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Late Pleistocene sea-level constraints across Antarctica

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ABSTRACT

Global sea levels during the last interglacial (LIG), 129,000–116,000 years ago, may have reached as much as 5–10 m higher than present. However, the elevation of the LIG highstand varies locally due to tectonics, subsidence, steric effects, and glacial isostatic adjustment (GIA). The variability brought upon by GIA can be used to constrain the past distribution of ice sheets including the source of higher sea levels during the LIG. In spite of its importance for fingerprinting the source of additional meltwater at the LIG, little is known about the elevation of LIG sea levels across Antarctica. In this study we review the geologic constraints on the elevation of the LIG highstand across Antarctica. We find that although several Late Pleistocene sea-level constraints are available across the continent very few of them provide definitive LIG ages. Arguably the most probable LIG sea-level indicators come from East Antarctica but most of them have age constraints approaching the limits of radiocarbon dating (>~45 ka) with many likely dating to Marine Isotope Stage 3, not the LIG. For West Antarctica, Late Pleistocene sea level constraints are confined to a few poorly or completely undated possible examples from the Antarctic Peninsula. Our review suggests that much more work is needed on constraining the elevation of the LIG highstand across Antarctica.

1. Introduction

Past interglacials provide important insights into the climate evolution of the Earth. The most recent of these, the Last Interglacial (LIG), also referred to as Marine Isotope Stage 5e, 129,000–116,000 years ago is of particular interest as CO_2 and global temperatures were both higher than the pre-industrial period (Capron et al., 2017). Thus, it can be used to gain insights into climate processes and feedbacks close to those expected by the end of the century, including the melting of ice sheets and their subsequent contributions to global sea-level rise (Rovere et al., 2016). During this time interval, global average sea levels were thought to have been approximately 5–10 m above present levels (Kopp et al., 2009; Dutton and Lambeck, 2012), although recent studies have suggested global averages closer to 1–4 m (Dyer et al., 2021; Dumitru et al., 2023). Determining exactly how much higher global sea levels were during the LIG is complicated by the impacts of glacial-isostatic adjustment (GIA; e.g. Lambeck et al., 2012; Creveling et al., 2015; Dutton and Lambeck, 2012; Dendy et al., 2017), which leads to variability of the level of the oceans across the globe due to deformation of the solid Earth and the Earth's geoid from the redistribution of mass across the globe. The impact of GIA also causes variations in the timing of the highstand across the globe (Lambeck et al., 2012), which when combined with the errors in dating creates difficulties in correlating highstands within the LIG. In addition, very slow vertical motions of the Earth's crust, such as those caused by dynamic topography (Austermann et al., 2017), deep-seated subsidence (Paine, 1993), and sediment loading (Simms et al., 2013), that might not be important at time scales relevant to the Holocene become important over the ~100,000+ years since the LIG. In order to best account for the impacts of GIA on the volume of extra meltwater in the oceans during the LIG requires a broad distribution of LIG sea-level indicators from across the globe. Furthermore, the distribution of relative sea levels across the globe can be used to pinpoint the sources of the extra meltwater contributed to the oceans during the LIG (Hay et al., 2014).

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A recent community-driven initiative to compile LIG sea-level indicators using a systematic approach compiled over 4545 LIG sea-level proxies (Rovere et al., 2023). This initiative, known as the World Atlas of Last Interglacial Shorelines (WALIS), summarized LIG sea-level indicators from 18 regions across the globe plus 4 global compilations related to specific data types or other closely related time periods (e.g. MIS5c and MIS5a). The WALIS framework provided a context in which future compilations and data could be added to the database. One notable omission in the original compilation was data from Antarctica (Fig. 1). Antarctica is of particular interest to this effort as it lies within the near field of the ice sheets and relative sea-level indicators from the southern-most continent may hold clues to the origin of the source of extra meltwater at the LIG. The purpose of this study is to review the pre-Last Glacial Maximum (LGM) sedimentary and geomorphic archives as well as their chronologies that may place constraints on LIG sea levels across Antarctica. In total we compiled 213 radiocarbon ages, 65 amino-acid racemization (AAR) values, 19 luminescence, 6 electron-spin resonance (ESR) ages, and 1 U-series age (Fig. 2). The data reviewed in this compilation are also available in the WALIS database (https://alerovere.github.io/WALIS/; last accessed May 7, 2024) and Zenodo (10.5281/zenodo.11141381, last assessed May 7, 2024).

2. Background

2.1. Geologic setting

East and West Antarctica have very different geologic structures. East Antarctica is the craton of the continent and is rimmed by a passive margin across most of its coasts except for its boundary with West Antarctica along the Transantarctic Mountains (Fig. 1). In general, the rocks beneath East Antarctic are old (up to 4.0 Ba; Boger, 2011) and with the exception of the Transantarctic Mountains (e.g. Goodge, 2020), its coasts are thought to be largely free of recent tectonic motion. In contrast West Antarctica is relatively young marked by Cenozoic-aged rifting in Mary Byrd Land (Spiegel et al., 2016) and Cenozoic subduction along the Antarctic Peninsula with subduction continuing beneath the South Shetland Islands today (Jabaloy et al., 2003). As a result, vertical tectonic motions are likely still important along the western portions of the Ross Sea including the Transantarctic Mountains (Jones, 1996; Hong et al., 2021), Mary Byrd Land (Spiegal et al., 2016), and along the Antarctic Peninsula, with evidence for Quaternary tectonic uplift in the South Shetland Islands (Pallas et al., 1997).

This geologic dichotomy between East and West Antarctica is also seen in the nature of the ice sheets. Except for a few localized basins (e.g. Wilks subbasin and the Amery trough), the ice in East Antarctica is largely grounded above sea level while the ice in West Antarctica is largely grounded below sea level (Lythe and Vaughan, 2001; Fretwell et al., 2012). In addition, the ice drainages are largely convergent across West Antarctica and divergent across East Antarctica (Anderson et al., 1999). As a result of this difference in glaciology, the ice sheet over West Antarctica is thought to be less stable than that over East Antarctica and is often pointed to as a potential source of extra meltwater and possible collapse during the LIG (Mercer, 1978; Lau et al., 2023). The overall volume of the Antarctic Ice Sheet is 27 million km^3, enough to raise sea levels 58 m (Fretwell et al., 2012). Loss of the West Antarctic ice sheet could have contributed as much as 3.3 m to sea-level rise during past interglacials, with the remainder possibly coming from vulnerable parts of the East Antarctic Ice Sheet, the Antarctic Peninsula, Greenland, or mountain glaciers.

Ice covers approximately 99.65% of Antarctica with only ~49,500 km^2 of ice-free land (Bockheim et al., 2015). This ice-free area is concentrated along the peripheral areas of the coast and a few isolated nunatuks in the inland regions of the continent. The largest expanses of ice-free land are along the Transantarctic Mountains and the Antarctic Peninsula with other important coastal ice-free areas in MacRobertson Land and Enberby Land (Bockheim et al., 2015). However, concurrent with and likely for a few thousand years after the "global" Last Glacial Maximum (LGM; ~20 ka, Clark et al., 2009), the ice was much more

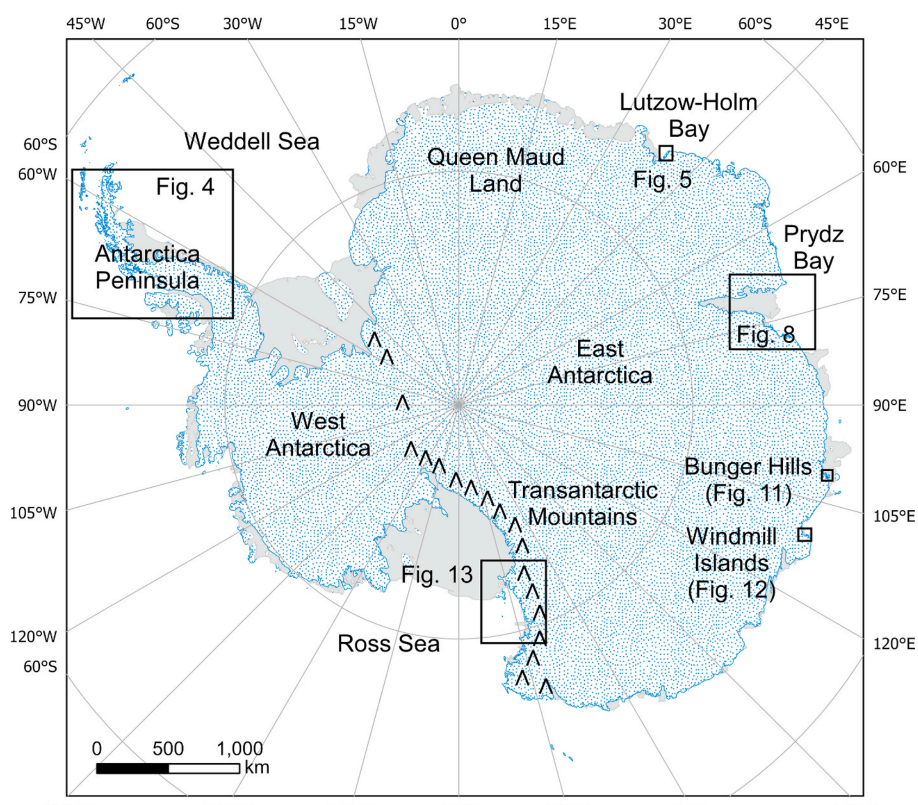

Fig. 1. Map of Antarctica showing the major zones of Antarctica and the location of sites mentioned in the text.

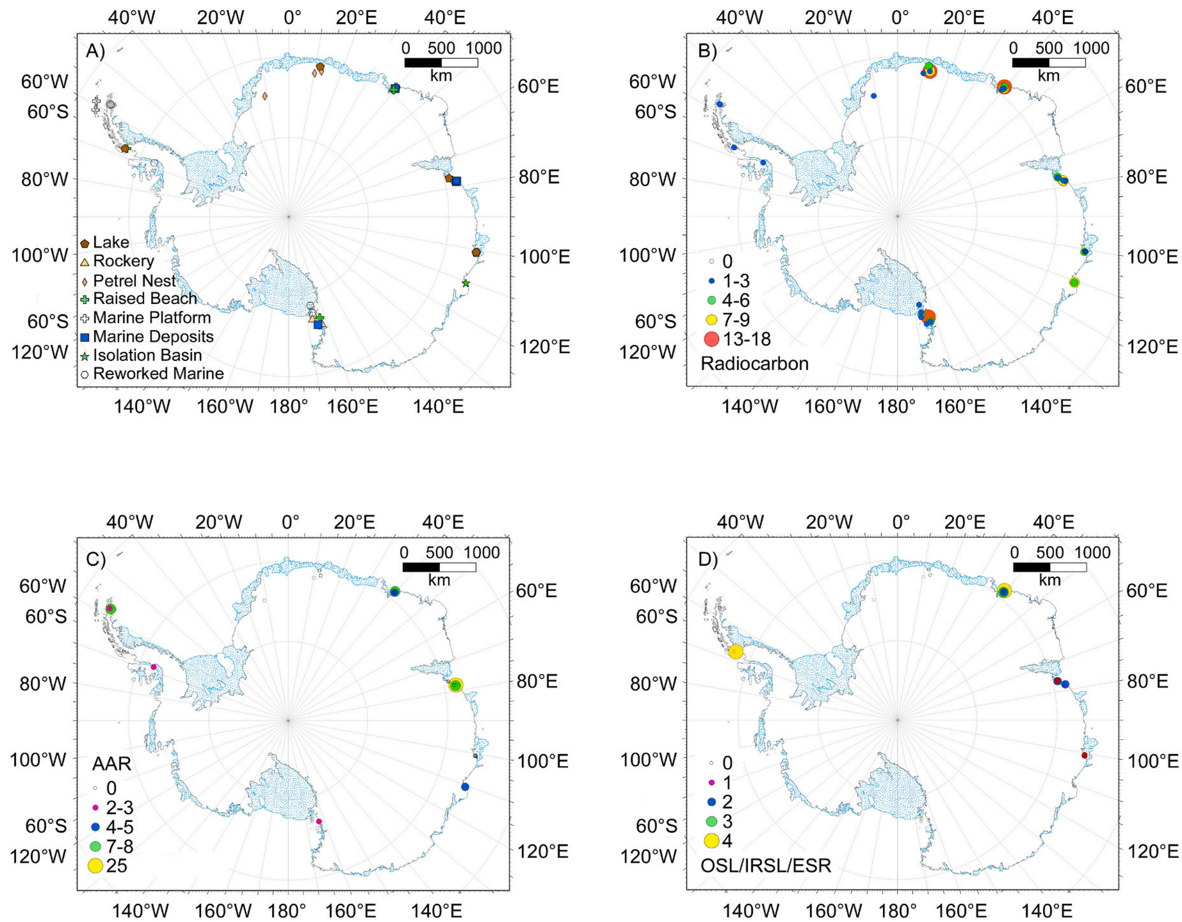

Fig. 2. Distribution of Late Pleistocene relative sea-level constraints based on indicator type (a), radiocarbon dating (b), amino acid racemization (c), and luminescence techniques (d).

extensive expanding all the way to the shelf edge in most locations (Anderson et al., 2002; Bentley et al., 2014) likely covering most of these coastal ice-free areas (with notable exceptions in the Transantarctic Mountains – e.g. the Dry Valleys) and encroaching on the nunatuks. Although still only roughly constrained, ice retreat from the LGM likely started earliest in the Antarctic Peninsula (Heroy and Anderson, 2007) with most shelves starting to be ice free no later than 11 ka with a similar ice-sheet configuration as today by 5 ka (Bentley et al., 2014; Jones et al., 2022). Minor oscillations of the ice may have continued through the late Holocene (Kingslake et al., 2018; Johnson et al., 2022; Groff et al., 2022) and as recently as the last 300–500 years (Simms et al., 2021; Jones et al., 2022). Little is known about the Quaternary ice extent prior to the LGM; although, it was likely similar to today at periods prior to the LGM within the Late Pleistocene, either during MIS5e or MIS3 (Hodgson et al., 2006).

2.2. Limitations of data collection and preservation in Antarctica

Due to its harsh polar conditions and recent glaciation, the quantity and quality of LIG and other Late Pleistocene sea-level proxies are far less than that at lower latitudes. Part of this dearth is the difficulty accessing many parts of the continent; another is due to the physical nature of the continent itself, such as the extensive erosion experienced along its margins during the LGM (Anderson et al., 1999; 2002). During the LGM, the ice sheets advanced to the shelf edge across much of the continent (Anderson et al., 2002; Bentley et al., 2014). This latest ice advance reoccupied cross-shelf glacial troughs, which themselves are the product of multiple glacial cycles. This, combined with multiple and localized glacial erosion events across most of the coastal zone (Anderson et al., 2002) means that Late Pleistocene sea-level proxies can be difficult to isolate from features that are the product of earlier glacial cycles. The handful of total cosmogenic nuclide (TCN) ages collected in these coastal areas suggest that enough of this erosion occurred during the LGM as to reset the cosmogenic profiles (e.g. Lindow et al., 2014). At the least, successive ice advances may have removed much of any of the previous coastal deposits that may have overlain features such as the pre-Quaternary marine terraces of the South Shetland Islands (Fig. 3). Evidence for this erosion and reworking of coastal deposits includes the 25 Late Pleistocene dated marine shells found in tills across the continent (Fig. 2; e.g. Clapperton and Sugden, 1982; Stuiver et al., 1981). In addition, some of those indicators that may have survived LGM erosion, either due to their protected settings or localized zones of cold-based ice, may still be overlain by ice. If the LIG did experience periods of less ice than today, as was the case for periods of the late Holocene (Yu et al., 2022), those indicators may still lie beneath the ice and thus as the ice continues to melt, more data may become available.

2.3. Factors influencing RSLs

Field observations of past sea levels at any location on the globe differ from the "global average" due to many local factors including GIA, tectonics, and more local steric affects such as ocean and wind currents. Taken together, the influence of all these factors plus the changes in the global volume of water in the oceans gives local or RSL. An important component of RSL is vertical land motions – both due to GIA and tectonics. The more extensive ice at the LGM (e.g. Anderson et al., 2002; Bentley et al., 2014) resulted in a GIA signal in many Antarctic RSL records larger than the global ice volume component at least for the

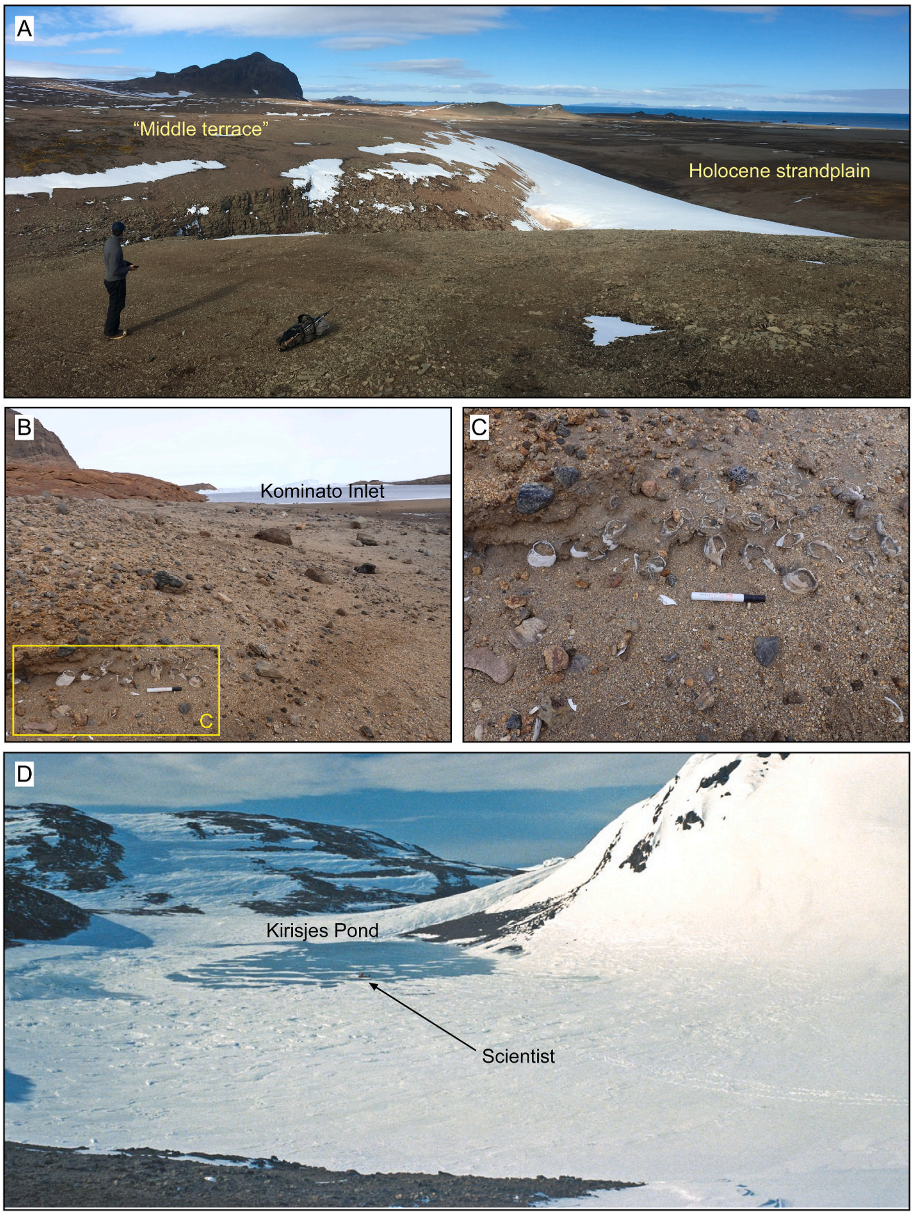

Fig. 3. Photographs of Late Pleistocene features from across Antarctica. A. Holocene strandplain and the Late Pleistocene "middle" terrace on Byers Peninsula, Livingston Island, the South Shetland Islands. B. Late Pleistocene marine deposits along the shores of the Kominato Inlet, Langhovde Peninsula Lützow-Holm Bay. C. Closer view of the marine shells within the Late Pleistocene deposits of Kominato Inlet. D. Kirisjes Pond, Larsemann Hills, whose sediments pre-date the LGM.

Holocene (Whitehouse et al., 2012). The significant LGM GIA signal, and its large uncertainties, in Antarctica complicates the interpretation of any Late Pleistocene RSL elevation observations. Depending on the tectonic setting, the influence of tectonics on local RSL can be important too (Simms et al., 2020). However, independent records of tectonic vertical motions are largely absent for most of Antarctica.

3. Approach

3.1. Sea-level indicators

Sea-level indicators from Antarctica are largely limited to raised beaches and marine platforms and isolation basins as saltmarshes, shallow-water corals, and many other sea-level proxies often used in lower latitudes are absent in Antarctica (Verleyen et al., 2020; Simms, 2023). Other limiting data such as marine and lacustrine deposits, penguin rockeries, and deposits around snow petrel nests are present but do not provide precise sea-level constraints. Instead, they can provide useful constraints on areas that were inundated during periods of relative sea-level rise in the case of marine deposits, and areas that have not been inundated in the case of lake deposits, penguin rockeries and snow petrel nests. In addition, some of these terrestrial limiting data (e.g. snow petrel nests) are found so far away from the coasts, or at altitudes that mean they are of little value in constraining past sea levels.

The two most common sea-level indicators preserved across Antarctica are isolation basins and raised beaches (Simms, 2023). Isolation basins arguably have the best-defined relationship to past sea levels as the height of the sill separating the small basin from the open ocean can be accurately measured (e.g. Zwartz et al., 1998; Watcham et al., 2011). When combined with the age of the transition from marine to lacustrine conditions recorded in sediments within the basin (e.g. Hafsten and Tallantire, 1978), it becomes a very valuable and precise constraint on past sea levels (Shennan et al., 1995). Six isolation basins with marine deposits and Late Pleistocene ages were compiled in this study (Table 1) along with 11 other lake basins with Late Pleistocene ages but only non-marine deposits.

Although more plentiful, the errors associated with using raised beaches as sea-level indicators are larger than that of using isolation basins. This larger error is a result of the uncertainties associated with not knowing the exact height of the beach ridges when they formed and the myriad of processes (e.g. storm versus swash) that produced a particular ridge (e.g. Tamura et al., 2012). However, approaches based on identifying specific stratigraphic contacts within the beach ridges (e.g. van Heteren et al., 2000; Rodriguez and Myers, 2006; Tamura et al., 2008; Costas et al., 2016; Barion et al., 2019) are improving sea-level constraints. These approaches have yet to be used in Late Pleistocene studies from Antarctica. The most common approach to using beach ridges in Antarctic sea-level research has been to subtract the elevation of the modern berm or youngest beach ridge from that of ancient ridges (e.g. Fretwell et al., 2010) or to simply use their deposits as either marine or terrestrial limiting (e.g. Miura et al., 1998a, 1998b).

Marine platforms also provide a potential sea-level indicator, which may have a precise relationship to past sea levels (e.g. Bradley and Griggs, 1976). Along cliff-lined coasts, wave-cut platforms form at the toe of the sea cliff in response to waves removing collapsed cliff material, usually during transgression (Sunamura, 1975). At the turnaround from sea-level rise to sea-level fall, the paleo-sea cliff is often preserved and the so-called "shoreline angle" thus becomes a well-constrained marker of past sea levels (Kelsey, 2015). Such erosional features have been identified throughout the South Shetland Islands of the Antarctic Peninsula (John and Sugden, 1971, Fig. 3). However, dating these features is often limited as it requires coastal deposits to be preserved ontop of the paleo-wave cut platform or to make assumptions about shielding through the water in the case of exposure dating. When deposits are found, the exact temporal relationship to the underlying wave-cut platform may not be known.

Ideally, the elevations reported are with respect to some known sea-level datum, with locally determined mean sea level being the standard (e.g. Woodroffe and Barlow, 2015). However, in Antarctica, long-term tidal records need to clearly define mean sea level are virtually non-existent, particularly at isolated field sites. With rare exceptions (e.g. Gardner et al., 2006; Simkins et al., 2013), the methods used to determine elevation and how sea level was defined are not given by the original studies. Only when specifically stated by the original authors do we give how elevation was measured and how sea level was defined. Otherwise we report the elevations as originally reported in the primary studies, acknowledging that the method of measuring elevation and the sea-level datum are not well defined. Thus the errors likely underestimate the true uncertainty in the observations.

3.2. Chronology

In addition to the scarcity of sea-level indicators, another limitation to reconstructing Late Pleistocene sea-levels in Antarctica is the difficulty in obtaining robust chronologies. First, material to date in Antarctica is scarce. Second, as with the LIG elsewhere, its timeframe is older than the useful range of radiocarbon dating (^{14}C, Ramsey, 2008) and thus material that comes back finite may relate to the LIG or any other time prior to 40–60 ka (e.g. the Pliocene; Pickard et al., 1988). Many 35–50 ka ages have been reported from Antarctica (e.g. Berkman et al., 1998; Miura et al., 1998a). These are difficult to interpret as they may represent true ages and have an important climatic story about MIS3 (Verylen et al., 2004) or they may represent LIG or older deposits with a small fraction of modern contamination (Takada et al., 2003; Hodgson et al., 2006). This difficulty in interpreting radiocarbon ages from Antarctica is compiled by the scarcity of identifiable macrofossils or bulk organic material to date in the first place. In our review we simply report the raw radiocarbon ages, uncalibrated, as ^{14}C years. We do, however, provide calibrated radiocarbon ages in the WALIS database, but note that the calibrations for these times frames are still being refined and many of the ages may be infinite.

Other methods that may work at the time scales of the LIG include optically stimulated luminescence (OSL), and its counterparts, thermoluminescence (TL), Infrared stimulated luminescence (IRSL) and ESR dating, TCN dating, and AAR. However, very few of these techniques have been applied to Late Pleistocene coastal deposits. Optically stimulated luminescence works on the premise that once quartz or feldspars are buried, natural radiation ionizes electrons in the mineral, some of which are trapped at defects in the crystal lattice. The number of trapped electrons accumulates over time and when stimulated by light, the accumulated energy is released as weak light, which is referred to as luminescence. As a result the luminescence signal is reset once exposed to sunlight. If the rate of accumulation is known luminescence intensity can be used to determine the deposit's age. This technique can be used to date materials as old as 0.5 Ma and thus theoretically could resolve deposits from the LIG. However, the quartz OSL signals in many coastal deposits within Antarctica are rather dim. Attempts to date quartz in coastal deposits have received mixed results (e.g. Simkins et al., 2016; Hong et al., 2020; Tamura et al., 2022; Theilen et al., 2023) leading some to use feldspar IRSL, a similar procedure but using a different band of light to stimulate the minerals (Tamura et al., 2022). To date, no conclusively LIG luminescence ages have been obtained from coastal deposits across Antarctica, although some Late Pleistocene ages from other environments have been obtained (e.g. Gore et al., 2001).

Similar to OSL dating, ESR works on the premise that radiation from natural sources builds up in traps with Earth materials. Thus, by measuring the amount of trapped signal, palaeodose, and natural radiation and taking their quotient, one can determine the age of the Earth material (Molodkov, 1988). This approach has been applied to more materials than OSL dating including materials as disparate as stalactites, fossil teeth, and mollusk shells (Rink, 1997; Duval et al., 2020). Within Antarctica, this method has been applied to shells with radiocarbon ages >30 ka with mixed success (e.g. Takada et al., 2003). Although the results show promise, they have not conclusively been shown to work in Antarctica, largely because independent ages for these older materials are lacking. Nevertheless, the theoretical age range for this technique is on the order of 2 Ma (Rink, 1997) and thus encapsulates the LIG.

Total Cosmogenic Nuclide dating works on the premise that exposed rock accumulates cosmogenic nuclides. If the rate at which those cosmogenic nuclides accumulate in rock surfaces is known their abundance can be used to determine the time in which the surface has been exposed. Complications arise including assumptions about surface erosion, soil, ice, or snow cover, but approaches for correcting for these issues have been proposed. This method has revolutionized Quaternary geology were it can be applied, particularly in the dating of landforms (Granger et al., 2013). For regions around Antarctica this has resulted in an explosion of studies using the method to determine when areas have become ice-free. It holds the potential to also determine the age of coastal features (e.g. Dawson et al., 2022), but has yet to be applied to coastal features in Antarctica, probably due to their scarcity of preservation owing to being overridden in ice and all the nuances associated with assumptions about ice cover, etc. that entails. Nevertheless, depending on which nuclide is measured, the method provides a way to determine ages back to the time frame of the LIG.

Amino Acid Racemization is a dating technique based on the rate in which amino acids within proteins found in shells, corals, teeth, and other biomineral materials break down into their enantiomers or diastereoisomers. If the original ratio of amino acids and the rate at which they break down are known, then an age since the organism's death can be determined (Wehmiller, 1984; Miller and Brigham-Grette, 1989). Within the Antarctic AAR has been most commonly applied to shell material (e.g. Pickard et al., 1988; Hirvas et al., 1993) with over 65 D/L values measured from deposits thought to be Late Pleistocene (Table 1). However, in all but one case (Gardner et al., 2006) the specific amino acid measured (e.g. aspartic acid, leucine, glutamic acid, alanine, etc.) was not given. In addition, obtaining absolute ages from the technique in

Table 1
Summary of sites.

Site	GenLoc	WALIS RSL IDs	Type	(Highest) Elevation (m)	Category	Lat	Long	Dated	14C	AAR	Lum/ESR	U–Th	Age Attribution	Confidence of Age
Fildes Peninsula	South Shetland Islands	4407	Marine Platform	48	Indicator	−62.206	−58.999	No	0	0	0	0	LIG	1
Byers Peninsula	South Shetland Islands	4406	Marine Platform	50	Indicator	−62.651	−61.045	No	0	0	0	0	LIG	1
Calmette Bay	Antarctic Peninsula	4485–4487	Raised Beach	40.8	Indicator	−68.064	−67.167	Yes	0	0	4	0	Holocene/ LIG?	2
Horseshoe Island	Antarctic Peninsula	NA	Lake	80	None	−67.828	−67.226	Yes	3	0	0	0	MIS3-LGM	4
Two-Step Cliff	Antarctic Peninsula	NA	Reworked Marine	94	None	−71.845	−68.232	Yes	2	3	0	0	rw LGM	2
St Martha Cove	James Ross Island	4408	Reworked Marine	18	None/Marine Limiting	−63.931	−57.804	Yes	3	8	0	0	Holocene	2
Cape Lachman	James Ross Island	NA	Reworked Marine	17	None	−63.794	−57.804	Yes	1	2	0	0	Holocene	2
Donning Maud #1	Queen Maud Land	NA	Petrel nests	1245	Terrestrial limiting	−74.577	−11.223	Yes	1	0	0	0	MIS3-LGM	3
Donning Maud #2	Queen Maud Land	NA	Petrel nests	1450	Terrestrial limiting	−71.367	12.583	Yes	3	0	0	0	MIS3-LGM	3
Donning Maud #3	Queen Maud Land	NA	Petrel nests	1420	Terrestrial limiting	−71.350	12.600	Yes	8	0	0	0	MIS3-LGM	3
Donning Maud #4	Queen Maud Land	NA	Petrel nests	1190	Terrestrial limiting	−71.367	12.583	Yes	15	0	0	0	MIS3-LGM	3
Donning Maud #5	Queen Maud Land	NA	Petrel nests	880	Terrestrial limiting	−71.767	10.183	Yes	1	0	0	0	MIS3-LGM	3
Schirmacher Oasis #1	Queen Maud Land	NA	Lake	100	Terrestrial limiting	−70.763	11.793	Yes	5	0	0	0	MIS3-LGM	3
Schirmacher Oasis #2	Queen Maud Land	NA	Lake	100	Terrestrial limiting	−70.763	11.740	Yes	5	0	0	0	MIS3-LGM	3
Kai-no-hama Beach	Lotzow-Holm Bay	4382, 4398-4399	Raised Beach	10	Indicator	−69.016	39.573	Yes	26	7	4	0	MIS3	3
Kitami Beach	Lotzow-Holm Bay	4383, 4396-4397	Raised Beach	12	Indicator	−69.013	39.555	Yes	4	0	0	0	MIS3	3
Soya Base	Lotzow-Holm Bay	4385, 4389-4391	Raised Beach	13	Indicator	−69.007	39.574	Yes	5	0	0	0	MIS3	3
West Ongul Island	Lotzow-Holm Bay	4392-4395, 4400-4402	Raised Beach	18	Indicator	−69.026	39.524	Yes	6	0	0	0	MIS3	3
Kominato-higashi Beach	Lotzow-Holm Bay	4379–4380	Raised Beach	12	Indicator	−69.179	39.679	Yes	9	4	2	0	MIS3	3
Lake Zakuro	Lotzow-Holm Bay	4381, 4386-4387	Raised Beach	6	Indicator	−69.178	39.647	Yes	7	0	0	0	MIS3	3
Kominato Inlet	Lotzow-Holm Bay	4388	Raised Beach	8	Indicator	−69.179	39.650	Yes	3	0	0	0	MIS3	3
Northern Langhovde	Lotzow-Holm Bay	4403–4405	Marine deposits	3	Marine limiting	−69.180	39.663	Yes	3	0	0	0	MIS3	2
Lake Nurume	Lotzow-Holm Bay	4467	Marine deposits	1	Marine limiting	−69.225	39.663	Yes	0	0	3	0	MIS3	2
Skarvnes	Lotzow-Holm Bay	4384	Raised Beach	8	Indicator	−69.447	39.562	Yes	1	0	0	0	MIS3	2
Kirisjes Pond	Larsemann Hills	4410	Isolation Basin	8	Indicator	−69.371	76.143	Yes	4	0	1	0	MIS3	3
Progress Lake	Larsemann Hills	4412	Lake	65	Terrestrial limiting	−69.402	76.389	Yes	6	0	2	0	LIG	3
Mochou Lake	Larsemann Hills	4411	Isolation Basin	10	Indicator	−69.373	76.367	Yes	5	0	0	0	MIS3	3
Heart Lake	Larsemann Hills	4413	Isolation Basin	5	Indicator	−69.376	76.383	Yes	2	0	2	0	MIS3	3
Lake Nella	Larsemann Hills	4415	Lake	15	Terrestrial limiting	−69.393	76.371	Yes	1	0	0	0	MIS3	2
Lake Reid	Larsemann Hills	4414	Lake	30	Terrestrial limiting	−69.386	76.378	Yes	5	0	1	0	LIG	3
Lake 73	Larsemann Hills	4416	Lake	85	Terrestrial limiting	−69.400	76.377	Yes	1	0	0	0	MIS3/LIG	2

(*continued on next page*)

Table 1 (*continued*)

Site	GenLoc	WALIS RSL IDs	Type	(Highest) Elevation (m)	Category	Lat	Long	Dated	14C	AAR	Lum/ ESR	U–Th	Age Attribution	Confidence of Age
Filla Inlet	Rauer Group	4417	Isolation Basin	−18	Indicator	−68.799	77.952	Yes	7	0	0	0	MIS3	3
Skua Lake	Rauer Group	4418	Lake	11.5	Terrestrial limiting	−68.812	77.872	Yes	7	0	0	0	LIG	3
Unnamed Lake	Rauer Group	4419	Lake	26	Terrestrial limiting	−68.813	77.852	Yes	1	0	0	0	LIG	3
Marine Plain	Vestfold Hills	4423	Marine deposits	20	Marine limiting	−68.636	78.150	yes	3	8	0	0	Pliocene	0
Davis Base	Vestfold Hills	4420–4422	Marine deposits	4	Marine limiting	−68.577	77.995	Yes	2	25	2	0	Pliocene?	2
Heidemann Bay	Vestfold Hills	NA	Reworked Marine	35	None	−68.589	77.945	Yes	2	0	0	0	rw LGM	3
PG1182	Bunger Hills	NA	Reworked Marine	61.9	None	−66.298	100.724	Yes	4	0	0	0	MIS3	3
PG1165	Bunger Hills	NA	Reworked Marine	101.5	None	−66.250	100.600	Yes	1	0	0	0	MIS3	3
PG1180	Bunger Hills	NA	Reworked Marine	36.9	None	−66.262	100.652	Yes	2	0	0	0	MIS3	3
BHO-11	Bunger Hills	4424	Lake	60	Terrestrial limiting	−66.284	100.795	Yes	0	0	1	0	MIS3	3
BHO-13	Bunger Hills	4425	Lake	80	Terrestrial limiting	−66.262	100.841	Yes	0	0	1	0	MIS3	3
BHO-44	Bunger Hills	4426	Lake	29	Terrestrial limiting	−66.288	100.631	Yes	0	0	1	0	MIS3	3
BHO-50	Bunger Hills	NA	Lake	NR	Terrestrial limiting	−66.283	100.614	Yes	0	0	1	0	MIS3	3
Browning Bay	Windmill Islands	4427	Isolation Basin	<-46	Indicator	−66.462	110.568	Yes	5	0	0	0	MIS3	2
Peterson Inlet	Windmill Islands	4428	Isolation Basin	−3	Indicator	−66.454	110.496	Yes	9	5	0	0	MIS3	2
Cape Ross	Ross Sea	4429	Raised Beach	32.2	Indicator	−76.733	163.000	yes	13	3	0	0	LIG (or older)	4
Cape Barnes	Ross Sea	NA	Reworked Marine	30	None	−77.569	166.252	Yes	3	0	0	1	rw LGM	3
Cape Bird	Ross Sea	NA	Reworked Marine	180	None	−77.233	166.429	Yes	4	0	0	0	rw LGM	2
Cape Royds	Ross Sea	NA	Reworked Marine	NR	None	−77.557	166.243	Yes	2	0	0	0	rw LGM	2
Minna Bluff	Ross Sea	NA	Reworked Marine	NR	None	−78.517	166.417	Yes	1	0	0	0	rw LGM	2
Cape Hickey Site 2	Ross Sea	4430	Rockery	49	Terrestrial limiting	−76.087	162.638	Yes	6	0	0	0	MIS3	3
Cape Hickey Site 3	Ross Sea	4431	Rockery	52	Terrestrial limiting	−76.087	162.638	Yes	1	0	0	0	MIS3	3
Beauford Island	Ross Sea	4432	Rockery	4	Terrestrial limiting	−76.931	166.910	Yes	3	0	0	0	MIS3	3
Western Ross Sea	Ross Sea	NA	Marine deposits	−888	Marine limiting	−75.960	164.910	Yes	2	0	0	0	MIS3	3

rw LGM = Older deposit reworked into a LGM till.
Confidence in Age (1 = lowest, 5 highest).

Antarctica has remained elusive because of the scarcity of independent chronologies to calibrate the method for the species and environmental conditions present in the region. One of the most important factors hindering the proper calibration of the method is the sensitivity of the decay of the amino acids to ambient temperatures (Miller and Brigham-Grette, 1989). In regions of extremely cold climates, such as Antarctica, species that are marine but then uplifted and exposed to colder terrestrial weather conditions will have complex thermal histories leading to large uncertainties in their interpretations (Miller and Brigham-Grette, 1989). In addition, large fluctuations in temperatures also impact the rate of racemization, thus the time spent in marine versus terrestrial settings becomes an important factor as does the depth of burial in establishing accurate racemization models.

4. Regions

4.1. Antarctic Peninsula

4.1.1. South Shetland Islands

The South Shetland Islands are one of the most accessible areas of Antarctica. That combined with the relatively large amount of ice-free land means that a considerable amount of Quaternary coastal work has been conducted on the islands, including the identification of inferred Late Pleistocene coastal features.

Adie (1964) was one of the first to comprehensibly pull together changes in sea levels across the South Shetland Islands. Further work by John and Sugden (1971) and Curl (1980) refined the phases of higher-than-present sea levels. They noted that the raised marine features of the islands can be grouped into 3 sets based on their broad elevations: 11–17 m, 27–50 m, and 85–102 m (John and Sugden, 1971). Higher platforms are present but not thought to be of marine origin and likely related to fluvial processes (John and Sugden, 1971). However, some of the platforms higher than 102 m are mantled by rounded cobbles interpreted to be marine in origin by some workers (Curl, 1980; Birkenmajer, 1998). The 11–17 m platform is mantled by Holocene-aged beach deposits (e.g. Hall, 2010), while the higher two platforms, although still undated, are almost certainly pre-Holocene in age, and likely formed during Late Pleistocene time periods. On the Fildes Peninsula of King George Island, the middle platform extends from 35 to 48 m and is backed by a 60 m high cliff (John and Sugden, 1971; WALIS RSL ID 4407). A similar platform is found at an elevation of 25–60 m on Byers Peninsula of Livingston Island and is overlain by up to 6 beach ridges (Lopez-Martinez et al., 1996; WALIS RSL ID 4406)(Fig. 3). The platform and cliff have the general morphology of the shoreline angle of marine terraces on other coastlines (e.g. Bradley and Griggs, 1976). The 85–102 m platforms are mantled by well-rounded pebbles lithologically distinct from the surrounding bedrock interpreted to represent older beach material (John and Sugden, 1971). Additionally, the morphology of the cliffs backing the higher platform, the discordant nature between the underlying strata and the platform surface (Pallas et al., 1995), and the presence of paleo "sea stacks" also suggest a marine origin to the platform. However, one set of authors points out that the older beach material is similar to a nearby conglomerate with Pliocene foraminifera and pectens (John and Sugden, 1971), leaving some ambiguity as to the marine origin of the 85-102 marine platform.

Unfortunately, the only age constraints on the upper platforms at 27–50 and 85–102 m is that they are younger than the youngest rocks cut by them suggesting younger than Pliocene based on biostratigraphy (Barton, 1965; John and Sugden, 1971) or latest Oligocene, possibly Miocene, based on absolute dating of basalts (Birkenmajer et al., 1985; Pallas et al., 1995; Smellie et al., 2021). However, even these age assignments are based on correlations across the islands that are difficult to substantiate due to ice cover and the outcrop locations being on different islands. The middle set of marine platforms at elevations of 27–50 m (John and Sugden, 1971) is the best candidate for an LIG marine platform (WALIS 4406–4407), although other higher platforms have been considered (Pallas et al., 1997). The 27–50 m platform is the first distinct platform above the dated Holocene features, is mantled by till (Curl, 1980) and other glaciated features returning latest Pleistocene to Holocene TCN ages (Seong et al., 2009), and is less dissected than the higher platforms (Arche et al., 1996). In addition, Holocene RSL curves from the region as well as sediment cores in other lakes suggest Holocene sea levels did not reach higher than 17–20 m (Watcham et al., 2011; others) and thus if marine in origin likely represent local highstands older than the LGM.

4.1.2. Marguerite Bay and George VI sound

Marguerite Bay has some of the highest raised beaches identified in all of Antarctica (Fig. 4). The highest are found in Calmette Bay along its eastern shores. At this location, a flight of raised beaches extends to a differential GPS-measured elevation of 41 m above present sea level (defined by a ~2-day tide gauge record; Bentley et al., 2005; Hodgson et al., 2013; Simkins et al., 2013). The lower beaches below ~21.7 m are Holocene in age (Simkins et al., 2013) but a distinct break in topography, potentially an old sea cliff, separates a higher set of beach ridges from the Holocene-dated lower beach ridges. Simkins et al. (2013) attempted to date the higher beach ridges with OSL. The attempt returned ages of 0.92–16.87 ka from the beaches at elevations of 31.8–40.8 m (WALIS RSL IDs 4485–4487). Removing the anomalously young ages, which may have been reset by frost processes or other reworking, leaves five ages of 9.25–16.87 ka (WALIS LUM 646–650). The 9.25 ka age (WALIS LUM ID 648) fits nicely with the timing of deglaciation of the bay from TCN and lake basin ages (Bentley et al., 2011; Hodgson et al., 2013) but the other 4 ages date to a time period when the bay was thought to be covered in ice. Simkins et al. (2013) thus interpreted the ages to represent Late Pleistocene beaches reworked by the advance or retreat of the LGM ice. However, it is not known whether that Late Pleistocene is the LIG or another event between the LIG and the LGM. Hodgson et al. (2013) provide three radiocarbon ages dating back to ~35,000 ^{14}C years (WALIS ^{14}C ID 1752–1754) within the sediments of an ice-covered lake on Horseshoe Island <30 km from Calmette Bay (Fig. 4) at a modern elevation of ~80 m suggesting the area was subject to a non-erosive glacial regime during that time. However, they also provide evidence in the form of washed in moss that the area became ice free for at least some period of time possibly as early as 28 ka before attaining its current deglaciated state around 10 ka. Could the beaches in Calmette Bay have formed around 28 ka or even older or are they simply early Holocene in age? In summary, these beaches may represent LIG beaches, but more work needs to be done to determine their age particularly given the poor-quality of the OSL signal from these rocks

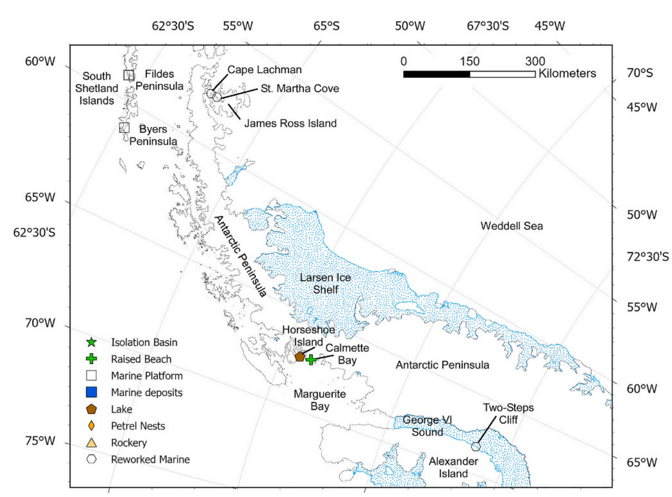

Fig. 4. Map showing the locations of sites mentioned across the Antarctic Peninsula.

(Simkins et al., 2016).

At Two-Steps Cliffs on the Alexander Island side of George VI Sound (Fig. 4), Clapperton and Sugden (1982) found marine shells reworked into a moraine at an elevation of 94–114 m likely left by ice derived from Alexander Island. Radiocarbon measurements (traditional, non-AMS) from the shells returned ages of 32,260 ± 360 and 30,600 ± 600 ^{14}C years (WALIS ^{14}C ID 1746–1747) that likely represent "radiocarbon dead" samples as AAR analysis yielding D-alloisoleucine/L-isoleucine (D/L) values of 0.169 (WALIS AAR ID #608), 0.113 (WALIS AAR ID #609), and 0.147 (WALIS AAR ID #610) suggest the shells are much older possibly dating to ~120,000 years depending on the assumptions made about the temperature that the shells were exposed to (Clapperton and Sugden, 1982). Unfortunately, the sea-level significance of these shells is unknown due to their being reworked into a moraine. At the least, their presence suggests an ice (and ice-shelf)-free George VI sound sometime prior to the LGM (Clapperton and Sugden, 1982), and before ice advanced from George VI Sound into Belgica Trough (after ~36,000 years; Hillenbrand et al., 2010).

4.1.3. James Ross island

On James Ross Island of the eastern Antarctic Peninsula (Fig. 4), Late Pleistocene reworked marine deposits are found at Cape Lachman and St. Martha Cove (Ingolfsson et al., 1992). Rabassa (1983) reports on the locally-defined Caleta Santa Marta Drift composed of glacigenic and marine deposits. A particularly distinct shell bed is found within the drift at Saint Martha's Cove that contains several *Laternula elliptica* shells in "live position" at an elevation of around 10.40–10.60 m (Rabassa, 1983; WALIS RSL ID 4408). A radiocarbon age from one of these shells dates to 34,115 ± 1110/975 ^{14}C years (WALIS ^{14}C ID 1748). The bed itself is part of a bedset truncated at its top by an erosional surface interpreted to be of marine origin with accompanying beach deposits at an elevation of 15.0 m. Higher, but undated, marine terraces and beaches have been reported at elevations as great as 100 m on the island (Rabassa, 1983).

Ingolfsson et al. (1992) returned to Saint Martha's Cove and neighboring Cape Lachman and obtained three more Late Pleistocene radiocarbon ages as well as D/L values. At Saint Maria's Cove the two Late Pleistocene ages date to 34,510 ± 1310 (at an elevation of 0–2 m; WALIS ^{14}C ID 1751) and 36,240 ± 1820 ^{14}C years (at an elevation of 18 m; WALIS ^{14}C ID 1750). The first of these two probably came from the same unit, albeit at a lower elevation, as the age obtained by Rabassa (1983). However, Ingolffson et al. (1992) also obtained D/L values from the 0–2 m deposit and found two populations. The first population of D/L values are higher and range from 0.046 to 0.054 (WALIS AAR ID 611–613) while the others range between 0.008 and 0.018 (WALIS AAR ID 614–616). Ingolfsson et al. (1992) interpreted these to represent two populations of ages. The latter population of lower D/L values is very similar to the D/L values they obtained from a Holocene shell (dated independently via radiocarbon) from elsewhere on the island. Based on this observation, Ingolfsson et al. (1992) suggest the deposit is Holocene in age with the older shells having been reworked into the littoral deposits while the younger Holocene ages represent the true age of the deposit. However, with no radiocarbon ages from the deposit itself (only D/L value correlations) and considering the *in-situ* nature of the older population of D/L values, some doubt remains as to whether the deposit is Holocene or Late Pleistocene in age. The second Late Pleistocene radiocarbon age from Saint Martha's Cove from an elevation of 18 m (which also returned D/L values of 0.107 and 0.118, WALIS AAR ID 617–618) and a third radiocarbon age of 35,490 ± 1550 ^{14}C years (WALIS ^{14}C ID 1749) obtained from similar deposits as the 0–2 m deposits at Saint Martha's Cove but on Cape Lachman are interpreted by Ingolfsson et al. (1992) to be from marine sediments reworked or pushed up by glacial processes in the region and thus likely do not constrain past sea levels. The D/L values from the Cape Lachman samples were 0.038 (WALIS AAR ID 619) and 0.026 (WALIS AAR ID 620).

4.2. Dronning Maud Land through the Lützow-Holm Bay

4.2.1. Dronning Maud Land

To date, no coastal deposits have been examined along the Dronning Maud Land Coast. Only freshwater limiting data have been studied from across many mountain nunatuks and other coastal oases of Dronning Maud Land. However, these deposits do contain 28 radiocarbon ages dating to times prior to the LGM. Radiocarbon ages from regurgitated snow petrel stomach oil at nesting sites suggest ice free regions continuing through the LGM (Thor and Low, 2011; Berg et al., 2019) back to >58,000 years, beyond the limit of reliable radiocarbon dating and represent MIS3 or possibly older (LIG?) deposits (Berg et al., 2019); however, more work is needed to determine the reliability of those near finite ages. Additionally, their distances from the coast (>150 km) and high elevations (>1000 m) provide no meaningful constraints on past sea levels, but do confirm the presence of open water within the foraging range of the birds. Similarly, Warrier et al. (2014) report radiocarbon ages as old as 30,800 ± 1500 ^{14}C years within a lake from the Schirmacher Oasis suggesting the area was ice-free through the LGM. However, similar to the snow petrel stomach oil deposits, the location of the lakes within an ice-shelf bound oasis at elevations of ~100 m or more (Choudhary et al., 2018) and no marine deposits provide little information on past sea levels other than they were not high enough to flood the oasis since at least ~40 ka.

4.2.2. Lützow-Holm Bay

Raised beaches and marine platforms have been mapped and reported at elevations as high as 35 m along the ice-free peninsulas and islands of the Soya Coast along the eastern shores of Lützow-Holm Bay (Omoto, 1977)(Fig. 4). However, although well-developed beaches are found at elevations up to ~19 m, the marine origin of the marine platforms mantled with sands and gravels above ~20 m is debatable (Yoshida, 1983). A great number (>100) of radiocarbon ages have been obtained from predominately marine shells from the raised beaches and other marine deposits within this area. Two broad areas, the Ongul Islands and Langhovde, contain not only Holocene-dated shells but also 63 radiocarbon ages older than the LGM (Meguro et al., 1964; Igarashi et al., 1995a, 1995b; Miura et al., 1998a,1998b ; Takada et al., 2003), with a single Late Pleistocene age also found on Skarvsnes (Yoshida, 1983) (Fig. 5). The Ongul Islands and Langhovde provide arguably the most-studied Late Pleistocene beach deposits anywhere in Antarctica. The presence of these older ages has led some authors to suggest the beaches may not have been encroached upon by the larger ice sheet during the LGM (Igarashi et al., 1995a; Miura et al., 1998a, 1998b), while others have suggested otherwise (Verleyen et al., 2017). Many of the raised beach deposits of the Ongul Islands and northern Langhovde contain two distinct stratigraphic units with the upper "regressive" deposits containing Holocene shells and the lower "transgressive" deposits containing Late Pleistocene shells (Maemoku et al., 1997; Miura et al., 1999). These Late Pleistocene uncorrected ages range from 22,800 ± 1000 (WALIS ^{14}C ID 1691) to 46,420 ± 1500 ^{14}C years (or greater) (WALIS ^{14}C ID 1666) with most in the ~33–43 ka range (Table 1).

These Late Pleistocene ages within raised beach deposits are found at more than 9 locations on East and West Ongul Islands and the Langhovde (Fig. 5). On East Ongul Island they can be found near Syowa Station (WALIS RSL IDs 4385, 4389–4391) and across Kitami Beach (WALIS RSL IDs 4383, 4396–4397) over to Kai-no-hama (WALIS RSL IDs 4382, 4398–4399 Fig. 5). Near Syowa Station, Fujiwara (1973) and Igarashi et al. (1995a, b) report radiocarbon ages ranging from 30,700 (WALIS ^{14}C ID 1698; WALIS RSL ID 4385) to 37,220 ^{14}C years (WALIS ^{14}C ID 1701; WALIS RSL ID 4389) from mollusk shell fragments (*Adamussium colbeki* and *Laternula elliptica;* marine bivalves) within raised beach deposits. The sedimentary context of the shells was not logged in detail but the elevations in which the samples were obtained range from 1 m above sea level (Nu-1; WALIS RSL ID 4389, WALIS ^{14}C ID 1712) to 18 m above sea level (Wo-28; WALIS RSL ID 4392, WALIS ^{14}C ID 1703).

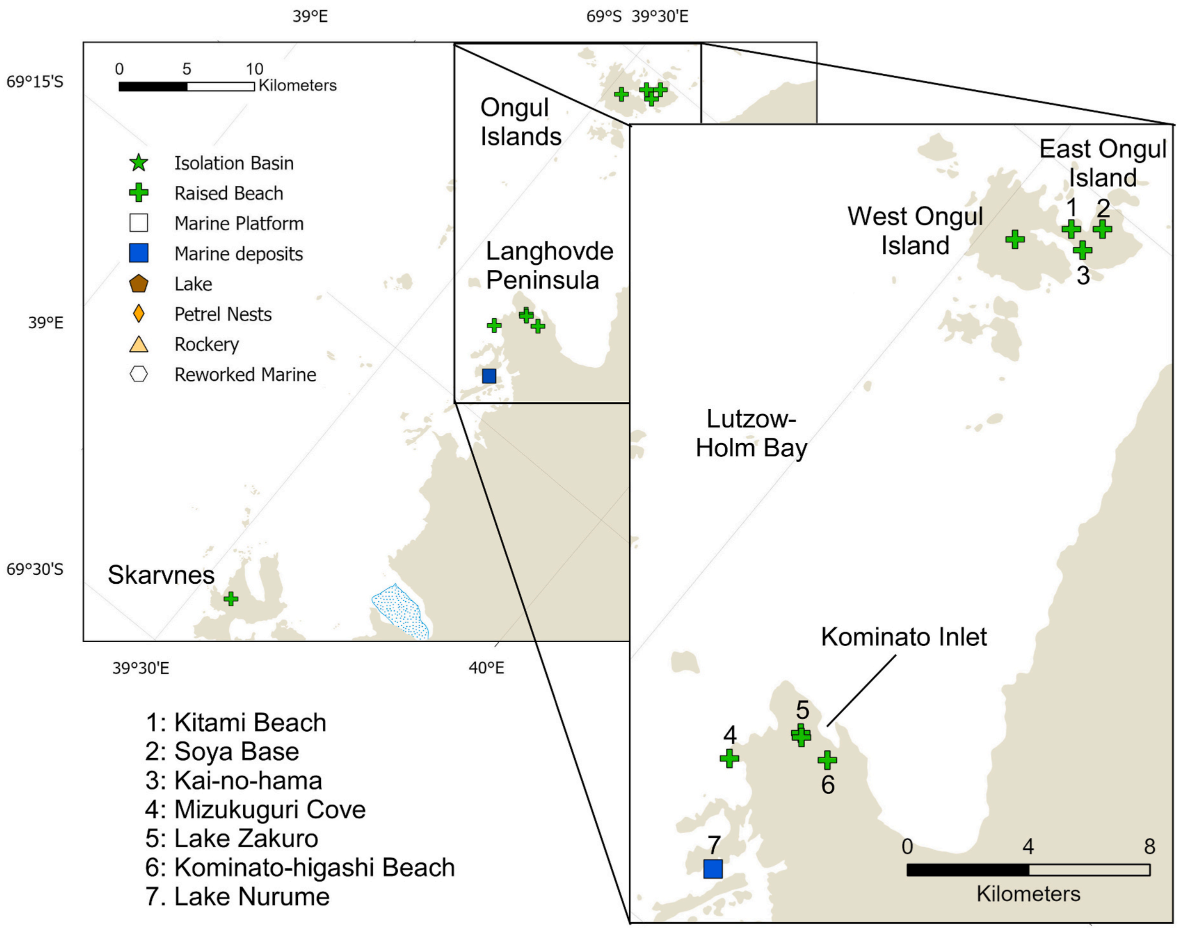

Fig. 5. Map showing the locations of sites mentioned across the Lutzow-Holm Bay.

Farther south on East Ongul Island, at Kitami-hama (WALIS RSL IDs 4383; 4396–4397), Meguro et al. (1964) were one of the first to report >30 ka radiocarbon ages. They describe a "terrace-like" feature composed of sands and gravels with a gently sea-ward dipping flat surface extending from an elevation of 17 to 10 m with the sands and gravels found as high as 20 m (Meguro et al., 1964). The sands and gravels contain plentiful mollusk, ostracod, and foraminifera shells (tests) along with echinoid spines with *Laternula elliptica* and *Adamussium colbecki* (marine bivalve) being the most common mollusk species represented. No detailed logging of the sedimentary deposits was conducted but the radiocarbon ages (WALIS ^{14}C IDs 1693–1696), which ranged from 25,400 ± 1200 (GaK-285; WALIS ^{14}C ID 1694) to 34,000 +

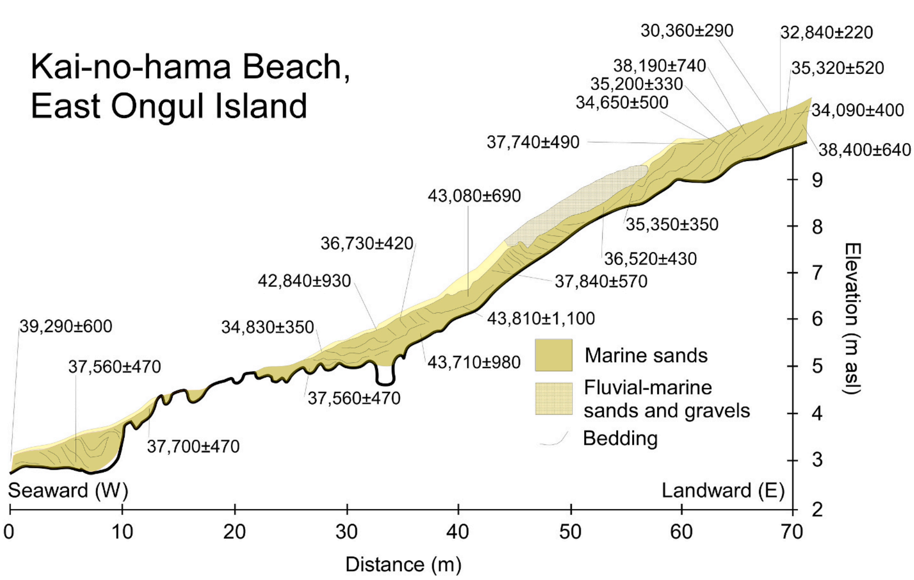

Fig. 6. Profile and stratigraphic description of the trench at Kai-no-hama, East Ongul Island. Ages shown are based on radiocarbon dating in ^{14}C years. Adapted from Miura et al. (1998a) and Takada et al. (2003).

3000/-2000 (GaK-286; WALIS ^{14}C ID 1695) ^{14}C years, were obtained from elevations ranging from 5 to 6 m (WALIS RSL ID 4383) to 12 m (WALIS RSL ID 4397) above sea level (Meguro et al., 1964).

Less than a km to the southeast at Kai-no-hama, Meguro et al. (1964) also report two additional Late Pleistocene radiocarbon ages of 22,800 ± 1000 (GaK-287; WALIS ^{14}C ID 1691, WALIS RSL ID 4398) and 29,400 + 2400/-1800 (GaK-288; WALIS ^{14}C ID 1692, WALIS RSL ID 4399) ^{14}C years from another sequence of raised beach deposits. These samples were collected at elevations of 9–10 m and 3–4 m, respectively and their host deposits contain fewer foraminifera and are sandier than the beach deposits at Kitami-hama. Miura et al. (1998a) returned to Kai-no-hama and excavated a trench from an elevation of 2.0–10.9 m above sea level within the raised beach deposits sampled by Meguro et al. (1964) (Fig. 6). The well-described trench wall contains multiple beds of bedded sands and gravels with both in-situ *Laternula elliptica* shells as well as reworked shell fragments and worm tubes (Fig. 6). The upper beds contain Holocene-age shells while 19 radiocarbon ages obtained from the lower beds (WALIS ^{14}C IDs 1675–1690) range from 43,810 ± 1100 (Beta-100332; WALIS ^{14}C ID 1683) to 30,360 ± 290 (Beta-100325; WALIS ^{14}C ID 1678) ^{14}C years. Takada et al. (2003) reported 3 more radiocarbon ages from the same trench (WALIS ^{14}C IDs, 1859–1860, 1864) that returned similar ages. The Late Pleistocene shells obtained by Miura et al. (1998a) at Kai-no-hama (WALIS RSL ID 4382) were obtained from elevations ranging from 3.0 to 10.2 m above sea level with no apparent trend between age and elevation (Fig. 7). One other Late Pleistocene age of 32,960 ± 600 ^{14}C years (WALIS ^{14}C ID 1713) at an elevation of 7.5 m (WALIS RSL ID 4391) was reported from East Ongul Island by Igarashi et al. (1995a) but its location and sedimentary context are not well constrained.

On West Ongul Island, Omoto (1977) obtained two radiocarbon ages from beach deposits on the island at elevations of 3.5 and 2.5 m above sea level (WALIS RSL IDs 4401, 4402). These samples collected by M. Nogami returned ages of 25,840 ± 2450 ^{14}C years (WALIS ^{14}C ID 1708) on an *Adamussium colbecki* shell and >31,510^{14}C years (WALIS ^{14}C ID 1709) on a *Laternula elliptica* shell, respectively. Igarashi et al. (1995a, b) obtained four additional Late Pleistocene radiocarbon ages (WALIS ^{14}C IDs 1703–1704, 1714–1715) at different locations across West Ongul Island at higher elevations ranging from 12 to 18 m (WALIS RSL IDs 4392–4395, 4400) above sea level. These ages ranged from 34,810 ± 520 ^{14}C years (Wo-32; WALIS ^{14}C ID 1714) from a *Laternula elliptica* shell to 38,160 ± 480 ^{14}C years (Wo-48; WALIS ^{14}C ID 1704) from an *Adamussium colbecki* shell fragment. Similar to East Ongul Island, all the beach deposits lie less than 20 m above sea level and contain a mix of both Late Pleistocene and Holocene ages.

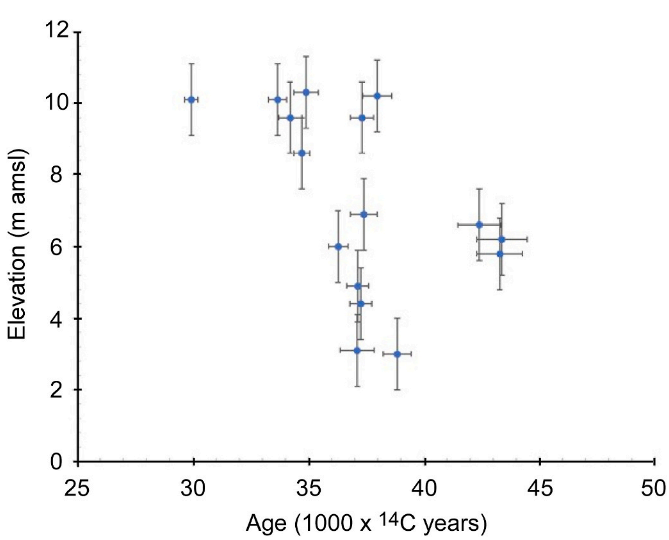

Fig. 7. Age-elevation relationship of radiocarbon dated shells within raised beach deposits at Kai-no-hama beach, East Ongul Island, Lützow-Holm Bay, East Antarctica. Age and elevations from Miura et al. (1998a).

In addition to the Ongul Islands, Late Pleistocene ages have been obtained from the raised beach deposits of northern Langhovde located ~15 km south of the Ongul Islands (Fig. 5). A marine embayment, Kominato Inlet, is bordered to the east by Kominato-higashi beach (Fig. 3) and to the west by a low-elevation saddle separating the inlet from Lake Zakuro, which presently lies below sea level. Nineteen Late Pleistocene radiocarbon ages have been reported from the deposits in and around the northern part of Langhovde. Eight of these ages (WALIS ^{14}C IDs 1666–1673) were obtained from two trenches excavated into the raised beaches of Kominato-higashi Beach, one to the east and one to the west (Maemoku et al., 1997; Miura et al. (1998a, b). The eastern trench was excavated at 4.0–9.6 m (WALIS RSL ID 4379) above sea level and the western trench at 0.8–5.1 m (WALIS RSL ID 4380) above sea level (Maemoku et al., 1997). Three bedsets (called layers by Miura et al., 1998b) were identified in the east trench while only two bedsets were identified in the west trench. The lower bedset in both trenches contains fine-to medium-grained sand with ***in situ*** marine shells, dominantly *Laternula elliptica*. The lower bedset is erosionally overlain by Holocene beach sediments, which are separated from the lower bedset by a distinct erosional surface, and may have extended to higher elevations (Maemoku et al., 1997). Ages from the lower bedset obtained from elevations of 2.2 (west trench) to 9.6 m (east trench) above sea level range from 32,430 ± 270 ^{14}C years (Beta-100346; WALIS ^{14}C ID 1670) to 46, 420 ± 1500 ^{14}C years (Beta-100347; WALIS ^{14}C ID 1666) (Maemoku et al., 1997; Miura et al., 1998a, 1998b). Similar to the ages obtained from the trench on East Ongul Island, the ages do not exhibit a relationship between elevation and age (Fig. 7). Another age of 23,830 ± 910 ^{14}C years (GaK-4148; WALIS ^{14}C ID 1699; uncorrected for $^{13}\delta$ C and "background") was also obtained from the beaches at an elevation of 5–6 m earlier by Moriwaki (1974).

On the other side of the Kominato Inlet from Kominato-higashi beach a saddle with a minimum elevation of 6 m separates the marine inlet from Lake Zakuro with a surface elevation of −9 m. The hypersaline lake is surrounded by raised beaches up to an elevation of 12 m above sea level. These raised beaches contain marine fossils including *Laternula elliptica* buried in live position (Miura et al., 1998a). A small (1 m × 1m x 1m) trench at an elevation of 3.2 m (WALIS RSL ID 4381) was excavated in the saddle by Miura et al. (1998a) who obtained a radiocarbon age of 46,120 ± 1000 (WALIS ^{14}C ID 1674). Six other Late Pleistocene ages (WALIS ^{14}C IDs 1700, 1705–1707, 1710–1711) were obtained from the raised beach deposits around the lake and western side of Kominato Inlet by Moriwaki (1974), Igarashi et al. (1998a, b), and Omoto (1977). These samples were obtained from *Laternula elliptica* and *Adamussium colbecki* shells at elevations of −4.6 m (WALIS RSL ID 4387) to as high as 8 m (WALIS RSL ID 4388). They ranged in age from >31,700 to 41,650 ± 910 ^{14}C years (Ko-20). Takada et al. (2003) report 5 more radiocarbon ages from 2 of the same trenches near Lake Zakuro as Miura et al. (1998a) at elevations ranging from 1.8 to 3.5 m. These 5 additional ages range from 34,720 ± 330 ^{14}C years (WALIS ^{14}C ID, 1857) to 42,930 ± 2000 ^{14}C years (WALIS ^{14}C ID, 1862).

Three other Late Pleistocene ages (WALIS ^{14}C IDs 1716–1718) of 34,750 ± 410 ^{14}C years (Ko-5, WALIS ^{14}C ID 1717) to 36,790 ± 540 ^{14}C years (Mk-14; WALIS ^{14}C ID 1718) on mollusk shells at elevations ranging from 1.5 to 3 m (WALIS RSL IDs 4403–4405) above sea level have been reported from Langhovde Peninsula, but their locations and the details of their hosting sediments have not been reported (Igarashi et al., 1995a). The three 200–260 ka IRSL ages of Tamura et al. (2022) discussed below (WALIS LUM IDs 662–664) were obtained from an interpreted marine deposit along the eastern shores of Lake Nurume (WALIS RSL ID 4467). The Late Pleistocene burrowed grey sands are unconformably overlain by a similar sand with shells radiocarbon dated to 6000–7000 ^{14}C years. Unfortunately, the elevation of the trench is not reported but the lake whose shores host the deposits is separated from the ocean by a sill of ~1.0 m (Ishiwa et al., 2021b).

Skarvsnes, another ice-free peninsula located ~30 km south of Langhovde, also contains raised beach deposits. However, outside of a singular age of 31,600 + 2800/-2100 ^{14}C years (GaK-2036; WALIS ^{14}C ID 1697) obtained from a mollusk fragment at an elevation of 8 m (WALIS RSL ID 4384; Yoshida, 1983), the beaches appear to be Holocene in age (Omoto, 1977; Miura et al., 1998a, 1998b; Yoshida, 1983).

Most of the Late Pleistocene ages from Lutzow-Holm Bay are at or near the limits of radiocarbon dating. Igarashi et al. (1995a) ague these >30,000 ^{14}C years ages are accurate based on the "background" of the TAMS measurement. If these ages are "radiocarbon dead", they may represent LIG, not MIS3 ages. Given the uncertainty associated with the ages being MIS3 or radiocarbon dead a couple attempts have been made using other chronological methods including ESR, IRSL, and AAR. Eight of the Late Pleistocene dated shells from two beaches on East Ongul Island (Kai-no-hama) and Langhovde (Kominato Inlet) were dated using ESR by Takada et al. (2003). The characteristics of the ESR signal were not ideal in that the ESR signal intensities were not stable, nor was the water content well constrained, resulting in two of these shells failing to produce an age. Nevertheless, Takada et al. (2003) obtained 6 ages within two populations spanning from 57 to 253 ka (WALIS ESR IDs 236–241. The first three, all obtained from *Laternula elliptica*, ranged between 43 ± 12 ka (the minimum age reported for sample 951227-4a; WALIS ESR ID 236) from an elevation of 2.4 m to 93 ± 27 ka (the maximum age reported for sample 960206-1-c; WALIS ESR ID 238) collected from an elevation of 10.4 m. A second population, also obtained from *Laternula elliptica*, ranged between 154 ± 8 ka (the minimum age reported for sample 960206-1-I; WALIS ESR ID 239) at an elevation of 9.7 m and 253 ± 43 ka (the maximum age reported for sample 960206-1-k; WALIS ESR ID 240) at an elevation of 8.6 m (Takada et al., 2003). One Holocene-aged shell was also dated using ESR. The ESR age was about half (e.g. ~1.6 ka versus ~3.5 ka) the radiocarbon age (Takada et al., 2003). Based on the poor signal quality, they interpret the older ages to suggest these shells date to either marine isotope stage 4 or 5 or marine isotope stage 6 or 7. The ages thus remain uncertain but they could very well represent LIG samples or MIS3 deposits. Tamura et al. (2022) also attempted to use a luminescence technique to date similar sediments on Langhovde. They initially tried OSL on quartz but the signals were too dim for a meaningful age analysis and thus turned to IRSL and post-IR IRSL. They obtained 3 preliminary ages ranging from 200 to 260 ka (WALIS LUM ID 662–664) from feldspar grains in a similar deposit as those with the >30 ka radiocarbon ages. These ages could be attributed to either incomplete sunlight bleaching before deposition or problems with the fading correction but are unlikely younger than MIS5 (Tamura et al., 2022).

Igarashi et al. (2001, 2002) used AAR to attempt dating the shells from East Ongul Island and the northernmost Langhovde. The D/L values from the 18 shells of the mollusk *Laternula elliptica* in the case of Groups 1 and 2 and unidentified bivalve fragments in the case of Group 3 fell into three groups. Group 1 had D/L values of 0.010–0.015, was found at elevations of 6–10 m, and represents the Holocene shells. Groups 2 and 3 were obtained from the Late Pleistocene shells and have D/L value averages of 0.024–0.066 (WALIS AAR IDs 604–605, 607) and 0.146–0.363 (WALIS AAR IDs 597–603), respectively. They were obtained from elevations of 4–6 m and 1–4 m, respectively. The relatively large differences between the two D/L values of groups 2 and 3 suggests the shells represent two different-aged deposits or, at the least, older shells were reworked into the raised beach deposits. Alternatively, they could represent different genera with difference racemization rates. Some of the other species found in association with the shells in Group 3, found at Mizukuguri Cove, are pre-Quaternary, potentially Pliocene, in age (Igarashi et al., 2001). However, they may have been reworked into the deposits from older sediments. The only radiocarbon age from Group 3 is a single date of 36,790 ± 540 ^{14}C years (Mk-14 in Igarashi et al., 1995a) at an elevation of ~1.5 m (WALIS ^{14}C ID 1718) Igarashi and Miura, 2002).

4.3. Prydz Bay area

Several ice-free regions can be found along the shores of Prydz Bay including the Larsemann Hills, Rauer Islands, and Vestfold Hills (Fig. 8). Although still a matter of discussion, it appears that glaciation in this region may not have been as extensive as other margins of Antarctica (Gibson et al., 2009; Mackintosh et al., 2014) and thus many Late Pleistocene lake basin fills are still preserved across the region. Each of these areas contains several lakes and other marine deposits that contain a record of sedimentation predating the global LGM (Hirvas et al., 1993; Hodgson et al., 2001, 2006, 2009; Berg et al., 2016).

4.3.1. Larsemann Hills

Over 150 lakes at elevations close to sea level to over 115 m have been studied across the Larsemann Hills along the margins of Prydz Bay with many of them returning Late Pleistocene ages (Gillieson et al., 1990; Burgess et al., 1994; Hodgson et al., 2001; Gao et al., 2020; Map). One of these lakes, Kirisjes Pond (Figs. 3 and 9; WALIS RSL ID 4410), with a sill separating it from the ocean at an elevation of ~8 m, contains ~150 cm of Holocene sediment overlying till. A pair of TL measurements were run from the till and returned ages of 24,000–35,000 and 30,000–43,000 yr BP (Verleyen et al., 2004; Hodgson et al., 2009; WALIS LUM ID 651–652). Below the till is two cm of consolidated sediments with marine diatoms and a radiocarbon age of >43,000 (Verleyen et al., 2004; Hodgson et al., 2009; WALIS ^{14}C ID 1755). Hodgson et al. (2009) provide three more radiocarbon ages from the same core of 26650 ± 220, 27000 ± 230, and 28750 ± 300 ^{14}C years (WALIS ^{14}C ID 1756–1758). These ages are younger than the other ~30–40 ka inconclusive ages from across Antarctica and more within the undisputed range of radiocarbon dating. Thus, both Verleyen et al. (2004) and Hodgson et al. (2009) interpret the deposit to represent MIS3, not the LIG.

Furthermore, Gao et al. (2020) cored another lake, Mochou Lake or L69 (Fig. 9; WALIS RSL ID 4411), in the region at a similar elevation as Kirisjes Pond of 10 m (stated as a sill height in Noronha-D'Mello et al., 2021). Gao et al. (2020) obtained another 16 bulk radiocarbon ages from a core taken in Mochou Lake, four of which predate the LGM (WALIS ^{14}C IDs 1774–1777). All four Late Pleistocene ages are in stratigraphic order, although two other ages interbedded with them are post-LGM in age, with two returning ostensibly non-finite ages of 20,795 ± 82 ^{14}C years (WALIS ^{14}C ID 1774) and 24,348 ± 150 ^{14}C years (WALIS ^{14}C ID 1775)). The other two ages are older approaching the limits of radiocarbon dating of 32,931 ± 260 (WALIS ^{14}C ID 1776) and 49,103 ± 659 ^{14}C years (WALIS ^{14}C ID 1777)). Marine diatoms and C/N were found in the second unit from the bottom of the core, which contained two of the Late Pleistocene ages (WALIS ^{14}C IDs 1775 and 1776). The oldest unit contains some brackish diatoms leading Gao et al. (2020) to the conclusion that the coast in the region experienced a transgression from ~50 ka to ~20 ka. Noronha-D'Mello et al. (2021) also cored Mochou Lake. They obtained bulk organic matter radiocarbon ages from the core with the deepest sample at 81 cm core depth returning a LGM/Late Pleistocene age of 21,180 ± 110 ^{14}C years (WALIS ^{14}C ID 1778). Low Sr/Br values suggest brackish conditions for the ~21 ka dated unit but a conclusive marine origin is not reported. The unknown origin of the organics dated in all of the Late Pleistocene radiocarbon ages leaves some room for better chronological constraints in the future. However, TCN ages from the same areas within the Larsemann Hills seem to support ice-free conditions during MIS3 (Liang et al., 2020); thus, if these ages stand, they provide some important constraints on MIS3 relative sea-levels.

Similar to Kirisjes Pond, neighboring Heart Lake (Fig. 9; WALIS RSL ID 4413) lies next to the ocean with a sill separating it from the ocean at an elevation of ~ 5 m (Verleyen et al., 2004). A core from the lake also contains sediments with marine diatoms at its base. Although the single radiocarbon age obtained from the basal marine-diatom bearing unit dates to ~10 ka, two other radiocarbon ages of 21,780 ± 160 ^{14}C years

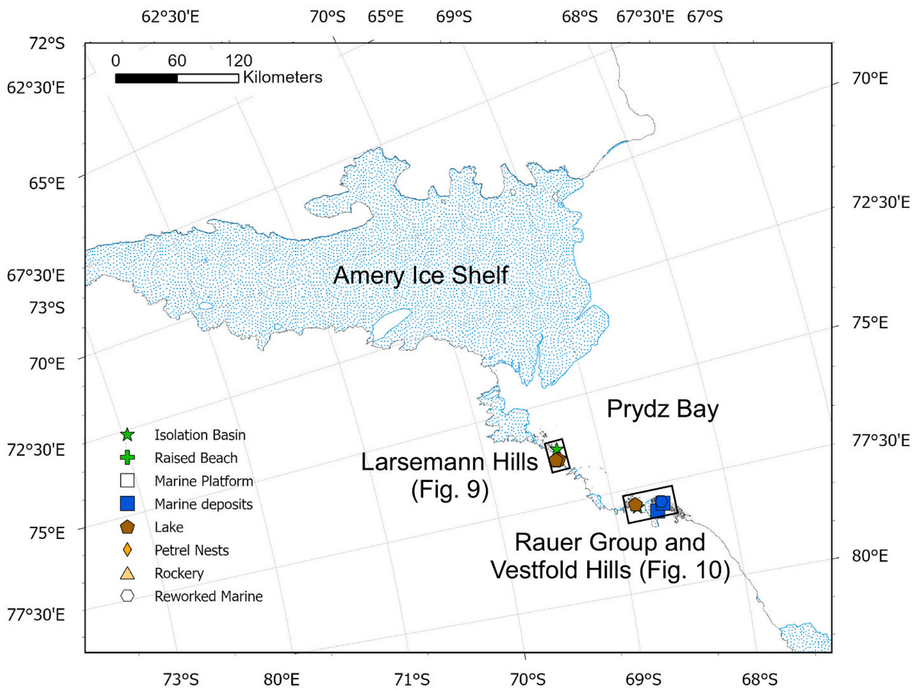

Fig. 8. Map showing the general locations of the Larsemann Hills, Vestfold Hills, and Rauer Group within Prydz-Bay, East Antarctica.

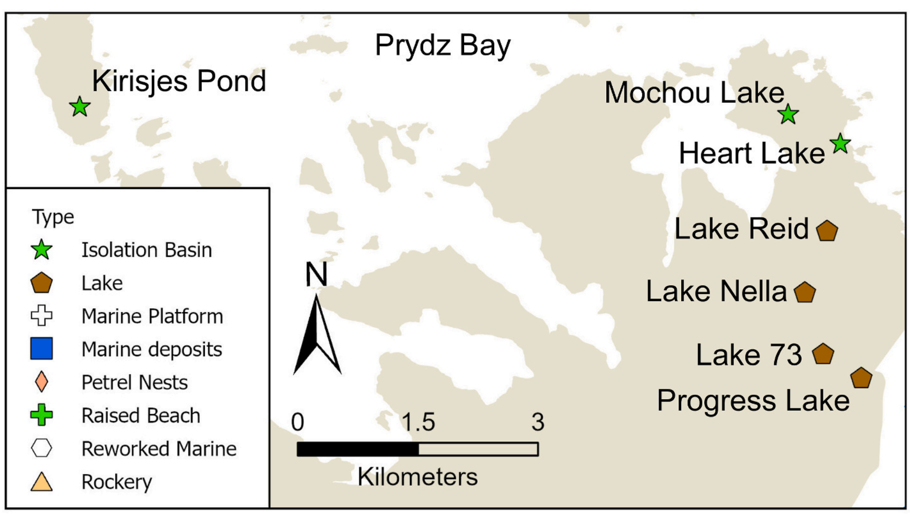

Fig. 9. Map showing the locations of sites mentioned across the Larsemann Hills. See Fig. 8 for general location.

(WALIS ^{14}C ID 1765) and 25,460 ± 230 ^{14}C years (WALIS ^{14}C ID 1766) and TL ages as old as 65,000–98,000 years (WALIS LUM ID 655) were obtained from the overlying till. Although Verleyen et al. (2004) interpret the older ages to be washed in material, given the old TL ages one possible interpretation is that the lower marine unit predates the LGM, either as a MIS3 deposit or maybe even the LIG.

Cores obtained from four other higher lakes in the Larsemann Hills also contain Late Pleistocene radiocarbon ages but do not contain evidence of marine conditions (e.g. marine diatoms)(Fig. 9). These include Lake Nella at an elevation of 15 m (Gillieson et al., 1990; WALIS RSL ID 4415), Lake Reid at an elevation of 30 m (WALIS RSL ID 4414), Progress Lake (WALIS RSL ID 4412) at an elevation of 65 m, and Lake 73 (WALIS 4416) at an elevation of 85 m (Hodgson et al., 2001). Although no evidence of marine conditions within Lake Nella have been reported, Burgess et al. (1994) provide an age of 24,940 ± 710 ^{14}C years (WALIS ^{14}C ID 1773) on well-preserved moss from the base of a 2.5 m core obtained from the lake's shoreline. Lake Reid contains 4 diatom-based zones, none of which contain marine diatoms (Hodgson et al., 2005). However, it does contain an LGM ^{14}C age of 18,790 ± 120 ^{14}C years (WALIS ^{14}C ID 1767) and four Late Pleistocene ^{14}C ages of 26,520 ± 260, 43,800 ± 2000, 41,800 ± 1500, and >39,700 ^{14}C years (WALIS ^{14}C IDs 1768–1771) as well as a "preliminary" TL age of 33,000–45,000 years (Hodgson et al., 2005; WALIS LUM ID 656). Based on polynomial age model extending to the base of the core as well as other environmental proxies in the core, Hodgson et al. (2005) and Cromer et al. (2006) interpret the base of the core represent MIS5e-aged sediments. If the age model is correct, that suggests that for at least the part of the LIG represented by the sediments in Lake Reid, LIG sea levels in Antarctica remained below 30 m.

Similar to Lake Reid, Progress Lake (Fig. 9) does not contain evidence of marine deposition but cores from it do contain six Late Pleistocene radiocarbon ages, three of which are infinite (WALIS ^{14}C ID 1761, 1763–1764), 2 more are >20 ka (WALIS ^{14}C ID 1760, 1762), and a sixth that dates to 20,920 ± 150 (WALIS ^{14}C ID 1759). In addition, the unit also contains TL ages of >100 ka (WALIS LUM ID 654) and 48–75 ka (WALIS LUM ID 653; Hodgson et al., 2001, 2006 – QSR). Although they acknowledge the possibility of the unit representing another interstadial, Hodgson et al. (2006) interpret the unit to represent LIG deposits. Its diatoms and carbonate and carbon concentrations suggest warmer periods during the LIG than today (Hodgson et al., 2006). No evidence of marine deposits has been reported for Lake 73, although little has been published on its deposits. However, one Late Pleistocene age of 32,220 ± 880 ^{14}C years (WALIS ^{14}C ID 1772) was found at the base of a core from Lake 73 (Hodgson et al., 2001). Without evidence of marine deposition, these lake deposits only provide terrestrial-limiting constraints, placing sea levels most likely below 15 m (Lake Nella) and certainly below 30 m (Lake Reid), while the data from Mochou Lake and Kirisjes Pond point to RSL above 10 m at some time prior to the LGM, most likely MIS3 but possibly the LIG.

4.3.2. *Rauer Group archipelago*

Several cores have been collected from the shallow marine inlets and coastal lakes of the Rauer Group, an island archipelago on the eastern shores of Prydz Bay (Fig. 10). These shallow-marine and lacustrine cores sampled both marine and terrestrial sediments with Late Pleistocene ages (Berg et al., 2010, 2016). Berg et al. (2009, 2010) obtained cores up to 21 m in length from two inlets near Filla and Flag Islands (Fig. 10), but only the deeper of the two inlets, Filla Inlet, contain sediments dating to before the LGM. The core from Filla Inlet reached a depth of 21.43 m (WALIS RSL ID 4417). Although the water depth in the inlet at the location of the core exceeded 38 m, the basin is separated from the ocean by sills on its north, south, and east. The deepest of these three sills lies at an elevation of -18 m below sea level. The deepest sedimentary unit in the core contains ample evidence of marine conditions including marine diatoms, shell fragments, echinoids, and a high salt content, although oxygen isotopic signatures suggest some sort of freshwater contribution to the basin at the time of unit one deposition (Berg et al., 2010). The humic acid and humic acid free fractions of the bulk organics at three different intervals within the lower part of the core returned Late Pleistocene ages, with another 10 younger (post-LGM) intervals also dated as part of the study. Those six ages (seven if including the one also reported in Berg et al., 2009; WALIS ^{14}C IDs 1779–1785) ranged from 29,550 ± 180 ^{14}C years (WALIS ^{14}C ID 1780) to 45,360 ± 2000 ^{14}C years (WALIS ^{14}C ID 1781). The lower unit with Late Pleistocene ages also contained species of diatoms thought to have gone extinct between 60 and 280 ka (Berg et al., 2010) suggesting the radiocarbon ages may be infinite. However, based on the radiocarbon ages as well as regional MIS3 ages, Berg et al. (2010) interpret the unit to represent MIS3 deposits, rather than the LIG. Regardless of the age, the sediments only provide marine-limiting data at a relatively deep water depth, −18 m.

Berg et al. (2016) obtained both TCN ages and sediment cores from the ice-free areas of the subaerial portions of the Rauer Group archipelago. The TCN ages span 37 to 128 ka but are on bedrock with little information to constrain past sea levels (Berg et al., 2016). However, the sediment cores were collected from shallow coastal lakes with sill elevations of 11.5 m for Skua Lake (WALIS RSL ID 4418) and an unnamed lake (WALIS RSL ID 4419) at an elevation (sill not specified) of 26 m. Radiocarbon ages from cores in both lakes returned Late Pleistocene ages. The sediments from Skua Lake are all non-marine in origin suggesting sea levels during the time of sediment deposition within the lake were always below 11.5 m. The lowest-most portions of the core return infinite ages of >52,800, >52,800, >56,600, >49,400, and >49,400 ^{14}C years (WALIS ^{14}C ID 1788–1792). All five ages were interpreted to represent LIG ages (Berg et al., 2016) suggesting sea levels during the LIG in this sector of Antarctica were less than 11.5 m. Two other Late Pleistocene ages of 36,400 ± 780 ^{14}C years (WALIS ^{14}C ID 1786) and 30,500 ± 250 ^{14}C years (WALIS ^{14}C ID 1787) were found in a similar overlying unit that, although non-marine, are interpreted to be "marine influenced" by Berg et al. (2016) based on the presence of evaporites. A second unnamed lake at a higher elevation of 26 m also contained a Late Pleistocene radiocarbon age of 35,700 ± 650 ^{14}C years (WALIS ^{14}C ID 1793). The age was from the marine shell *Laternula* (sp.) and was within a mud unit with other marine fauna. However, Berg et al. (2016) suggest the materials were reworked into the basin via glacial processes and do no represent in situ deposition, thus their sea-level significance is unknown.

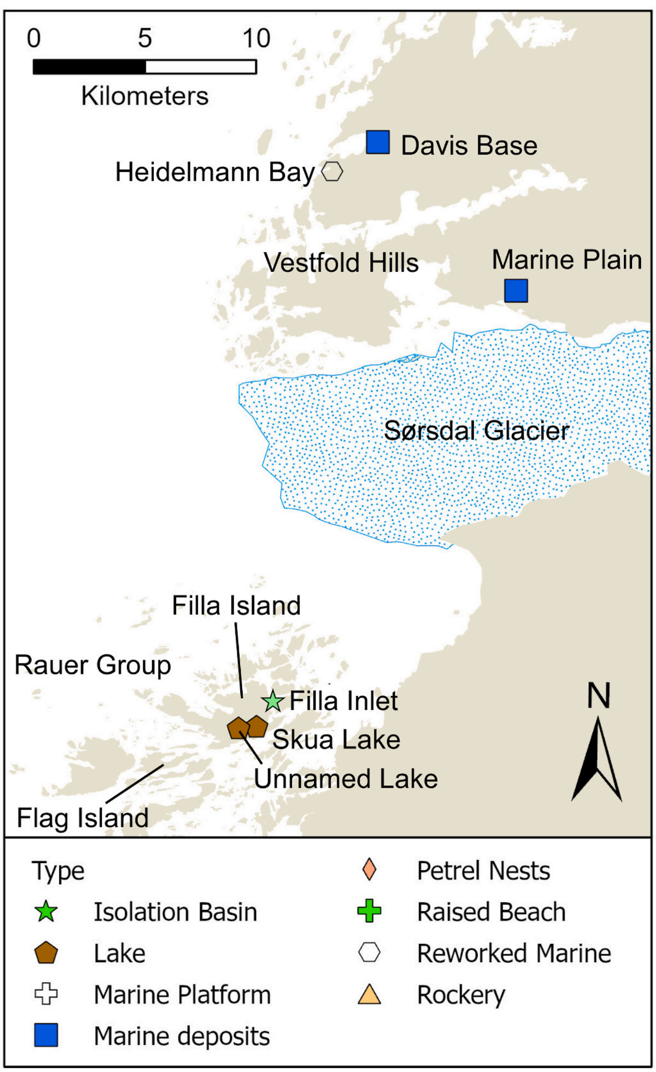

Fig. 10. Map showing the locations of the other Prydz Bay sites including the Vestfold Hills (top) and the Rauer Group Islands (bottom). See Fig. 8 for general location.

4.3.3. *Vestfold Hills*

A number of studies have dated stratigraphic sections within the Vestfold Hills returning ages that date to or predate the LGM (Hirvas et al., 1993; Gibson et al., 2009) and even back to the Pliocene (Pickard et al., 1988). Adamson and Pickard (1983) and Zheng et al. (1983) both obtained Late Pleistocene radiocarbon ages from the "Marine Plain" in the Vestfold Hills (Fig. 10; WALIS RSL ID 4423). This extensive marine plain is found at an elevation of about 20 m filling in many of the low areas between bedrock hills across the Vestfold Hills and appears to be overlain by till from the LGM. In natural cuts it is more than 8 m thick and contains marine shells and diatoms in a sandy matrix (Zhang et al., 1983). Originally interpreted as Holocene in origin, Adamson and Pickard (1983) obtained radiocarbon ages from organic marine sediments within two cuts within the plain returning ages >28,000 and > 24,000 ^{14}C years (WALIS ^{14}C IDs 1794–1795). Zhang et al. (1983) also obtained an age from shell material from the same unit. Their age was 31,000 ± 474 ^{14}C years (WALIS ^{14}C ID 1796)). Pickard et al. (1988) revisited the age of the unit noting the presence of now extinct fauna and AAR ages of >2 million years (WALIS AAR IDs 621–623) and assigned it an age of Pliocene. It also contains Pliocene vertebrate fossils (Quilty, 1991). A more detailed diatom biostratigraphic survey of the unit by Harwood et al. (2000) firmly places the deposits as early Pliocene (4.5–4.1 Ma). Thus, this marine unit lying at an elevation of 15–20 m likely pre-dates the Quaternary and represents a Pliocene, not LIG sea-level constraint.

Hirvas et al. (1993) dug three pits up to 4 m deep near the Australian Davis Base into a unit very similar to the "Marine Plain" location of Adamson and Pickard (1983) but ~8 km to the north (Fig. 10; WALIS RSL IDs 4420–4422). The pits dug down to bedrock sampled four units overlain by a cobble pavement at the surface. The basal unit was a till, which was overlain by a shelly gravel in turn overlain by another till with shelly sands ontop of the upper till. Shell material, forams, and marine diatoms were found throughout the section. Well-preserved shells from the shelly gravel returned finite radiocarbon ages of 46, 400 ± 1200 ^{14}C years (WALIS ^{14}C ID 1797). A slightly younger age of 43,200 ± 1600 ^{14}C years (WALIS ^{14}C ID 1798) was obtained from another bivalve in the upper shelly sand. In addition to the radiocarbon ages, a preliminary TL age of 440-410 ka (WALIS LUM ID 657) was also obtained from the shelly gravel (Hirvas et al., 1993). This TL age was not corrected for feldspar fading. Twenty-nine D/L values of the shells within the shelly gravel suggests they predate the LIG (Hirvas et al., 1993; WALIS AAR IDs 624–652) and may date to much older (e.g. 1 Ma+). Thus, although not discussed by the author, the deposits may correlate to the Pliocene Marine Plain of Pickard et al. (1988) but at the least also appear to pre-date the LIG.

In addition to studies reporting ages from the marine sands, Late Pleistocene radiocarbon ages from aragonites and peat and a shell within tills have been reported by Aharon (1988), Hirvas et al. (1993), and Pickard (1985), respectively. The three aragonite radiocarbon activity ages with ages varying between 29,600 ± 600 and 31,900 ± 800 ^{14}C years were paired with a U-series age of 35,500 ± 2000 years (Aharon, 1988). The aragonites were interpreted to have been precipitated form subglacial meltwater during the advance of the LGM ice. The age obtained from a reworked peat in a till by Hirvas et al. (1993) was 37,520 ± 1930 ^{14}C years (WALIS ^{14}C ID, 1800). Pickard (1985) also reports a Late Pleistocene age of >33,000 ^{14}C years (WALIS ^{14}C ID 1799) reworked into a moraine in Heidemann Bay in the Vestfold Hills (Fig. 10). As none of these sets of ages have a known relationship to marine sediments or paleo-sea levels they provide little information on LIG sea levels.

4.4. Wilkes land

4.4.1. Bunger Hills

The Bunger Hills are the largest expanse of ice-free areas in East Antarctica (Fig. 11). Although it appears some of the hilltops of the area were ice free earlier than many other areas of Antarctica (Gore et al., 2001), the Late Pleistocene ages obtained from kame terraces and glacial lake shorelines are all post-local LGM and none have a closely defined relationship to past sea levels (WALIS RSL IDs 4424–4426; LUM IDs 658–661). They range in age from 41 ± 12 ka (WALIS LUM ID 658) to 21 ± 8.9 ka (Gore et al., 2001). Thus, although they provide terrestrial limiting constraints on MIS3 sea levels they do not constrain LIG sea levels.

Melles et al. (1997) and Kulbe (1997) also report 7 Late Pleistocene ages (WALIS ^{14}C IDs, 1850–1856) within sediment cores collected in lake basins within the Bunger Hills. The ages of Melles et al. (1997) and Kulbe (1997) are all based on radiocarbon dating of marine sapropel sediments reworked into tills (Berg et al., 2020). The ages range from 24, 140 ± 400 ^{14}C years (WALIS ^{14}C ID, 1850) to 35,700 ± 1300 ^{14}C years (WALIS ^{14}C ID, 1853). Melles et al. (1997) describe the sediments containing the Late Pleistocene ages as consolidated tills. Because of their likely reworked nature, they cannot be used to constrain past sea levels.

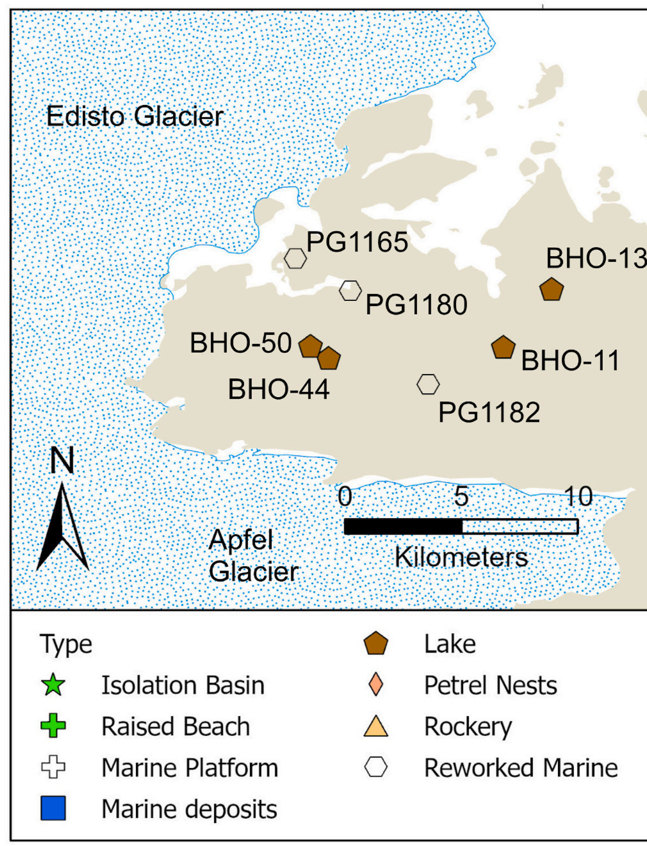

Fig. 11. Map showing the locations of Late Pleistocene ages obtained in the Bunger Hills. Samples labeled "BHO" are OSL ages from kettle and glacial lake shorelines collected by Gore et al. (2000). The PG samples are from sediment cores from lake basins collected by Melles et al. (1997) and Kulbe (1997). See Fig. 1 for general location.

4.4.2. Windmill Islands

Kirkup et al. (2002) and Cremer et al. (2003) studied 2 marine sediment cores from two basins in the shallow regions of the Windmill Islands (Fig. 12). Both cores penetrated through a Holocene marine unit overlying a till and into an underlying "overconsolidated" marine unit. The first of the cores, PG1433 (WALIS RSL ID 4427), obtained in −46 m of water in Browning Bay but separated by a sill of unknown water depth contains marine diatoms and pigments in the sapropel unit at its base (Cremer et al., 2003; Hodgson et al., 2003). Five radiocarbon ages (WALIS ^{14}C IDs, 1801–1805) from bulk organics from the unit range from 38,120 ± 1470/1240 ^{14}C years (WALIS ^{14}C ID, 1801) to 46,860 ± 2450/1870 ^{14}C years (WALIS ^{14}C ID, 1803; Cremer et al., 2003). The second core, PG1430 (WALIS RSL ID 4428), was taken in neighboring Peterson Inlet and contains a mix of marine and freshwater species, but Cremer et a. (2003) and Hodgson et al. (2003) favor a marine interpretation similar to that of PG1433. Although taken in −25 m of water, the inlet it was taken from is separated from the ocean by a sill of −3 m water depth (Cremer et al., 2003). The nine radiocarbon ages (WALIS ^{14}C IDs, 1806–1814) from this core are a mix of bulk organic (n = 2) and shell fragments and echinoids (n = 9). The two bulk organic samples returned ages of 33,590 ± 1000/890 ^{14}C years (WALIS ^{14}C ID, 1806) and 26,130 ± 950/850 ^{14}C years (WALIS ^{14}C ID, 1807). The 7 carbonate samples from shell fragments and echinoids all returned infinite ages ranging from >48,960 ^{14}C years (WALIS ^{14}C ID, 1813) to >52,060 ^{14}C

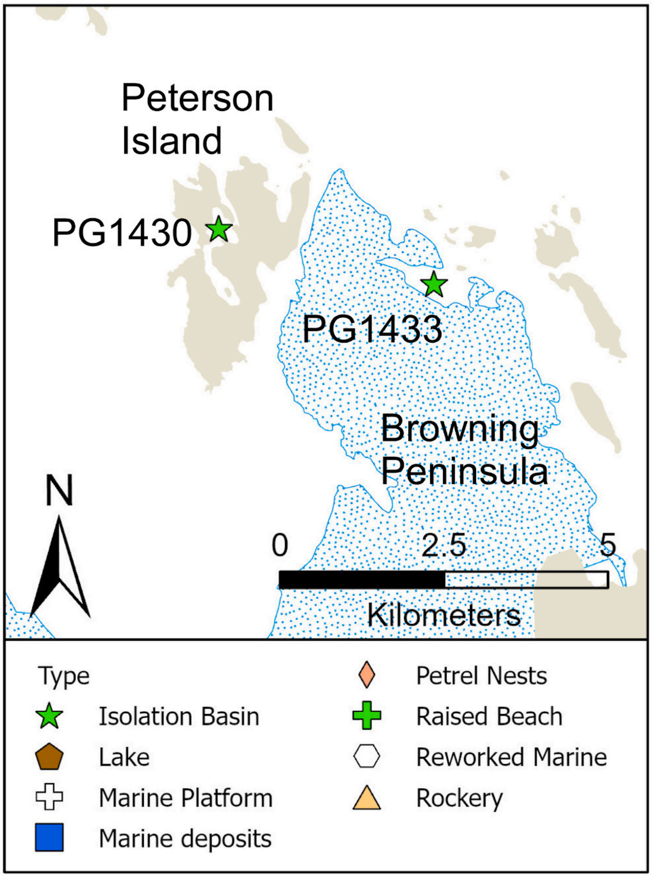

Fig. 12. Map showing the locations of Late Pleistocene sites within the Windmill Islands. See Fig. 1 for general location.

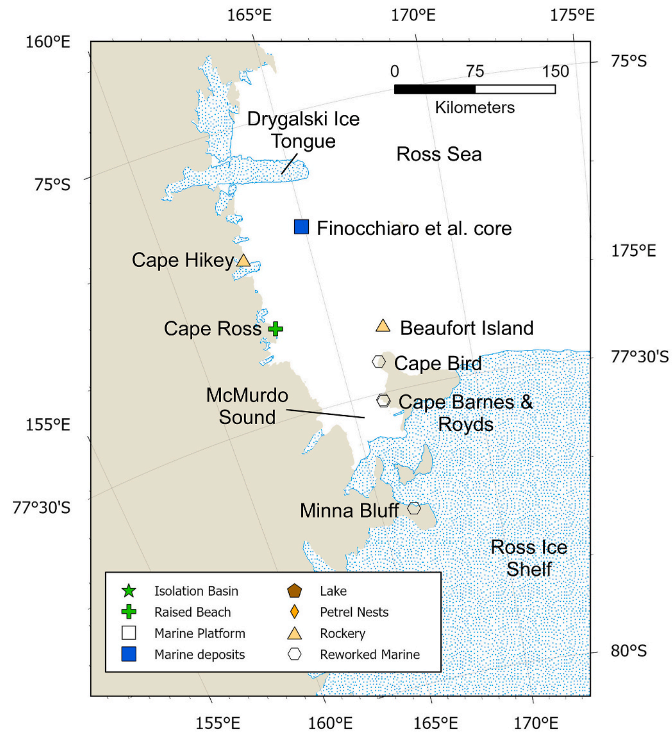

Fig. 13. Map showing the general locations of Late Pleistocene deposits mentioned in the Ross Sea. See Fig. 1 for general location.

years (WALIS ^{14}C ID, 1809–1810). In addition, Kirkup et al. (2002) report 5 AAR age estimates from shells from the core. The D/L values suggest ages of 73 ka (WALIS AAR ID 653), 120 ka (WALIS AAR ID 657), and 525 ka (WALIS AAR ID 655) with two other indeterminate ages (WALIS AAR IDs 654, 656; Kirkup et al., 2002). However, both Kirkup et al. (2002) and Cremer et al. (2003) interpret the carbonate ages to represent material washed into the basin and the bulk organic ages to represent the true age of the deposit. Thus, they interpret the marine units to be MIS3.

4.5. Ross Sea

Some of the first reported Late Pleistocene radiocarbon ages from marine deposits in Antarctica are from the western Ross Sea. Speden (1962) and Hendy et al. (1969) describe the marine fauna of relatively high (>100 m) outcrops of Quaternary marine sediments locally named the Scallop Hill Formation. Speden (1962) obtained a radiocarbon age of 43,600 ± 6700 ^{14}C years (WALIS ^{14}C ID, 1833) from shells in these deposits at an elevation of 180 m at Cape Bird (Fig. 13). Similarly, Hendy et al. (1969) obtained another Late Pleistocene radiocarbon age of 36, 000 ± 2600 ^{14}C years (WALIS ^{14}C ID, 1828) from a shell at an elevation of 30 m from Cape Barnes. Debate at the time centered around how the shells attained their current elevations with suggestions of both post-glacial rebound and "upthrusting" by glaciers or ice shelves. Denton et al. (1970) revisited the site of Hendy et al. (1969) and obtained 2 other Late Pleistocene radiocarbon ages from marine shells of >49,000 ^{14}C years and >47,000 ^{14}C years (WALIS ^{14}C ID, 1829–1830). One was from the Hendy et al. (1969) site and the other was from a location about 30 m higher. However, after further mapping of Cape Barnes, Denton et al. (1970), and later Stuiver et al. (1981) who also obtained 2 more ages of 36,300 + 1200/-1100 ^{14}C years (WALIS ^{14}C ID, 1831) and 39, 000 + 2100/-1700 ^{14}C years (WALIS ^{14}C IDs, 1831–1832) from similar shells on Cape Royds (Fig. 13), suggested the deposits were not in place but reworked into a moraine locally termed the "Ross Glaciation II" event. Furthermore, Stuiver et al. (1981) also reported a U–Th age of 120,000 ± 6000 years (WALIS U-TH ID 3388) from mollusks shells from the reworked deposits on Cape Barnes. Nevertheless, due to their reworked nature, the ages of Hendy et al. (1969), Denton et al. (1970), and Stuiver et al. (1981) provide little information on Late Pleistocene sea levels, only limited constraints on the age of local glaciations in the region.

Dochat et al. (2000) also revisited the western Ross Sea Late Pleistocene ages, but at Cape Bird near the site of Speden (1962). They obtained 3 more Late Pleistocene ages (WALIS ^{14}C IDs, 1834–1836) from Quaternary marine shells ranging in radiocarbon age from 28,160 ± 390 ^{14}C years (WALIS ^{14}C ID, 1836) to 40,155 ± 1350 ^{14}C years (WALIS ^{14}C ID, 1834) on Cape Bird, but not at the exact location as Speden (1962). Similar to Denton et al. (1970) and Stuiver et al. (1981), they suggested the marine shells were reworked into moraines and not in place, thus also providing little information on Late Pleistocene sea levels. A tenth Late Pleistocene age of >51,000 ^{14}C years (WALIS ^{14}C ID, 1837) from a marine shell at Minna Bluff (Fig. 13) collected by Kellogg and Truesdale (1979) probably also reflects a reworked deposit.

Arguably the best potential LIG site in Antarctica is that of Gardner et al. (2006) at Cape Ross (Fig. 13; WALIS RSL ID 4429). Originally thought to represent a series of Holocene beach ridges, Gardner et al. (2006) obtained 13 Late Pleistocene ages (WALIS ^{14}C IDs, 1815–1827) ranging from 22,060 ± 190 ^{14}C years (WALIS ^{14}C ID, 1827) from an elephant seal skin reworked into a beach at a differential-GPS measured elevation of 26 m to several 40 ka ages (WALIS ^{14}C IDs, 1815–1819) from marine mollusk shell valves and fragments in beaches at elevations between 28 and 30.9 m above modern sea level. The beaches continue to an elevation of 34 m. Gardner et al. (2006) dug pits into the raised beaches and noted 3 stratigraphic units. Six radiocarbon "dead" ages (WALIS ^{14}C IDs, 1815–1819, 1822) and three aspartic acid D/L values of 0.245, 0.255, and 0.252,interpreted as 300–600 ka (WALIS AAR IDs

658–670), were obtained from the lower unit, suggesting it is older than the LIG, speculatively MIS11. Five additional ages from the lower two units returned radiocarbon ages of 22,060 ± 190 ^{14}C years (WALIS ^{14}C ID, 1827) to 38,900 ± 3100 ^{14}C years (WALIS ^{14}C ID, 1820) as well as two more ages of 28,580 ± 920 ^{14}C years (WALIS ^{14}C ID, 1825) and >26,400 ^{14}C years (WALIS ^{14}C ID, 1826) in an abandoned penguin rookery. Penguin DNA were also examined within the middle unit and based on current mutation rates of penguins (Lambert et al., 2002) the middle unit may be 100 ka in age (Gardner et al., 2006). The top unit contains Holocene radiocarbon ages and likely represents wind reworked Holocene material (Gardner et al., 2006).

Another source of RSL constraints from the western Ross Sea are abandoned penguin rockeries. Although their relationship to past sea-levels is not as well defined as raised beaches or isolation basins, they do provide terrestrial limiting data. Emslie et al. (2007) sampled 3 paleo-rockery sites in the southwestern Ross Sea that contained Late Pleistocene radiocarbon ages, two sites at Cape Hickey and a third site on Beaufort Island (Fig. 13). The elevations of the two highest at Cape Hickey were 49 (WALIS RSL ID 4430) and 52 m (WALIS RSL ID 4431), while the lowest of the three sites was located on Beaufort Island at an elevation of 4 m (Fig. 13; WALIS RSL ID 4432). The seven ages (WALIS ^{14}C IDs, 1840–1846) obtained from the two highest rockeries ranged from 27,170 ± 250 ^{14}C years (WALIS ^{14}C ID, 1843) to 43,010 ± 1400 ^{14}C years (WALIS ^{14}C ID, 1845; Emslie et al., 2007). The three ages from the 4-m site were all infinite with ages >44,000 ^{14}C years (2x) and >47, 600 ^{14}C years (WALIS ^{14}C IDs, 1847–1849).

Finocchiaro et al. (2007) retrieved a sediment core at a water depth of 888 m from a deep basin in the western Ross Sea (Fig. 13) and penetrated the interpreted LGM till. Beneath the interpreted LGM till lies another marine mud similar to the muds at the surface today. Two Late Pleistocene acid insoluble radiocarbon ages of 28,070 ± 600 ^{14}C years (WALIS ^{14}C ID, 1839) and 29,550 ± 480 ^{14}C years (WALIS ^{14}C ID, 1838) were obtained from the lower unit. Although it points to an ice-free Ross Sea prior to the LGM, the depth and context of the core provide little information about RSL prior to the LGM. Other studies on marine cores in the Ross Sea have returned Late Pleistocene ages (e.g. Licht and Andrews, 2002; Bart and Cone, 2012). Some of these ages have been interpreted as post-glacial units with a significant amount of reworked old carbon, resulting in radiocarbon ages much older than the age of the unit itself (Licht and Andrews, 2002). Regardless of whether they represent pre- or post-LGM sediments, the great water depths in which they were collected preclude their use in constraining Late Pleistocene sea levels.

5. Discussion

5.1. MIS3 versus MIS5

Late Pleistocene coastal deposits providing reasonable constraints on past sea-level elevations have been found at a number of places across Antarctica including the Soya Coast, the Larsemann Hills, Rauer Group, Windmill Islands, Vestfold Hills (although likely Pliocene), and Cape Ross. In addition, Late Pleistocene terrestrial and marine limiting data have been found in the Bunger Hills and portions of the western Ross Sea. However, most of these past sea-level constraints have been interpreted to be MIS3 and not MIS5e. A MIS3 age is not unreasonable (Ishiwa et al., 2020). Some ice sheet model simulations suggest possible periods of significant ice loss across Antarctica during MIS3 (e.g. de Boer et al., 2012) and some studies of Antarctic ice sheet elevation changes suggest periods of draw down between the LIG and the LGM (e.g. Johnson et al., 2017). Other glaciated locations within the Southern Hemisphere also point to a period of less ice during MIS3 (e.g. Jomelli et al., 2018). Furthermore, there is a growing body of evidence suggesting relative sea levels during MIS3 were higher than traditionally interpreted from the oxygen isotope record alone (Simms et al., 2009; Pico et al., 2016; Dalton et al., 2022) and thus implying less ice within the cryosphere at this time.

Although many of the Late Pleistocene deposits have been interpreted as MIS3 in age, this interpretation is not without discussion. For the Soya Coast, the 63 Late Pleistocene radiocarbon ages are at the limits of radiocarbon dating with 5 of the ages derived from the same deposits giving infinite ages. Unfortunately, attempts to date the same deposits with other techniques have been equally inconclusive. For example, Takada et al. (2003) obtained 6 ESR ages from the same shells radiocarbon dated to ~34–43 ka along the Soya Coast. Their results, although not conclusive, suggest the shells were much older ranging between 43 ka and 253 ka. They interpret some of the shells to date to MIS4 or 5 and others to an older interglacial, possibly MIS6-7. As a test of using ESR on these shells, they also obtained an ESR age of a Holocene-aged shell, which was also dated using radiocarbon. Unfortunately, although similar, the ages did not agree as the ESR age was 1.5–1.7 ka while the radiocarbon age was ~3500 ^{14}C years (Takada et al., 2003). The MIS7 interpretation is supported by Tamura et al. (2022) who attempted to date similar deposits using OSL, but with quartz grains displaying extremely low sensitivity, they turned to IRSL dating of the feldspar grains. Their ages returned MIS7 ages but they were obtained from a unit without marine shells with 35–40 ka radiocarbon ages. Thus, although they likely dated the same marine unit as the earlier studies from the region, their correlation with the other units is not definitive. Additionally, the 10 measured D/L values have yet to produce numerical ages (Igarashi and Muira, 2002). Other studies from other sites across Antarctica have been just as inconclusive. Within the Larsemann Hills, Hodgson et al. (2001) obtained infinite ages (>45 ka) in Progress Lake from a sediment unit that contained a sub-Antarctic diatom flora. This sediment unit was attributed to MIS5 based on the full interglacial conditions required for this diatom community to become established. However, radiocarbon and TL measurements from other lake sediments in the Larsemann Hills give ages of >45 ka (radiocarbon), 48–72 and > 100 ka (TL) (Hodgson et al., 2006). More work is required to establish if these sediments date from MIS3 or MIS5 (the LIG) or if they represent two or more units juxtaposed? In terms of sea-level constraints only one lake, Kirisjes Pond, contains clear evidence of a marine highstand during MIS3 (Hodgson et al., 2009). Furthermore, Late Pleistocene radiocarbon ages of 24–35 ka from marine deposits in the Vestfold Hills were later shown to be Pliocene based on their diatom fauna and *in situ* extinct bivalves (Pickard et al., 1988). Thus, more work is needed to definitively conclude a MIS3 or LIG age for most of these areas.

5.2. Height difference between Late Pleistocene and Holocene highstand elevations

A comparison between the elevation of the Holocene marine limit or highstand and that of the MIS3 and/or MIS5 highstands may have important implications for the past ice sheet configurations (e.g. Ishiwa et al., 2021). However, before examining this difference, acknowledgement should be made that the age of many of the Late Pleistocene features remains uncertain and the shoreline features across the continent may be of different ages. Nevertheless, the observation of elevation differences may provide clues as to the impacts of tectonics and GIA effects driven by the past distribution of ice sheets (both the LGM and previous ice sheet states). The largest potential difference between the elevations of the Late Pleistocene and Holocene highstand is within the Antarctic Peninsula (Fig. 14), although these are also the least constrained chronologically. Potential Late Pleistocene raised beaches in Marguerite Bay lie approximately 20 m above Holocene counterparts, but those inferred Late Pleistocene beaches may represent early Holocene, rather than Late Pleistocene beaches (Bentley et al., 2005; Simkins et al., 2013). Unfortunately, the only dated lake basins in the region (e.g. Hodgson et al., 2012) are too high to independently verify the proposed Holocene marine limit of less than ~24 m. Late Pleistocene sea levels may have also been higher across the South Shetland Islands (43–48 m vs. 20 m, the highest Holocene beach ridge in the South Shetland

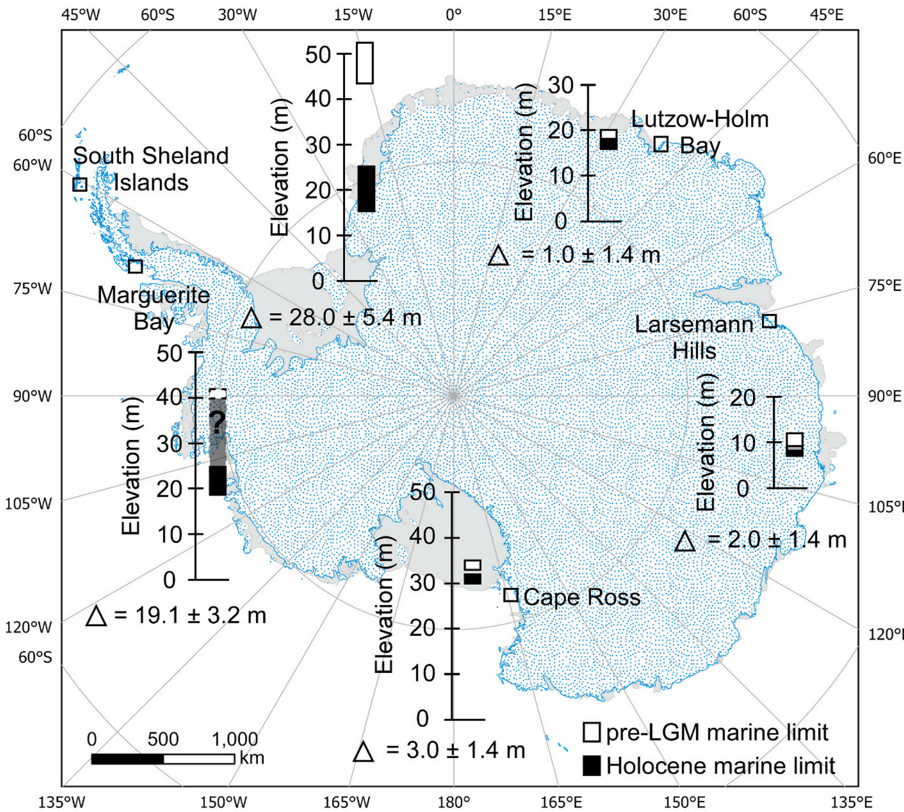

Fig. 14. Map with bar graphs illustrating the difference in highstand elevations between the Late Pleistocene and Holocene highstands.

Islands, Fretwell et al., 2012), but they overlie an active subduction zone and the potential difference in highstand elevations may simply reflect the long-term tectonic uplift, which is estimated to be 0.22–0.48 m/ka (Watcham et al., 2011). In addition, the Late Pleistocene wave-cut platform has yet to be constrained chronologically.

The differences in elevations between the Late Pleistocene and Holocene shoreline features are probably more meaningful for East Antarctica than West Antarctica due to the similarities in the Late Pleistocene and Holocene sea-level indicators, the generally more tectonically stable geologic setting of East Antarctica (outside of the Transantarctic Mountains), and the generally better studied/documented nature of those features in East Antarctica compared to West Antarctica. Within East Antarctica, these differences can be observed in Lützow-Holm Bay, the Larsemann Hills, and the Ross Sea. Other areas in East Antarctica do indicate Late Pleistocene sea levels at much lower elevations (e.g. Rauer Group, Windmill Islands). However, these data are largely from nearshore marine cores and terrestrial evidence for the Late Pleistocene marine limit is, to date, lacking. Without a clear Late Pleistocene highstand or marine limit elevation, a comparison with the Holocene is not possible in these locations.

The Holocene marine limit varies across the ice-free areas of Lützow-Holm Bay (Miura et al., 1998a, 1998b; Verleyen et al., 2017). Although the highest Holocene marine limit is 32.7 m based on a Holocene-dated raised beach at Skarvness, only one Late Pleistocene constraint is found on that peninsula (Fig. 5). Although its elevation is much lower at 8 m, its Late Pleistocene age is highly suspect (Omoto, 1977). The areas within Lützow-Holm Bay with the best evidence for a Late Pleistocene age are farther north at Langhovde and the Ongul Islands (Fig. 5). The Holocene marine limit at these locations is much lower, likely due to its location farther north and thus farther afield of the additional LGM ice load (Miura et al., 1998a, 1998b; Verleyen et al., 2017). The Holocene marine limit in Langhovde is 17 m based on raised beach and 16 m in the Ongul Islands based on both raised beaches and lake basins (Omoto, 1977; Hayashi and Yoshida, 1994; Miura et al., 1998a, 1998b; Verleyen et al., 2017). The Late Pleistocene marine limit is more difficult to quantify as most Late Pleistocene beach deposits are unconformably overlain by Holocene beach deposits (Omoto, 1977; Miura et al., 1998a, 1998b) and thus their true highstand elevation may be underestimated. Nevertheless, the highest Late Pleistocene ages come from beach deposits as high as 18 m (Igarashi et al., 1995a, 1995b), although deposits are only well described up to an elevation of ~11 m (Miura et al., 1998b). Assuming the higher of these two approximates the true Late Pleistocene marine limit, there is little difference between the Late Pleistocene and Holocene marine limit (Fig. 14).

The difference in elevation between the Late Pleistocene and Holocene highstand or marine limit in the Larsemann Hills is small (Fig. 14). The Holocene highstand within the Larsemann Hills reached ~8 m based on the highest isolation basin with marine deposits (Verleyen et al., 2005; Hodgson et al., 2016), while the highest evidence of Late Pleistocene sea levels is ~10 m (Gao et al., 2020). The uncertainty in the elevation of this Late Pleistocene highstand is related to the uncertainty in the indicative meaning of the marine deposits within Mochou Lake and the lack of an accurately surveyed sill-height. The lake lies at an inferred elevation of 10 m (unknown sill elevation), but the indicative meaning of the marine deposits is unknown; e.g. no marine limiting data for Late Pleistocene times is found on the peninsula. Farther north, the Holocene marine limit rises to 9 m in the Vestfold Hills (Zwartz et al., 1998; Verleyen et al., 2005; Hodgson et al., 2016), but the elevation of the Late Pleistocene highstand is largely unconstrained and the marine-limiting deposits at elevations of up to 15 m represent Pliocene, not late Pleistocene-aged deposits (Pickard et al., 1988).

The last area with enough data to allow a comparison between the Late Pleistocene and Holocene highstand or marine limit elevations is the Ross Sea (Fig. 14). The Holocene marine limit based on the highest raised beach elevation for the area is 31 m (Baroni and Orombelli, 1991; Hall and Denton, 1999) while the highest Late Pleistocene dated material is found at an elevation of 32 m with the hosting flight of beach ridges reaching an elevation as high as 34 m (Gardner et al., 2006).

However, the potential impact of vertical tectonic motion needs to be considered given the setting of these sea-level indicators within the Transantarctic Mountains. Late Pleistocene ages from marine shells have also been found at higher elevations (e.g. Dochat et al., 2000) but they likely represent material reworked into younger tills, not *in situ* marine shells (e.g. Stuiver et al., 1981; Dochat et al., 2000).

What is clear is that prior to the LGM, Antarctica experienced a period of ice conditions similar to today with sea levels at or slightly above their Holocene maximum. The significance of that similarity will largely depend on whether they represent MIS3, potentially another MIS5 interstadial, or LIG features. Ishiwa et al. (2021) examined the implications of this difference if the Late Pleistocene features represented MIS3 deposits and were free of any significant tectonically-driven vertical motion. Noting the similarities in elevations of the Late Pleistocene and Holocene sea levels despite the near 40 m difference in global sea levels at this time, they conducted a series of GIA experiments for different ice sheet growth scenarios. They suggest that more ice during MIS5d through MIS4 within the Indian Ocean sector of Antarctica are required to produce the MIS3 sea levels observed across East Antarctica. A similar study to determine the meaning of the differences in elevations between the Late Pleistocene and Holocene shoreline features if they represented MIS5 including the LIG has yet to conducted. Does the similarity in elevations between the two in East Antarctica reveal anything about the potential source of extra meltwater during the LIG? Is the difference in West Antarctic elevations real or are the features simply late Holocene features in the case of Marguerite Bay and the difference in elevations within the South Shetland Islands simply a reflection of tectonic uplift? Addressing these questions would require accounting for the GIA impacts of not only potential differences in the ice during MIS5 but also the uncertainties in the ice sheet during the LGM and the intervening stadials and interstadials (e.g. MIS3 and MIS4). In either case, what is needed is better ages for the known Late Pleistocene sea-level indicators and a better geographic spread in their documentation – particularly from West Antarctica.

5.3. Future needs

As with most Quaternary datasets from Antarctica, better methods for determining the age of the known Late Pleistocene sea-level indicators are needed– particularly to determine their MIS3 versus LIG or older age. Revisiting the high beach ridges in Marguerite Bay with TCN ages could determine whether such a significant height difference exists between Late Pleistocene (either MIS3 or the LIG) and Holocene sea levels in the Antarctic Peninsula. Using OSL or other luminescence methods to date marine features throughout Antarctica has been meet with mixed results, but thus far only applied to a handful of locations. Revisiting the sites with only radiocarbon ages using OSL may help resolve the uncertainty in age of many of these features. Along the Pacific Coast of the US, stable carbon and oxygen isotopes have been found to be useful in distinguishing interstadials from the LIG (e.g. Muhs et al., 2020), could such approaches help resolve the uncertainty in the MIS3 versus LIG age of mollusks in locations such as Lützow-Holm Bay? Geographically, more data is needed from areas within West Antarctica outside of the Antarctic Peninsula to better tackle the question of whether or not the West Antarctica Ice Sheet collapsed during the LIG.

6. Conclusions

Two hundred and three radiocarbon ages, 65 amino-acid racemization (AAR) values, 25 optically stimulated luminescence (OSL)/thermoluminescence (TL)/infrared stimulated luminescence (IRSL)/electron-spin resonance (ESR) ages, and 1 U-series age was compiled from published sources to examine the constraints on Late Pleistocene sea levels across Antarctica. The initial purpose was to compile what is known about LIG sea levels across the continent suggested by some to be the source of the extra meltwater delivered to the oceans during the last highstand in sea levels. However, no conclusively LIG sea level indicators have been described from Antarctica to date. Many sea-level constraints pre-date the global LGM, but their ages are only poorly constrained. Most constraints are based on radiocarbon dating towards its limits (e.g. 30–40 ka; although the southern Hemisphere radiocarbon calibration now extends to 55,000 calendar years BP, Hogg et al., 2020) and thus uncertainty remains as to whether they represent MIS3 or LIG (or even older) deposits. Attempts to date these deposits with other methods have produced similar ambiguous ages. Clearly more work is needed to determine the age of these deposits. Despite this uncertainty, some patterns emerge as to the differences between Late Pleistocene sea levels and Holocene marine limits. Across East Antarctica, the preserved Late Pleistocene sea-level indicators show very little difference between their elevations and those at the Holocene marine limit. In contrast, although poorly dated, the Late Pleistocene sea level indicators from West Antarctica are higher than their Holocene counterparts. However, many of these are poorly dated and may even represent Holocene deposits. Additionally, some of these areas are subject to tectonic uplift and the differences may reflect tectonics rather than isostatic processes.

CRediT authorship contribution statement

Alexander Ray Simms: designed the experiment and compiled the data. Takeshige Ishiwa, Dominic Hodgson, and Toru Tamura: assisted in that compilation and provided field photos. Regina DeWitt: aided in the OSL descriptions and writing. Alexander Ray Simms wrote the manuscript with input from Takeshige Ishiwa, Dominic Hodgson, Toru Tamura, and Regina DeWitt.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data are available as a supplemental file.

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Appendix A. Supplementary data

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