickening of the Antarctic ice sheets.

1. INTRODUCTION

This letter outlines advances made in our knowledge of the most recent deglaciation in Antarctica driven by measurements of in situ ^{14}C, a rare nuclide made in near-surface rocks and minerals by cosmic rays. The concentration of cosmogenic nuclides like in situ ^{14}C in a surface is directly proportional to the time the surface was most recently uncovered by receding ice. Measuring cosmogenic nuclide concentrations is a common way of studying glacier chronologies (Schaefer and others, 2022; Balco, 2011). Concentrations are converted to exposure ages using production rates and, for radioactive nuclides, their half-lives. Most exposure dating studies use ^{10}Be or combine it with ^{26}Al (with half-lives of 1.4 and 0.7 Myr, respectively) (Balco, 2011). The short half-life of ^{14}C (5730 years) provides some unique advantages in exposure dating studies, which we describe below. A growing number of laboratories capable of extracting in situ ^{14}C and automation of the extraction process have led to the nuclide being measured at an enhanced rate over the last decade (Fig. 1a). These measurements are advancing our knowledge of the most recent deglaciation in Antarctica, especially where inferences from long-lived nuclides are limited. We also describe how in situ ^{14}C is measured, where in Antarctica it has been measured, and potential future research priorities that can be addressed using this nuclide.

2. WHY IS IN SITU ^{14}C USEFUL?

Exposure dating studies rely on the assumption that concentrations accumulated in a single period of exposure. Cosmogenic nuclides are predominantly made in the upper few metres of rock, and we rely on erosion during glaciations to “reset” surfaces. Preserved beneath cold-based ice, long-lived nuclides like ^{10}Be can persist for multiple glacial-interglacial cycles, breaking the assumption of one period of exposure. In situ ^{14}C is much less sensitive to this nuclide “inheritance” because the half-life is so short that ^{14}C accumulated prior to the Last Glacial Maximum (LGM) will have decayed away by now, regardless of how much erosion took place. In situ ^{14}C exposure ages are therefore essentially free of inheritance.

Another useful aspect of in situ ^{14}C is the potential to constrain the maximum extent of LGM ice. A balance between production and decay is reached after about 5.5 times the half-life of a radioactive cosmogenic nuclide, at which point a surface is “saturated”. This means a surface is saturated with in situ ^{14}C after ≈30 kyr of exposure. When we measure a concentration equivalent to saturation, we know that the sample has been exposed for at least 30 kyr, and thus was not covered during the LGM. Hence, surfaces saturated with in situ ^{14}C provide unambiguous evidence for the extent of ice during the LGM.

3. HOW IS IN SITU ^{14}C MEASURED?

The utility of in situ ^{14}C exposure dating has long been known (e.g. Lal, 1987, 1988; Lal and Jull, 2001) but it was not until the 2010s that measuring it became relatively routine. Building on methods for measuring in situ ^{14}C in extraterrestrial samples (Goel and Kohman, 1962; Suess and Wänke, 1962), Lifton and others (2001) developed the methods for extracting carbon from quartz used in laboratories today. Whilst methods differ with laboratory, the key steps are similar: carbon is liberated through the melting of quartz under vacuum, oxidised to form CO_2, then purified using liquid nitrogen. Some extraction lines use a tube furnace and flux to reduce the melting point of quartz (Lifton and others, 2015; Goehring and others, 2019a; Lamp and others, 2019), whilst others use an electron bombardment or resistance furnace without flux (Fülöp and others, 2015; 2019; Lupker and others, 2019). Samples are sent for AMS measurement as CO_2 (Hippe and others, 2013; Lupker and others, 2019) or after dilution and graphitisation (e.g. Lifton and others, 2015).

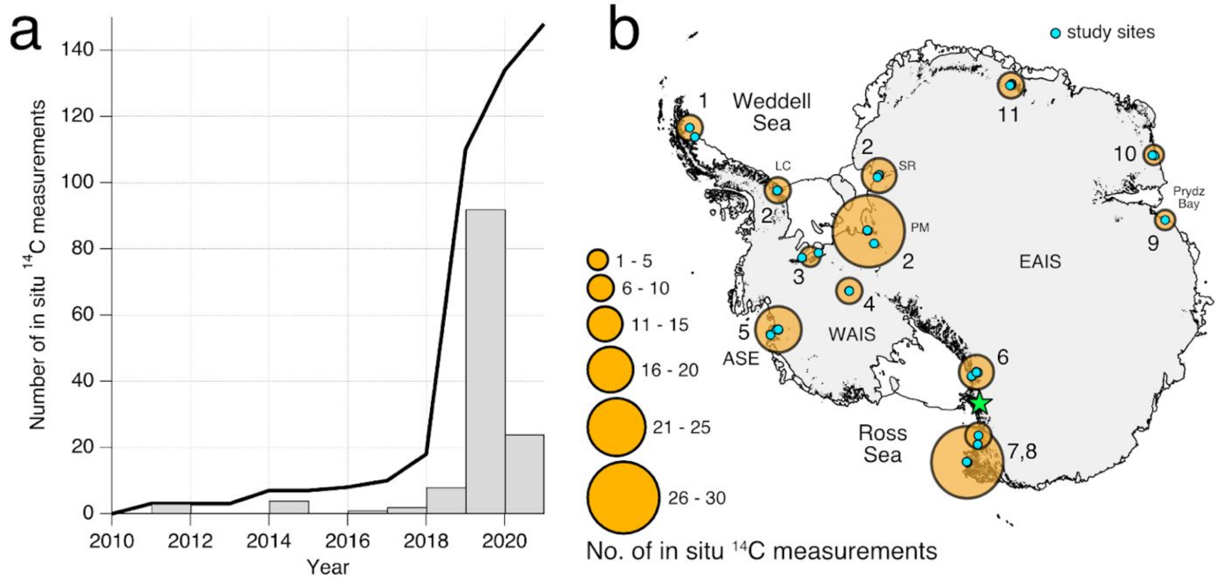

Fig. 1: a) Running (black) and yearly (grey bars) total in situ ^{14}C measurements from Antarctica (excluding CRONUS A). **b)** Sampling locations of all published subaerial in situ ^{14}C measurements from Antarctica, excluding those of CRONUS-A (green star). WAIS and EAIS are the West and East Antarctic Ice Sheets, respectively. LC is the Lassiter Coast, SR the Shackleton Range, PM the Pensacola Mountains, and ASE the Amundsen Sea Embayment. Numbers correspond to the study the measurements are sourced from: 1. Jeong and others (2018), 2. Nichols and others (2019), 3. Fogwill and others (2014), 4. Spector and others (2019), 5. Johnson and others (2017, 2020), 6. Hillebrand and others (2021), 7. Goehring and others (2019b), 8. Balco and others (2019), 9. Berg and others (2016), 10. White and others (2011), 11. Akçar and others (2020). Map made with Quantarctica (Matsuoka and others, 2018).

The rise in studies applying in situ ^{14}C over the last decade (Figure 1a) has been fuelled by a number of factors. Most importantly, an increasing number of laboratories are capable of extracting carbon from quartz. Automation of the extraction process has increased sample throughput, particularly at Tulane University (Goehring and others, 2019a). A gradual reduction in ^{14}C in process blanks has improved the detection limit. Repeat measurements of the in situ ^{14}C concentration of the interlaboratory comparison material CRONUS-A (Jull and others, 2015) have been used to characterise the reproducibility of in situ ^{14}C measurements (approximately 6 %; Nichols and others, 2019) and calibrate the production rate used by the online exposure age calculators (Balco and others, 2008) and the Informal Cosmogenic-Nuclide Exposure-age Database (ICE-D, ice-d.org, Balco, 2020). Standardisation of data reduction (Hippe and Lifton, 2014) and the identification of a source of contamination from a commonly used method of quartz isolation (Nichols and Goehring, 2019) have also contributed to the now relatively routine measurement and application of in situ ^{14}C.

4. WHERE HAS IN SITU ^{14}C BEEN MEASURED?

Measurements of in situ ^{14}C are reported from all sectors of Antarctica but are focused in the Ross, Weddell, and Amundsen sea embayments, with a dearth of measurements in East Antarctica and few on the Antarctic Peninsula (Fig. 1b). Post-LGM exposure ages constrain deglaciation at most sites, and saturated measurements constrain the limit of LGM ice in the Shackleton Range (Nichols and others, 2019), close to the West Antarctic Ice Sheet (WAIS) Divide (Spector and others, 2019), and adjacent to Prydz Bay (Berg and others, 2016). Samples saturated with in situ ^{14}C are also observed on blue ice moraines in Queen Maud Land (Akçar and others, 2020). CRONUS-A, also sourced from Antarctica (Fig. 1b), is saturated with ^{14}C and has been measured at least 75 times.

The most obvious places to measure in situ ^{14}C for exposure dating studies are those yielding solely or primarily pre-LGM exposure ages from long-lived nuclides, and thus inferences on the extent of LGM ice are limited. This is the case at the Lassiter Coast in the Weddell Sea Embayment (WSE) (Fig. 1b), where the majority of ^{10}Be ages exceed 100 ka (Fig. 2). Taken at face value, one could infer that ice has not been thicker here for hundreds of thousands of years, certainly not during the LGM. However, in situ ^{14}C measurements made from the same site, with many of the same samples, yield Holocene ages (Fig. 2), showing that i) ice was at least 380 m thicker than present at the LGM, ii) deglaciation occurred relatively rapidly, and iii) this region was covered by cold-based ice that preserved ^{10}Be that accumulated during previous periods of exposure.

A similar pattern of pre-LGM ^{10}Be ages and post-LGM in situ ^{14}C ages is observed at other sites in the WSE. Limited LGM thickening inferred from predominantly pre-LGM ^{10}Be ages in the Shackleton Range (Hein and others, 2011) and Pensacola Mountains (Balco and others, 2016; Bentley and others, 2017) was used to benchmark ice sheet models for some time (e.g., Whitehouse and others, 2017; Kingslake and others, 2018). These interpretations led to relatively little post-LGM ice volume change in the WSE (when compared with previous reconstructions, see Bentley and Anderson (1998)) becoming the predominant reconstruction amongst the palaeo community (Hillenbrand and others, 2014). Subsequent measurements of in situ ^{14}C yielded post-LGM ages at both locations, showing that, rather than limited thickening, ice was at least 310 and 800 m thicker than present at the LGM (Nichols and others, 2019). Other locations with multiple samples yielding pre-LGM ages from long-lived nuclides and post-LGM in situ ^{14}C ages are the Flower Hills and Meyer Hills in the Ellsworth Mountains (Fogwill and others, 2014) and the Darwin–Hatherton Glacier System in the Ross sector (Hillebrand and others, 2021).

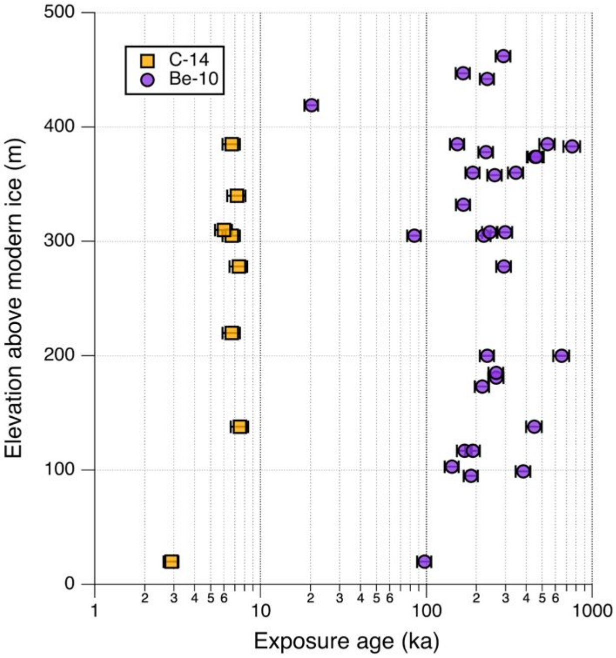

Fig. 2: Exposure ages from the Lassiter Coast (Nichols and others, 2019; Johnson and others, 2019) sourced from ICE-D using the LSDn scaling method. Error bars show external uncertainties but are often smaller than symbols.

In situ ^{14}C can also be useful at sites yielding post-LGM ^{10}Be ages. For example, in the Amundsen Sea Embayment (ASE), Johnson and others (2020) use measurements of in situ ^{14}C to identify a smaller degree of inheritance in their exposure ages. Here, ^{10}Be ages (n=9) indicate deglaciation happened about 17 ka, whilst in situ ^{14}C ages (n=8) show it occurred about 6 ka, a not insignificant difference of 11 kyr. Samples with post-LGM ^{10}Be ages and younger in situ ^{14}C ages are also observed at sites in northern Victoria Land (Balco and others, 2019; Goehring and others, 2019b), with an additional sample in the Flower Hills (Fogwill and others, 2014). Evidently, even when ^{10}Be ages at a site postdate the LGM and thus we know the degree of ice thickness change, there could still be a detectable amount of inheritance skewing our understanding of the timing of deglaciation.

Glacier chronologies are constrained solely with in situ ^{14}C measurements (without accompanying long-lived nuclides) at some locations, such as the Whitmore Mountains close to WAIS Divide (Spector and others, 2019) and some sites in northern Victoria Land (Goehring and others, 2019b). Additionally, at many sites in Antarctica, concordant in situ ^{14}C and ^{10}Be exposure ages are observed (White and others, 2011; Balco and others, 2019; Goehring and others, 2019b; Hillebrand and others, 2021).

To summarise, measurements of in situ ^{14}C have improved our understanding of deglaciation in all sectors of Antarctica but have had the most impact in the WSE and ASE. In the WSE we now know how thick ice was at the LGM and when this sector of the ice sheet thinned. In the ASE, we know that ice thinned later than indicated by ^{10}Be ages. Elsewhere in Antarctica, some sites have been studied solely using in situ ^{14}C, whilst at other sites in situ ^{14}C ages corroborate those from longer-lived nuclides.

5. FUTURE RESEARCH PRIORITIES

The proposed future research priorities for in situ ^{14}C below are separated into two categories: those related to measuring in situ ^{14}C, and those related to applying it.

5.1 Measuring in situ ^{14}C

Most studies measure in situ ^{14}C in quartz but the nuclide is produced in other materials such as calcium carbonate (Handwerger and others, 1999) and olivine (Pigati and others, 2010). Establishing methods for the extraction of carbon from these materials would expand the number of locations we can study with in situ ^{14}C beyond only those rich in quartz.

Whilst we have learnt much about deglaciation in Antarctica from in situ ^{14}C in recent years, we have also learnt much about measuring the nuclide itself, and some questions remain unanswered. Some studies observe in situ ^{14}C concentrations in excess of theoretical limits (Balco and others, 2016; Akçar and others, 2020), whilst another observes measurement reproducibility lower than that expected from measurement uncertainties alone (Nichols and others, 2019). When sample contamination can be ruled out, mass movement and supraglacial transport could explain elevated concentrations (Balco and others, 2016), whilst unrecognised measurement error could explain the limited reproducibility. Further work dedicated to method development is needed to isolate what is i) limiting measurement reproducibility and ii) contributing toward concentrations exceeding theoretical limits.

5.2 Applying in situ ^{14}C

Further exposure dating studies using in situ ^{14}C would be useful in areas unstudied with cosmogenic nuclides or those yielding solely or primarily pre-LGM ages from long-lived nuclides (e.g. Hodgson and others 2012). Additionally, there are a few applications beyond traditional exposure dating yet to be used (or to their full potential) that could improve our knowledge of the history and glaciology of the Antarctic ice sheets.

One application is the combining of ^{14}C and ^{10}Be measurements in glacier forefields to quantify glacial erosion (Rand and Goehring, 2019), but this may be limited to smaller glaciers such as those on the Antarctic Peninsula.

An application used once in Antarctica is the assessment of numerical ice sheet model outputs with single measurements of the nuclide. Many numerical ice sheet models are benchmarked against exposure age datasets recording deglaciation. By assuming samples were saturated prior to LGM burial, individual measurements of in situ ^{14}C can be used to assess both advance and retreat phases of model outputs (Spector and others, 2019). More generally, targeting exposed surfaces high above modern ice elevations could help provide more upper constraints on LGM ice thicknesses to help validate numerical ice sheet model outputs.

Finally, an application of in situ ^{14}C which holds perhaps the most potential is using subglacial measurements to constrain Holocene thinning and subsequent thickening (and associated grounding line retreat and readvance) of the Antarctic ice sheets. A number of studies, both through geologic observations (Siegert and others, 2013; Wolstencroft and others, 2015; Greenwood and others, 2018; King and others, 2022) and modelling (Kingslake and others, 2018), infer that the Antarctic ice sheets were smaller than present in the Holocene and subsequently grew to their present configuration. Through the measurement of carbon in subglacial sediments, two studies (Venturelli and others, 2020 and Neuhaus and others, 2021) report the first direct evidence of a Holocene grounding line readvance in the Ross sector. Further direct evidence for a Holocene readvance can be obtained through in situ ^{14}C measurements in subglacial bedrock, because significant concentrations in subglacial bedrock unambiguously requires Holocene exposure, either complete or through relatively thin ice (Johnson and others, 2022). Whilst previous studies have investigated long term changes in the Greenland Ice Sheet by measuring long-lived nuclides in subglacial material (Schaefer and others, 2016; Christ and others, 2021), there are no published subglacial measurements of in situ ^{14}C from beneath any ice sheet. If above background in situ ^{14}C indicative of a Holocene readvance is measured in samples collected from beneath the Antarctic ice sheets, multiple studies will be required to confirm if this ice sheet behaviour is widespread or localised.

6. CONCLUSIONS

To summarise, the cosmogenic nuclide in situ ^{14}C has been measured at an enhanced rate over the last decade, fuelled by the automation of the extraction process and an increasing number of laboratories now capable of extracting it. Measurements of in situ ^{14}C have been used in exposure dating studies to shed light on deglaciation in all sectors of Antarctica, but especially in the Weddell Sea Embayment. Some studies observe in situ ^{14}C concentrations exceeding theoretical limits and also measurement reproducibility lower than expected, which can hopefully be addressed with dedicated work on understanding the extraction process and geomorphic scatter. Whilst there are many locations in Antarctica where traditional in situ ^{14}C exposure dating studies would be useful, there are also a number of other applications of the nuclide that hold much potential, including using subglacial measurements to constrain episodes of thinning and rethickening in the Holocene.

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