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Earth Sciences

Depositional landforms and sediments in western Vestfold Hills, East Antarctica

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Abstract

Areas around western Vestfold Hills, East Antarctica, feature two sedimentary units in outcrops and excavations. Uppermost Dingle Sand is a gravelly, silty sand with boulders, which drapes bedrock ridges and more thickly covers valley floors and continues below modern sea level. Underlying Vestfold Beds are gravelly, muddy sands that are found in deeper valley fills. High-resolution aerial photography, topographic and bathymetric surveys, sediment grain size and field observations indicate that Dingle Sand formed as ablation till during the last deglaciation. Post-depositional modifications of Dingle Sand by decay of ground ice, mass movement, water, wind and marine transgression and regression have altered the texture, structure and fossil content in this region. Vestfold Beds are older, finer-grained tills. Indirect age estimation of Dingle Sand suggests deglaciation-age deposition with younger (Holocene) reworking in places, whereas Vestfold Beds may be as old as the Pliocene. These sediments post-date the early Pliocene Sørsdal Formation found on Marine Plain in southern Vestfold Hills. Identification of Dingle Sand as a separate, primarily glacial deposit helps clarify the glacial history of the Vestfold Hills. Evidence for marine modification of the deposits after deglaciation suggests that other regions might also have glacial deposits interpreted as marine because of post-depositional processes.

Key words: Deglaciation, Dingle Sand, glacial stratigraphy, isostatic rebound, sea level, Vestfold Beds

Introduction

Ice-free terrestrial and fringing marine areas of Antarctica are important environments as they host key habitats for vegetation, birds and mammals and have rich marine fauna. They can preserve Antarctic environmental histories in landforms and sediments that, integrated with records from marine deposits and ice cores, allow understanding of the past evolution and future trajectories of change of the Antarctic ice sheets and ice-free areas (e.g. Gore *et al.* 2001, Gibson *et al.* 2009, Bentley *et al.* 2014, Hodgson *et al.* 2016, White *et al.* 2022).

Vestfold Hills, at 413 km^2, is a large ice-free area in East Antarctica (Fig. 1). Studies of its glacial deposits and environmental history have focused on patterns of glaciation and deglaciation, ice marginal processes and glacial sediment genesis (Adamson & Pickard 1986a, Fitzsimons 1990, 1996, 1997, Gore *et al.* 1994, 2003, Fabel *et al.* 1997, Gore 1997, Gibson *et al.* 2009). A regional advance of the ice-sheet margin to the north-west (Fig. 1a), termed the Vestfold Glaciation (Adamson & Pickard 1983, 1986a), covered all of Vestfold Hills at some time prior to the Holocene, leaving striated bedrock surfaces. Following regional retreat of the ice-sheet margin, a small, late Holocene advance and retreat of the northern edge of Sørsdal Glacier occurred onto the southernmost peninsula (Fig. 1a). The latter advance left little glacial debris behind, with the main evidence of its passing being in the form of north to south-orientated striations created by basal sliding (Adamson & Pickard 1986a, Gore 1997). In contrast, glacial sediments are abundant in some parts of western and south-western Vestfold Hills, where extensive valley-fill sediments are mantled with boulders and sandy deposits.

The stratigraphy, depositional environments and chronology of these sediments are not well understood. The first excavations into the valley fills of western Vestfold Hills were for geotechnical investigations (Makarucha 1984), followed by pits to help understand the Quaternary origins of the sediments (Hirvas *et al.* 1993, Colhoun *et al.* 2010). We examine an area of western Vestfold Hills in which these preliminary investigations of the valley fills were undertaken for glacial and environmental history purposes (Fig. 1b; Adamson & Pickard 1986a,b, Hirvas *et al.* 1993, Gore *et al.* 2003, Colhoun *et al.* 2010). We also document the processes that produced the sediment stratigraphy and landforms as the region was deglaciated, inundated with seawater in some areas, and then emerged from the sea with isostatic rebound. We use multiple lines of evidence to show that some glaciogenic deposits have been preserved in valley fills despite being overridden during glaciations and despite modification by marine, fluvial, nival and aeolian processes. The result is a sedimentary unit of relatively uniform texture but with a complex origin that varies depending on its position in the landscape. This interpretation confirms the

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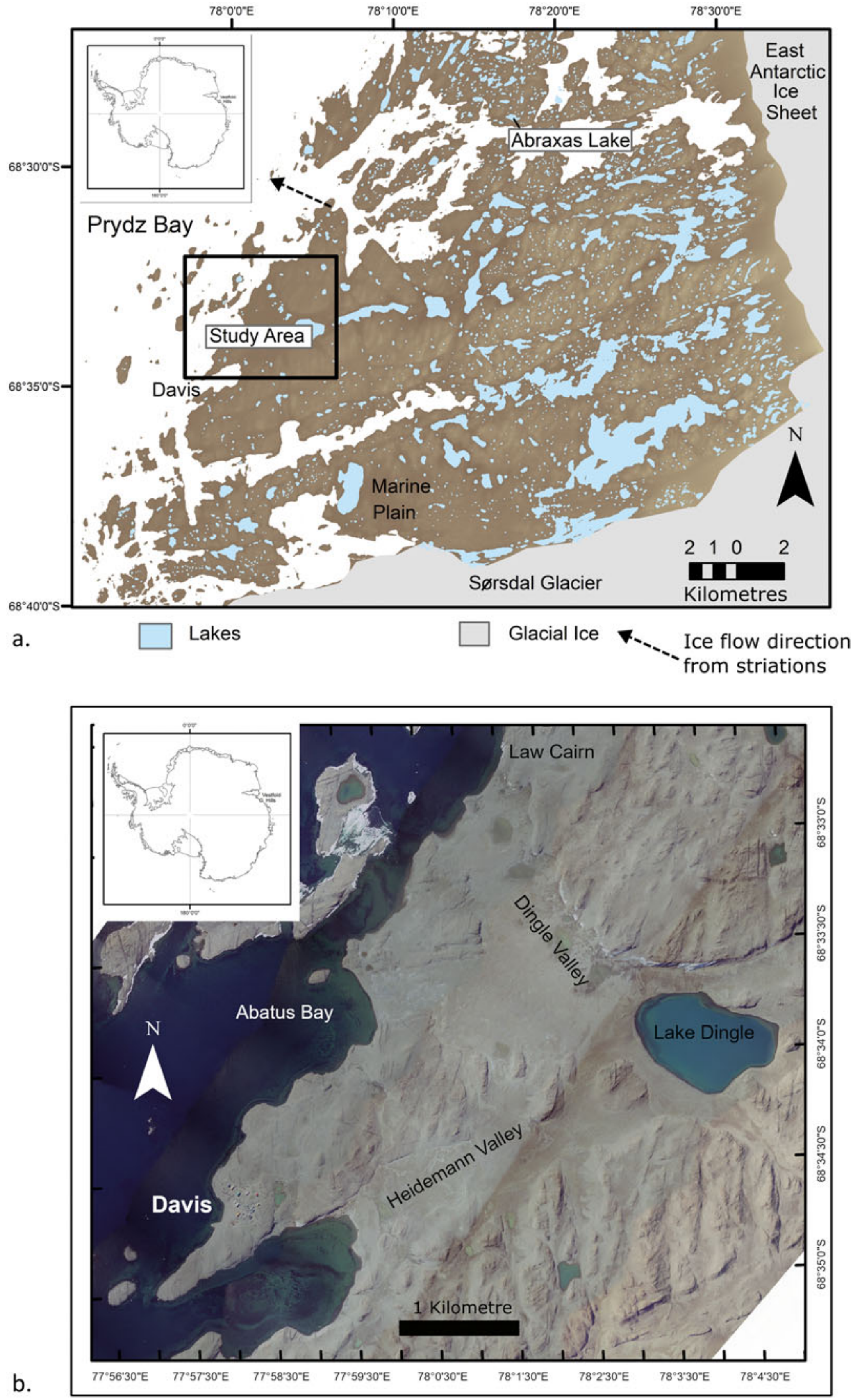

Figure 1. a. Vestfold Hills and study area, with locations outside the study area mentioned in the text. Mean bedrock striation orientation from Adamson & Pickard (1983). **b.** Aerial photomosaic of the study area with place names.

widespread distribution of glacial sediments across the Vestfold Hills (Gore *et al.* 2003) and their extension into adjacent marine embayments. These surficial deposits overlie older sediments, which have been suggested to be Pliocene tills that represent former glacial occupation of western Vestfold Hills (Hirvas *et al.* 1993, Colhoun *et al.* 2010), and therefore they record a Plio-Pleistocene history of glacial advance and retreat. We propose stratigraphic nomenclature that distinguishes these deposits as an aid to interpreting the late Neogene history of the Vestfold Hills.

Methods

Field area

The Vestfold Hills lies between 68°21'S and 68°41'S and between 77°49'E and 78°35'E. The islands and hills reach altitudes of up to 60 m in the coastal zone, rising to 156 m inland near the ice-sheet edge (Fig. 1a). The climate is cold-polar, with a mean maximum temperature of -7.4°C and a mean minimum temperature of -13°C. Summer maximum temperatures regularly exceed 0°C and have reached 13°C (Bureau of Meteorology 2023). Snowfall and rainfall are low, with a mean annual precipitation of 70.5 mm water-equivalent. Ice melt can occur throughout the summer, with irradiance being a dominant factor even with air temperatures < 0°C (Gore & Pickard 1998). Strong winds occur from the north-east (067°True), with less common, gentler sea breezes coming from the south-west in summer. The north-easterly winds dominate surface processes on land, with ventifacts, wind scours, lee-side dunes, snowbanks and marine salt spray accumulations all indicating wind as a dominant geomorphic agent (Pickard 1982, Adamson & Pickard 1986b). Mean wind speeds vary from 17 to 26 km h^{-1}, and maximum gusts of 206 km h^{-1} have been recorded (Bureau of Meteorology 2023). The prevailing north-easterly winds blow across land areas and marine inlets (named 'fjords'). This wind direction and the coastal geometry mean that sea ice breaks out progressively from the south-west, with the edge of the fast ice retreating toward the north-east.

Remote sensing and topographic surveying

This study is focused on the western end of Broad Peninsula from Dingle Lake in the east to Davis Station in the west. The northern limit corresponds to Law Cairn and the southern extent is defined by the southern edge of Heidemann Valley (Fig. 1b). We extend the study area below sea level using high-resolution multibeam bathymetry from the adjacent sea floor (Fig. 2; O'Brien *et al.* 2015).

We use high-resolution aerial photography and elevation data not available to previous investigators and the results from 111 pits dug for geotechnical investigations in the area over the last 30 years (Fig. 2). Surface morphology data now extend below sea level with high-resolution multibeam bathymetry (O'Brien *et al.* 2015). These data allow us to provide greater context for previous studies of Quaternary history (Adamson & Pickard 1986a, Hirvas *et al.* 1993, Colhoun *et al.* 2010) and sediments (Zhang & Peterson 1984, Adamson & Pickard 1986b, Gore *et al.* 1994, 2003). We also identify processes of sediment transport, deposition and deformation in the intertidal zone and landscape of the study area to provide insights into the probable post-depositional development of sediment characteristics.

Aerial photographs were taken in 1997 using a Zeiss UMK 1318 camera and flown at an altitude of 1500 m (Fig. 2). Photographic prints were scanned, with the resulting files merged and georeferenced to produce an Enhanced Compression Wavelet (ecw) file, which was loaded into the Esri software *ArcGIS*. The resulting images have pixels representing ~0.2 m on the ground and provide clear images of small features at scales of ~1:800, with many individual boulders visible. The aerial photographic images were the primary dataset used to produce a land systems map that combines geological and landform characteristics. Units were traced by hand in *ArcGIS* shape files (O'Brien *et al.* 2014).

Topographic datasets were collected at different times by unrelated field programmes, so areas of overlapping coverage are small. However, the improved accuracy and resolution of each dataset provide new insights into the large-scale topography of sediments in the area. A digital elevation model (DEM) derived from the 5 m contour map of the Vestfold Hills was used for quality assessment of other datasets. These contours were prepared by photogrammetric techniques controlled by survey marks. Topographic light detection and ranging (LIDAR) was flown by helicopter over the area covering Heidemann Valley to Dingle Lake (Fig. 2). These data were processed to give a 1 m *ArcGIS* grid tied to mean sea level (MSL) and compared to the contour-derived DEM and land survey data around Davis Station (Lieser *et al.* 2016). Comparison of the LIDAR grid with benchmarks and the surveyed positions and elevations of buildings reveal some discrepancies between the land data and the LIDAR grid; however, horizontal differences are < 2 m and vertical accuracy is ~0.2 m.

Surveying of surface locations and elevations took place using a Leica dual-frequency global positioning system (GPS) receiver with real-time kinematic (RTK) corrections applied (GPS RTK). The survey was tied to the GPS Base Station at Davis Station in the south-western corner of the study area, enabling accuracy better than 0.1 m. Fieldwork took place during various summers from 1982 onwards but mainly in 2012/2013, mapping excavations and collecting topographic transects by walking and taking surface elevation measurements at various spacings from the ground surface, excluding boulders standing above the general surface.

Multibeam bathymetry was acquired in shallow-water areas adjacent to the study area in 2010 using a multibeam echo sounder (Fig. 2; O'Brien *et al.* 2015). Data were acquired using a Kongsberg EM 3002D 300 kHz dual-head multibeam sonar. Motion referencing and navigation data were collected using an Applanix Position and Orientation system (PosMV 320), coupled with a *C*-Nav Differential GPS (2050R), providing horizontal positional accuracy of ±0.2 m. Data were processed using Caris *HIPS/SIPS* v7.1 software. Processing of the multibeam data to account for tides and vessel motion (pitch, roll and heave) and to remove erroneous values and icebergs was completed during the survey. Further processing after the survey removed more complex artefacts and converted the data to MSL. Interpolated bathymetric surfaces were exported as a 2 m-resolution grid for mapping into *ArcGIS*. Further analyses and interpretations are in O'Brien *et al.* (2015) and Smith *et al.* (2015). There are measurable discrepancies between digital elevation datasets in the small areas where they overlap, and attempts to integrate them and resolve their differences have involved resampling to lower resolution (Smith 2015). Elevation datasets were used to characterize landform morphology qualitatively without making a quantitative comparison of their morphologies, so these differences do not affect their utility for our research.

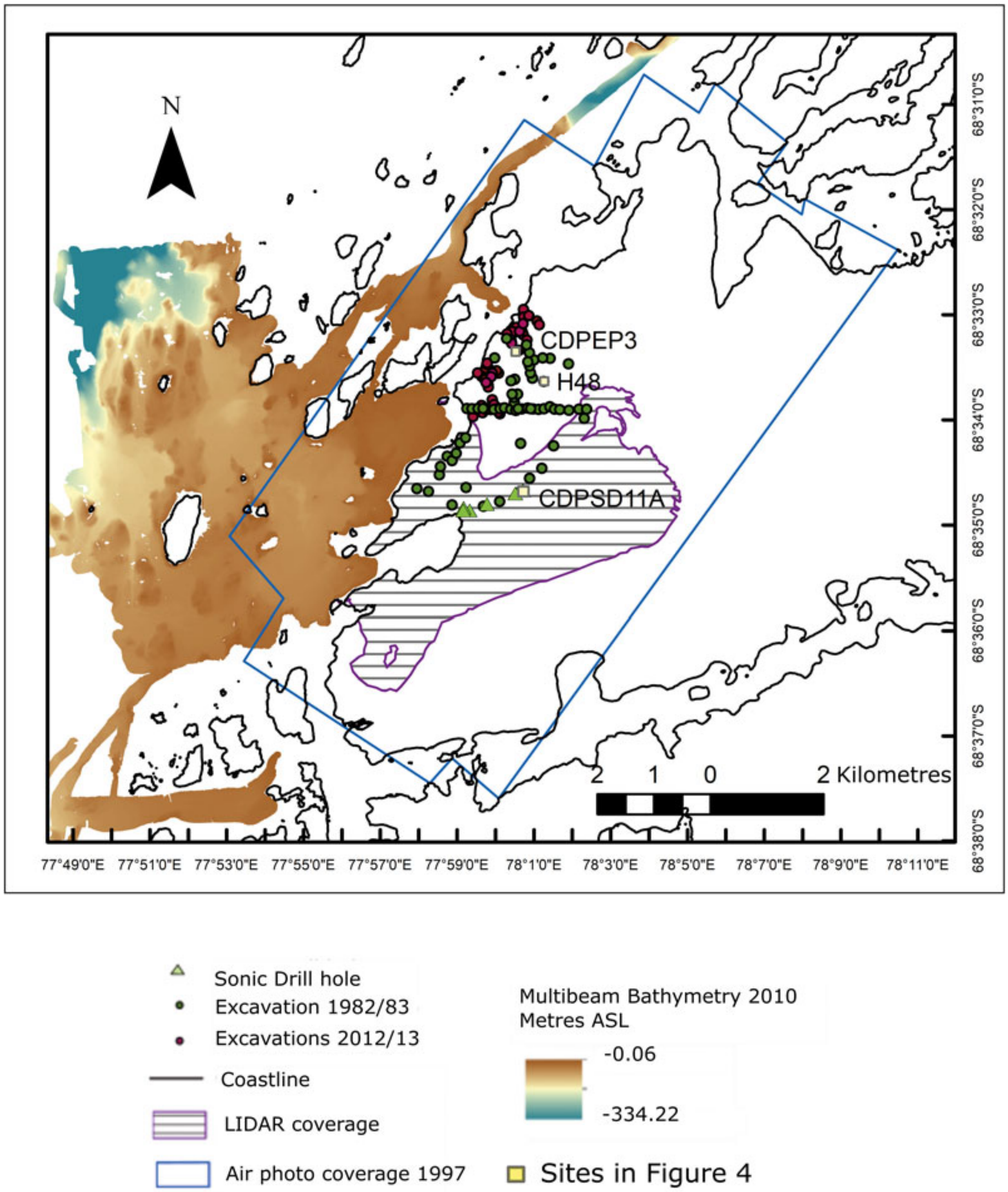

Figure 2. Sample locations and data coverage. ASL = above sea level; LIDAR = light detection and ranging.

Geomorphology, sediments and stratigraphy

Geomorphic processes, particularly sediment movement in the intertidal zone, were investigated by mapping erosional, transportational and depositional features and sediments on aerial photographs and field observations during the 1988/1989, 1989/1990, 1992/1993 and 2012/2013 summers. Excavations were made into sediments for geotechnical studies using hand-dug pits, excavator pits and percussion drill holes over several periods starting in 1982 (Makarucha 1984). Hand pits were dug using shovels or hand augers to refusal (the depth beyond which it was not possible to proceed). Refusal typically occurred within 2 m depth. Pits were described and photographed, and samples were taken for grain size analyses. Excavator pits were dug to a maximum depth of 2 m for safety reasons and described, photographed and sampled. Data from 111 pits were used in this study (Fig. 2). Grain size analyses were carried out using sieves and hydrometer (Standards Australia 2014) following geotechnical protocols, with particles < 75 μm diameter defined as 'fines' (silt plus clay), in contrast to the < 62.5 μm silt plus clay used commonly in the geological literature (Blott & Pye 2012). Sieve and hydrometer analyses were processed using the software *GRADISTAT* (Blott & Pye 2001), which calculates and plots grain size information. Drill cores were collected along a transect in Heidemann Valley (Fig. 2) during 2016 using a sonic drill rig. Cores were stored in plastic sleeves and core trays, then the stratigraphy was described.

Results

Sediments and stratigraphy

Our excavations revealed two distinguishable and mappable sedimentary units (Figs 3a,b & 4). Previous studies in Heidemann

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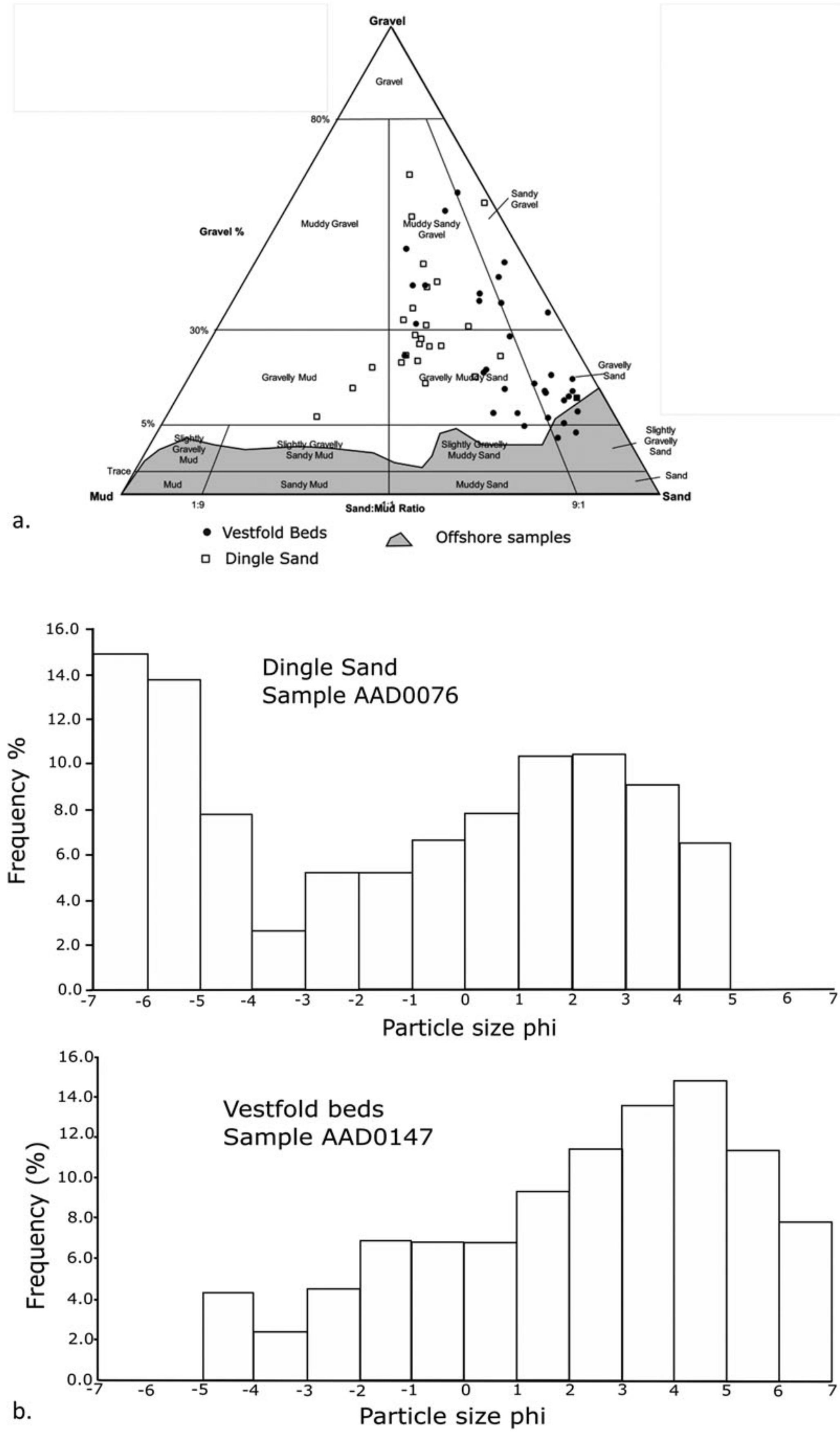

Figure 3. a. Grain size of Dingle Sand, Vestfold Beds and marine samples adjacent to the Vestfold Hills shown as a triangular plot. Terminology from Blott & Pye (2001). Marine sample range generalized from O'Brien *et al.* (2015). **b.** Typical grain size distribution of a sample from Dingle Sand and Vestfold Beds as histograms.

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Valley, Dingle Valley and the present study area that used hand pits and shallow drill holes (Makarucha 1984, Hirvas *et al.* 1993, Quilty & Franklin 1997) encountered similar stratigraphy, although they either did not use lithostratigraphic terminology or sought to subdivide the section still further (Hirvas *et al.* 1993). An upper, sandy unit had been recognized throughout the study area overlying finer, less well-sorted sediment commonly described as till or diamict (Makarucha 1984, Hirvas *et al.* 1993, Quilty & Franklin 1997). In our study, the upper sandy interval was recognizable as a unit in most areas overlying a finer unit that was more poorly sampled but still distinct. We propose that the two units be given lithostratigraphic names to aid subsequent discussion: the upper unit being designated Dingle Sand (named after a prominent lake and valley in the area) and the lower unit Vestfold Beds (Fig. 4).

Dingle Sand is the uppermost sedimentary unit in the landscape of the western Vestfold Hills study area. It forms sheet-like areas, terraces and ridges. It drapes many hills, and sediment of this type has been excavated on bedrock hills 25–35 m above sea level (Makarucha 1984). It is thin to absent on many bedrock hills and in depressions in the valleys. It is a fine to coarse, black to light grey to yellow and red-brown sand with gravel ranging in size from pebbles to boulders. Pebbles to boulders are sub-rounded to angular, and striated clasts, although rare, can be found in the sediments. The sand is silty in places (Fig. 3a,b), but the fine fraction is poorly to non-cohesive. Texture varies from well to poorly sorted. Fossils of marine organisms including clams, worm tubes, gastropods and sponge spicules are present in places (Gore *et al.* 1994), but the most abundant of these are the clam *Laternula elliptica* (P.P. King, 1832), in life position and as fragments (Fig. 5).

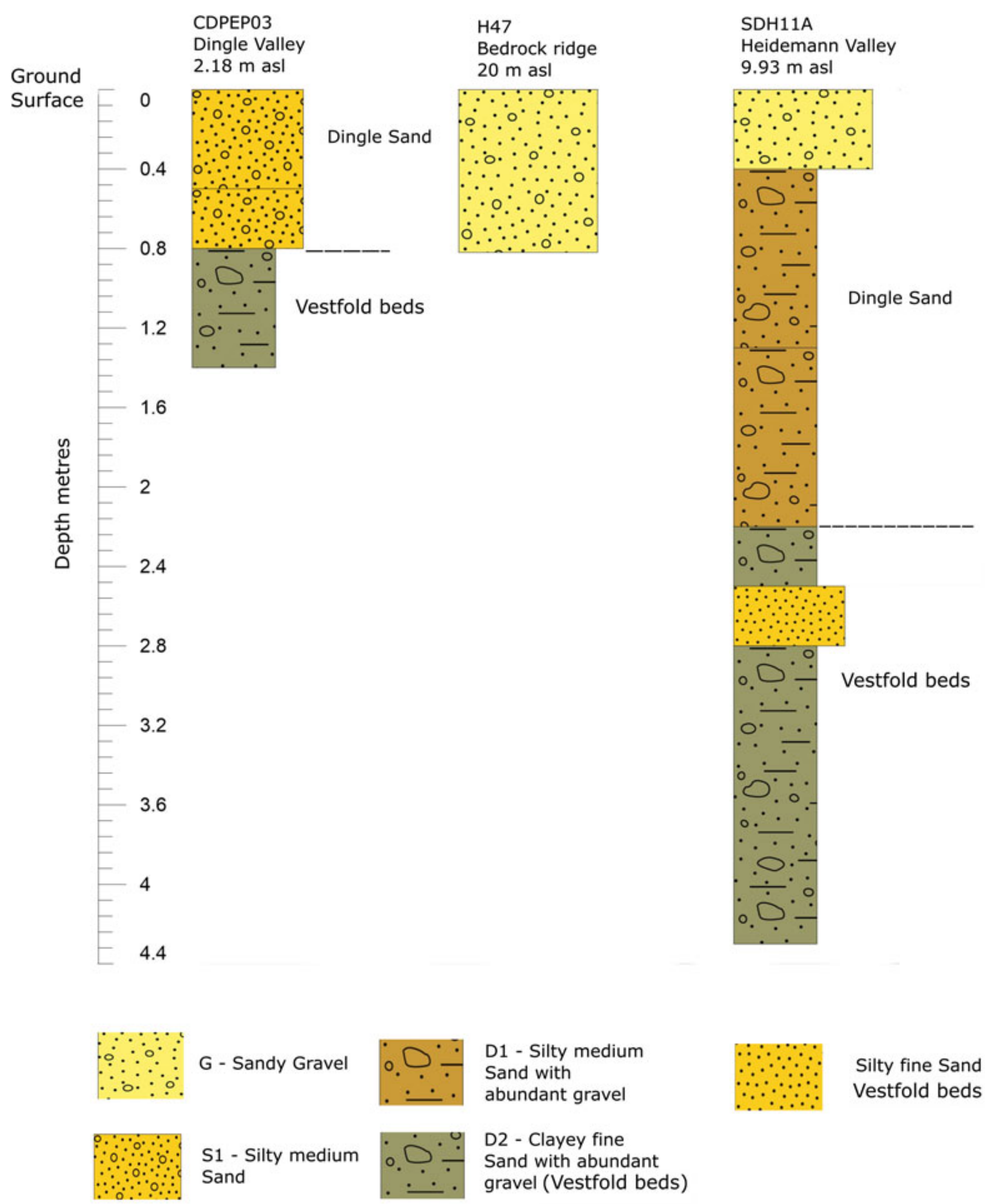

Figure 4. Examples of Dingle Sand overlying Vestfold Beds in an excavator pit (CDPEP03), hand pit (H47) and sonic drill core (SDH11A). Sample locations are in Fig. 2. asl = above sea level.

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Figure 5. Dingle Sand (Facies S2) with near-complete *Laternula elliptica* shells. Excavator pit CDPEP03, Dingle Valley.

Valleys show a ridge-and-depression topography with ridges of thicker Dingle Sand up to 3 m high and 200 m across separating depressions up to 800 m across. This topography is present both onshore (Figs 6–8) and offshore, where it is visible in multibeam data from areas unaffected by ice-keel scouring (Abatus Bay, Fig. 7; O'Brien *et al.* 2015). These features are on multiple scales. Small depressions appear as sub-circular to irregular closed depressions metres to tens of metres across (Figs 6, 8 & 9), while large depressions are irregular areas of thin to absent Dingle Sand hundreds of metres across and, on land, commonly hosting ephemeral lakes formed by melting of snowbanks. Smaller depressions may be isolated, whereas larger ones tend to form intersecting groups. The nested scale of depressions is illustrated by a surveyed transect from Dingle Valley, starting at the low tide line and extending south-east along the valley (Fig. 6). The profile crosses two ridges, both standing 2 m above adjacent depressions. The ridge that is farther inland is ~170 m across, and its surface shows numerous shallow depressions ~30 cm deep and 5–20 m across (Fig. 6). These depressions are commonly elongated north-east to south-west. The DEMs of Abatus Bay and Heidemann Valley reveal a nested hierarchy of depressions, with large depressions 200–800 m in diameter occupying most of the valleys and smaller depressions from 2 to ~80 m in diameter hosted within the larger ones and within ridges. Larger depressions in Heidemann Valley and Abatus Bay show arcuate edges that resemble the margins of shallow lakes or coastal lagoons (Figs 7 & 9), suggesting that these features may have been former coastal lagoons or lakes.

Ridges are made prominent on aerial photographs by more abundant boulders, whereas depressions accumulate sand, mud and water (Fig. 6). Boulders are also visible on the ridges on the multibeam data (O'Brien *et al.* 2015, their fig. 9b). Core holes in Heidemann Valley drilled several ridges and showed that the thickness of the ridges is typically entirely Dingle Sand (Fig. 9a,b).

Dingle Sand comprises four facies (Figs 3 & 4). Facies S1 - the most common facies - is poorly sorted, gravelly, silty, medium to coarse sand with boulders. Excavations on bedrock ridges that are draped with Dingle Sand encountered this facies at up to 0.8 m thick (Fig. 4). Pit profiles showed the deposits to be massive, with no discernible sedimentary structures. Facies S2 - poorly sorted medium sand in the order of 1 m thick with shelly fragments - was found in some depressions between ridges. Shell material varied from small fragments to near-intact bivalves in life position (Fig. 5). Facies G consisted of sandy, fine gravel. Facies D1 consisted of silty, medium to coarse sand with abundant pebbles. Mud and gravel fractions are more abundant than in Facies S1, making the use of the term diamicton (code D) appropriate for this facies. The mud fraction is non-cohesive. The mud fraction in all Dingle Sand facies is non-plastic, reflecting minimal clay content.

Vestfold Beds is named after the 'Vestfold Till' proposed by Hirvas *et al.* (1993). They and Colhoun *et al.* (2010) documented deep pits dug by mechanical excavator into the sediments of Heidemann Valley. While they suggested up to four units of glacial till in these excavations, the difficulty of correlating these individual units, especially between small hand-dug pits, hand augers and drill holes, leads us to combine these sediments into one lithostratigraphic unit. Vestfold Beds is mostly mid-grey to dark grey and black, poorly sorted, silty to clayey sand, with gravel from pebbles to boulders and some thin clay beds and coarse sand patches (Fig. 4, Facies D2). The fine fraction is cohesive. Shelly material (typically platelets or hinges of *L. elliptica*) is present in places as fine fragments a few millimetres across. Coarse sand patches are present, forming small lenses (< 2 cm) and rounded bodies.

Vestfold Beds underlies Dingle Sand in most places within the valleys and is visible at some depressions that provide a window through Dingle Sand. The boundary between the units varies by several metres in elevation. In pits, Vestfold Beds is mostly massive, structureless, gravelly, silty to clayey sands (diamicton; Figs 4 & 10), but in large excavations irregular, rounded bodies of coarse sand up to several metres across have been observed.

Grain size variations

Both Dingle Sand and Vestfold Beds have a sand to muddy sand matrix with gravel in the form of pebbles to large boulders. The primary difference is the tendency for Vestfold Beds to have more of the < 75 μm fraction (Fig. 3a,b). Although there is overlap in texture between the two units, Dingle Sand samples are almost entirely non-plastic, whereas Vestfold Beds samples are commonly plastic or cohesive. In some locations, Dingle Sand samples include fine sediment washed into the location by local surface run-off. Both units are mostly poorly to very poorly sorted. Vestfold Beds displays symmetric to fine-skewed size distributions, while Dingle Sand shows fine-skewed, symmetric and coarse-skewed distributions (Fig. 3b).

Age estimates

The ages of Vestfold Beds and Dingle Sand are not known with certainty. Dating via cosmogenic isotopes on glacial erratics in eastern Vestfold Hills coupled with ^{14}C ages from offshore sediment cores and with rock relative weathering patterns reveal the currently accepted exposure (deglaciation) age range of 14 to ~11 ka before present (BP; Fabel *et al.* 1997, Fabel & Stone 2016, White *et al.* 2022). However, uncertainty remains as to the former geometry and retreat history of the ice over Vestfold Hills, mainly due to the evidence that Abraxas Lake, in northern Vestfold Hills, may have remained free of ice during the Last Glacial Maximum *c.* 20–18 ka BP (Gibson *et al.* 2009), similarly

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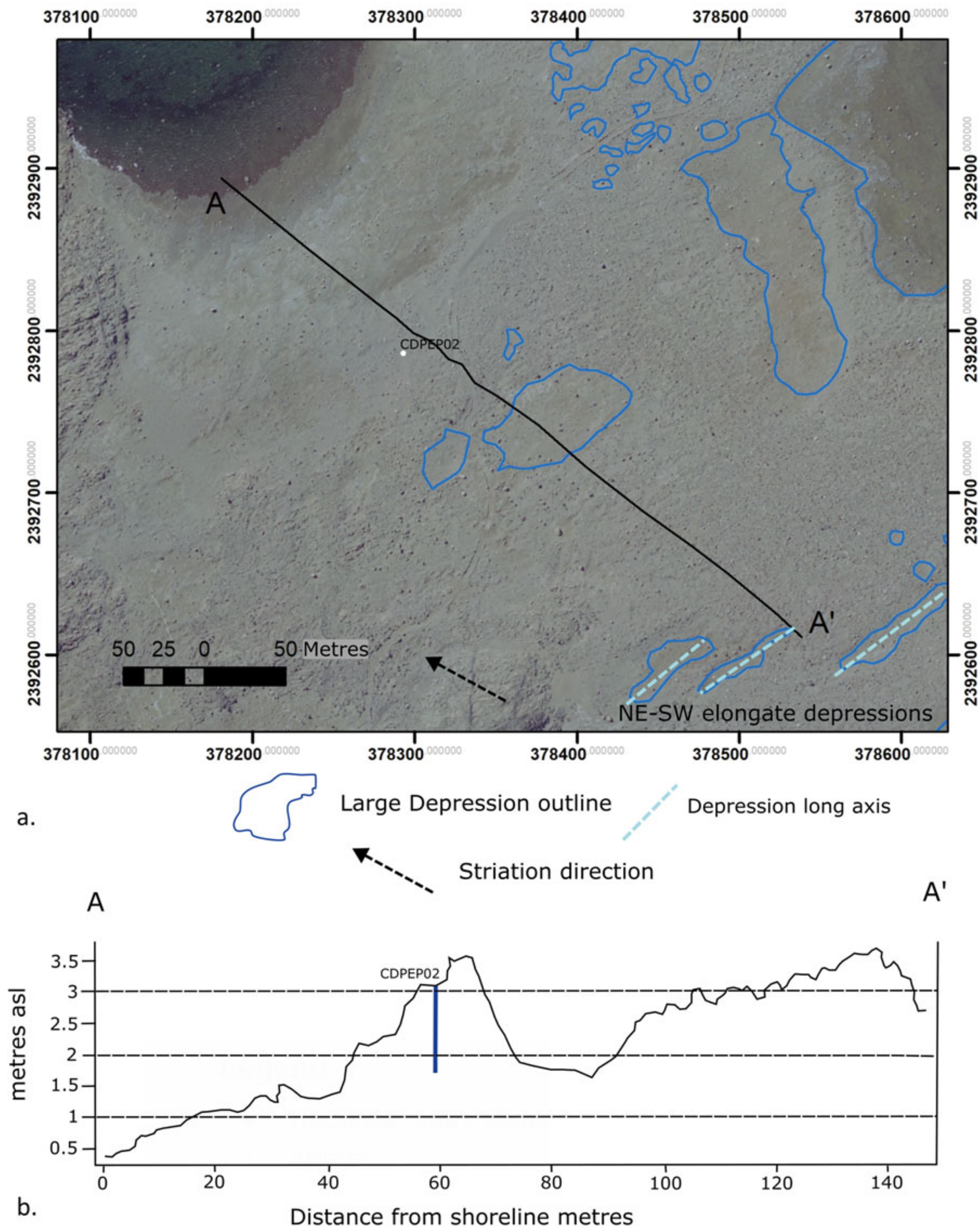

Figure 6. a. Air photo of ridges and depressions in Dingle Sand, Dingle Valley. Orientation of elongate depression shown. Direction of bedrock striations from Adamson & Pickard (1983). **b.** Topographic profile A-A' based on RTKGPS transect with thickness of Dingle Sand in excavator pit CDPEP02. CDPEP02 encountered 1.4 m of Dingle Sand before halting in frozen sand. asl = above sea level.

to Larsemann Hills to the west (White *et al.* 2022) and Bunger Hills to the east (Gore *et al.* 2001).

The Holocene environmental history of Vestfold Hills is much better constrained, with radiocarbon ages of shells and lake sediments that reflect palaeoenvironment, isostatic uplift, a mid-Holocene marine transgression to 10 m above sea level and with subsequent emergence of the land to its current height and coastline shape (e.g. Adamson & Pickard 1983, 1986a, Zhang & Peterson 1984, Zwartz *et al.* 1998). Hodgson *et al.* (2016) reviewed, recalculated and republished these radiocarbon dates and provided calibrated ages (Fig. 11). A dated shell sample from Dingle Sand from the edge of Dingle Lake at an elevation of 6 m (Zhang & Peterson 1984, p. 29) had a recalculated age of 5457 ± 77 calibrated years BP (ZDL79) using an Antarctic marine

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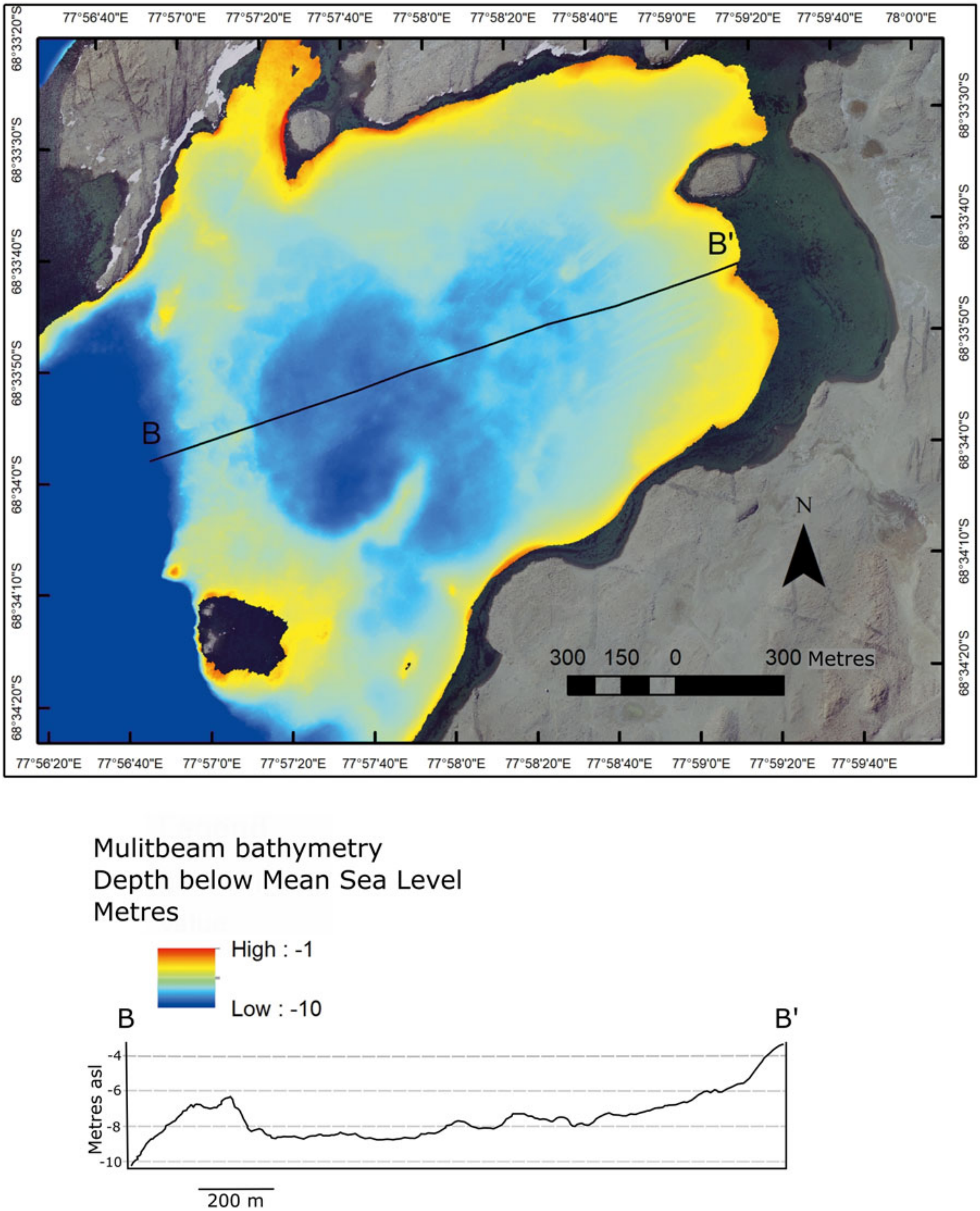

Figure 7. Abatus Bay multibeam bathymetry 2 m grid and profile B-B'.

reservoir age correction of 900 a (Hodgson *et al.* 2016). This age is consistent with reworking of Dingle Sand by marine processes during the mid-Holocene sea-level high-stand. Thus, Dingle Sand was probably deposited during deglaciation from ~14 ka to 5457 ± 77 a BP, with subsequent reworking during relative sea fall to the present day.

Sediments that equate to Vestfold Beds have been examined in trenches and pits in Heidemann Valley (Hirvas *et al.* 1993, Colhoun *et al.* 2010). Calcareous marine fossils (bivalves, foraminifera) yielded ^{14}C ages beyond the technique range. Thermoluminescence dates were > 300 ka BP (Hirvas *et al.* 1993), and amino acid racemization dates of mollusc shell yielded youngest ages of 2.61 ± 0.39 Ma BP and maximum ages of 3.49 ± 0.59 Ma BP, suggesting a Pliocene age (Colhoun *et al.* 2010) for at least some of that material. The differences in texture suggest that Vestfold Beds sediments were not reworked by fluvial, marine and aeolian processes to the same extent as Dingle Sand sediments.

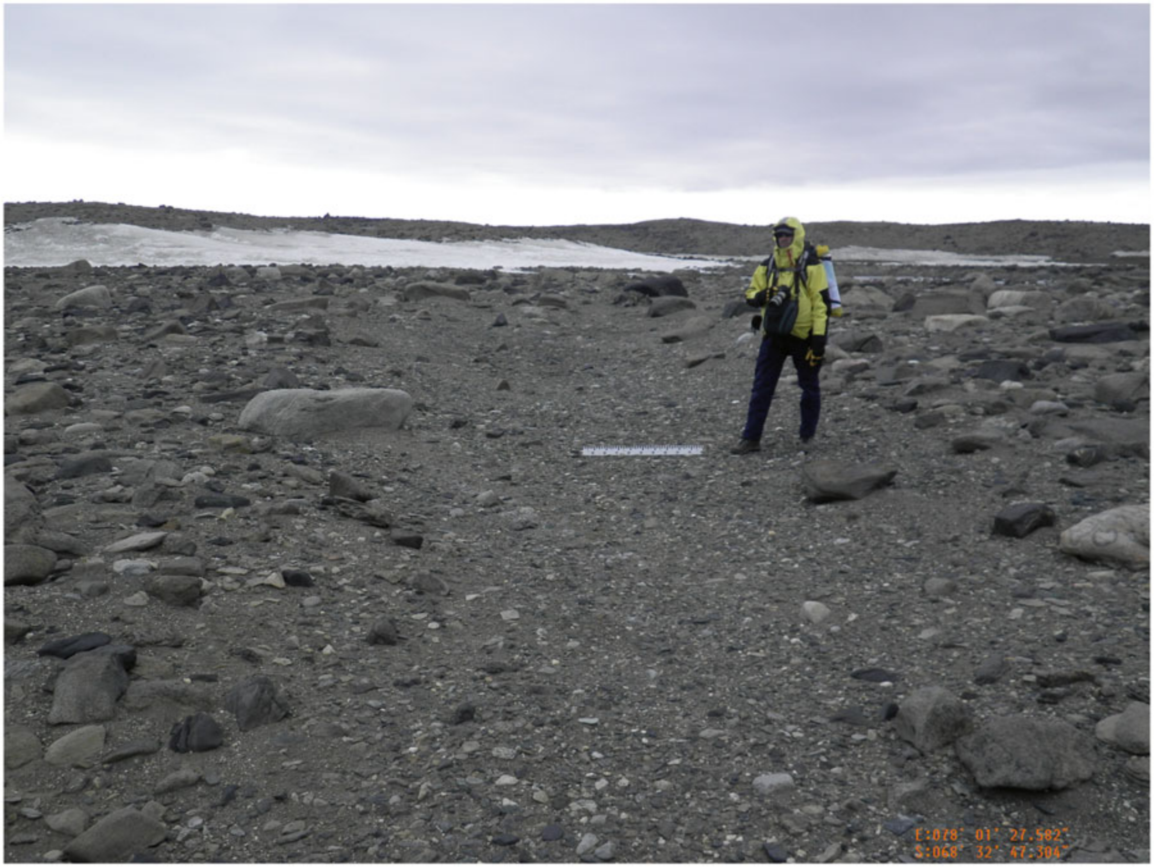

Figure 8. Small depression in a ridge of Dingle Sand, Dingle Valley. This and similar ridges could have formed from sediment redistribution during deposition, from ice-marginal fluvial processes or later from push by sea ice or ground ice cracks. Subsequent infilling of the depression with sands and gravels would then occur with periglacial or aeolian activity.

Sediments dated to the early Pliocene (~4.5–3.5 Ma BP) have been described from Marine Plain in south-western Vestfold Hills (Whitehead *et al.* 2001). These diatomaceous siltstones and sandstones have been named the Sørsdal Formation (4.5–4.1 Ma BP). They contain within them a sandy diamictite of glacial origin named the Graveyard Sandstone Member, and in their upper parts are limestone lenses containing the Pliocene bivalve *Chlamys* (*Zygochlamys*) *tuftsensis* Turner, 1967. These shallow marine Sørsdal Formation sediments are fundamentally different in composition, texture and origin from the diamictons of Vestfold Beds. Sørsdal Formation sediments are the oldest Cenozoic deposits presently known from Vestfold Hills.

Geomorphic processes

Surface sediments in Vestfold Hills are subjected to processes that modify their texture and structure. During an ice-margin advance, ice moving across the marine inlets would erode those soft, wet sediments and bulldoze or freeze on and stack and smear that material down-ice (Gore *et al.* 2003). In contrast, advancing ice could slide across low-relief permafrosted sediments, much like any other soft rock. In this way, pre-existing sediments in terrain pockets, such as Marine Plain and Vestfold Beds valley fills, could be preserved through successive ice advances. Mass movement and fluvial processes are active near the ice edge at present (Fitzsimons 1990, 1996, 1997, Gore 1992, Gore & Pickard 1998), modifying the physical and chemical characteristics of sediments (Gore *et al.* 2003). In our study area, other processes are also important and probably modified the stratigraphy, texture or chemistry of surface sediments. These are aeolian erosion, transport and deposition, shoreline and marine processes and ground ice.

Aeolian erosion and deposition occur across Vestfold Hills, but particularly in the west, where surface sediments are sandier and where sand accumulations are common (Adamson & Pickard 1986b, Gore *et al.* 2003). Strong winds create wind scour around large boulders, and desert pavements develop by the winnowing of sand-sized material between pebbles. Wind scours and lee-side dunes are ubiquitous across our study area. Most clasts protruding over 100 mm above the ground surface have at least a small lee-side dune, and many boulders have crescentic scours around them leading to dunes downwind (Fig. 12a). The largest lee-side dunes are sand bodies in the lee of hills with steep slopes. Lee-side dunes form conical to elongate aprons of fine to medium sand on the south-western sides of bedrock ridges (Fig. 12b). These aprons can spread out into flat sheets of sand with wind ripples. Deposition of wind-driven snow mixed with sand and silt creates sediment-rich snowbanks. Sand and silt also accumulate on sea ice, to be subsequently deposited on the sea floor (Franklin 1997). Melting of the sea ice deposits the sediment, forming sheet-like silty sand with rills on the sediment surface in places. Finer size fractions can accumulate in shallow meltwater ponds in topographic depressions. Sand sheets are particularly well developed in intertidal zones with minimal wave action

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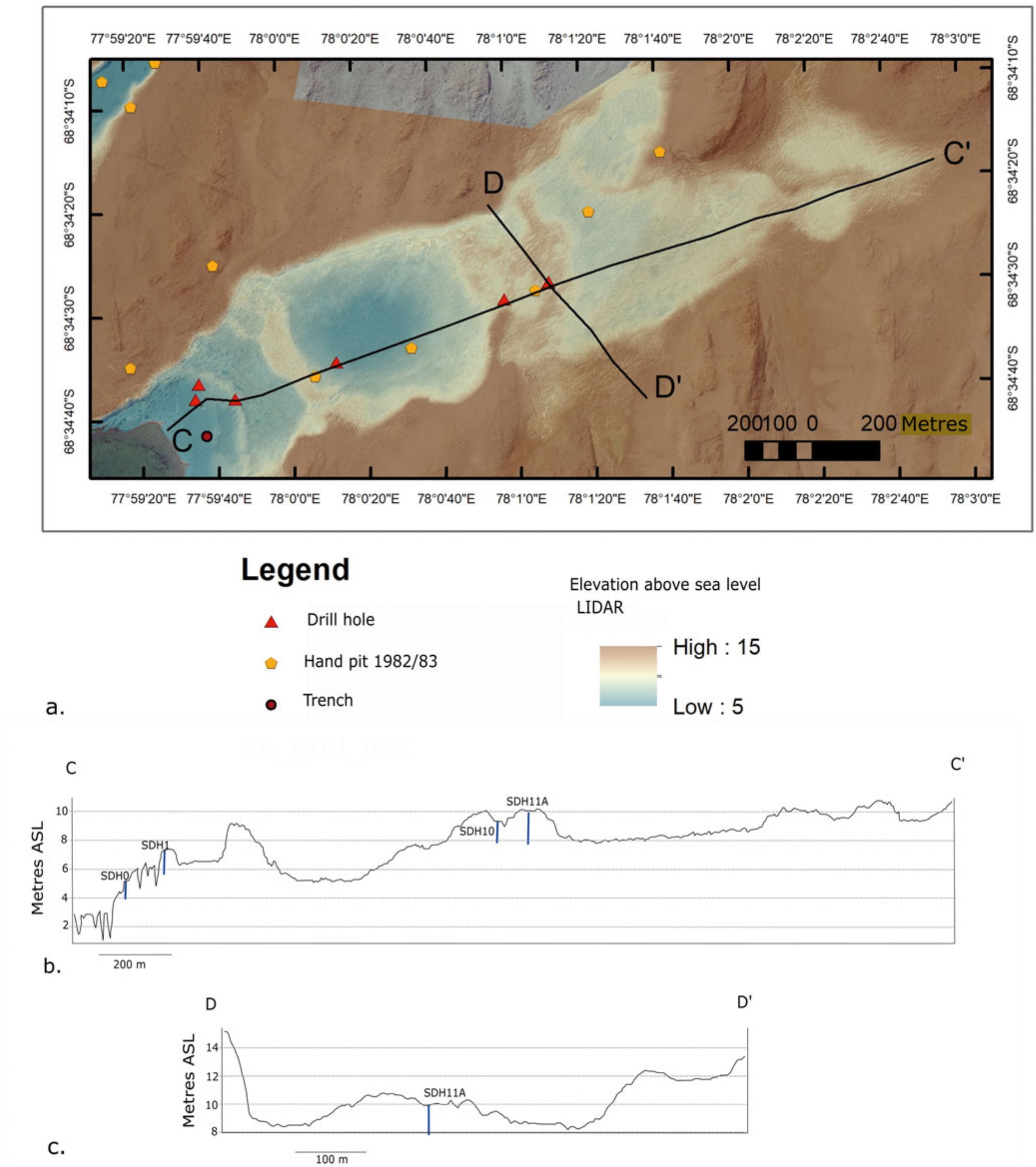

Figure 9. a. Heidemann Valley light detection and ranging (LIDAR) digital elevation model overlain on aerial photography. Topographic profiles and excavations are shown. **b.** Topographic profile C-C' along Heidemann Valley, with the thickness of Dingle Sand found in drill holes shown. **c.** Topographic profile D-D' across Heidemann Valley, with the thickness of Dingle Sand in drill hole SDH11A shown. ASL = above sea level.

(Fig. 13). These sediments are gravelly sand to gravelly muddy sand.

Areas where sea ice melts early in the summer are subjected to wave action and have sandy beaches, whereas areas of persistent sea ice are subjected to significant ice disturbance by ice rafting. South-westerly sea breezes and the incoming tide drive sea ice shoreward. This process thrusts boulders short distances, creating irregular piles of boulders up to 0.5 m high and ridges of finer gravel tens of centimetres high (Fig. 14a,b). Outgoing tides strand sea ice, which melts in place. This sea-ice movement disturbs

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Figure 10. Dingle Sand overlying Vestfold Beds in excavator pit CDPEP03 (pit location in Fig. 2). White line follows the contact between units.

sediments, creates shallow depressions and ridges, stacks boulders and breaks shells in the upper part of the sediment.

Two types of ground ice disturb sediments. Cracks in sediment surfaces exist for tens of metres in intertidal and supratidal areas (Fig. 15a) and more rarely through glacial tills (Adamson & Pickard 1986b), particularly on the southernmost peninsula. Excavation of these cracks shows them to be vertical zones of interstitial ice rather than bodies of clean ice. They form rapidly once dry sediment is wet by snowmelt and disappear when the sediment desiccates. In the intertidal zone, flat-lying ice lenses form small domes of sediment (Fig. 15b). The ice is clear and typically forms ~10 cm below the surface, creating domes of 20–50 cm in diameter.

Multibeam data from Abatus Bay (Fig. 7; O'Brien *et al.* 2015, their fig. 9b) show that Dingle Sand continues below present sea level with similar small-scale topography and abundant boulders. Grain size data (O'Brien *et al.* 2015, their fig. 10) show surface sediments below sea level to be finer and less gravelly than those onshore (Fig. 3a), indicating the addition of mud by wind or marine currents. Sand ribbons with ripples show that bottom currents are active (O'Brien *et al.* 2015). The presence of mid- to late Holocene marine fossils (Adamson & Pickard 1983, 1986a) in deposits below +9 m above sea level show that marine processes affected these surficial deposits during higher relative sea level, though for a shorter time than areas presently still below sea level. Studies of the modern offshore environment (e.g. Smith *et al.* 2015) found that benthic fauna vary with local habitats, with many areas dominated by macroalgae or mobile benthos such as echinoids and amphipods. The most abundant species with high preservation potential is the bivalve *L. elliptica*. Modern *L. elliptica* are found between the intertidal zone and at -700 m (Waller *et al.* 2017), where they reside in the bed with siphons protruding above the sediment-water interface.

The effects of post-depositional geomorphic processes on sediments are:

1) Reworking of the surface by wind erosion and thin, unchannelized flow of meltwater from snowbanks with redeposition of sand and mud in depressions and marine embayments;
2) Destruction of sedimentary structures by ground ice and bioturbation;
3) Reworking of surface boulders and sediment by ice push in the intertidal zone;
4) Wave reworking in areas exposed to strong winds from the north-east;

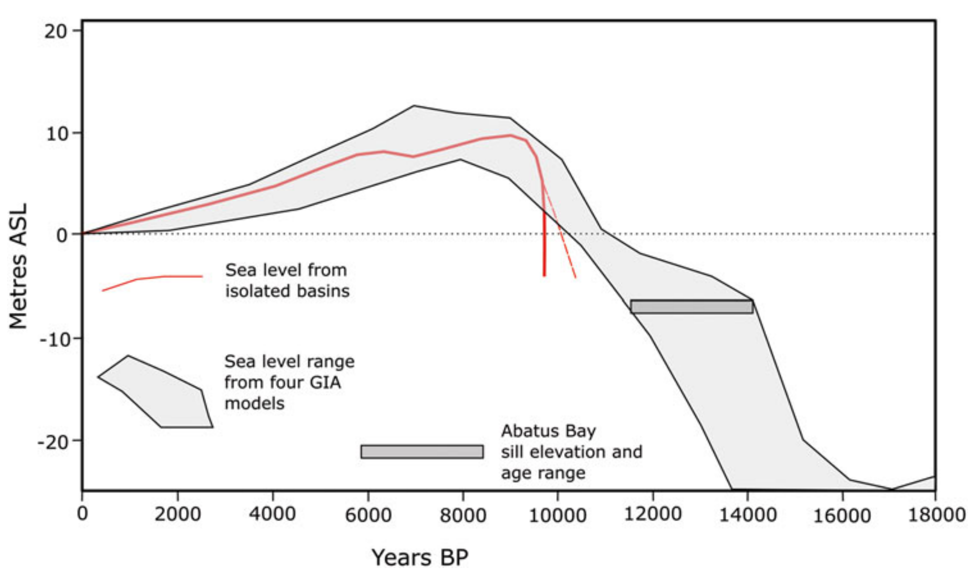

Figure 11. Sea-level curves (after Zwartz *et al.* 1998, Hodgson *et al.* 2016). The sea-level curve from closed basins is derived from Zwartz *et al.* (1998) using recalibrated ^{14}C ages and data from the Rauer Islands. The sea-level range from glacial isostatic-adjusted (GIA) models shows the envelope defined by four GIA model sea-level curves (Hodgson *et al.* 2016). The shaded box shows the possible dates for flooding of Abatus Bay based on the elevation of the bay sill. ASL = above sea level.

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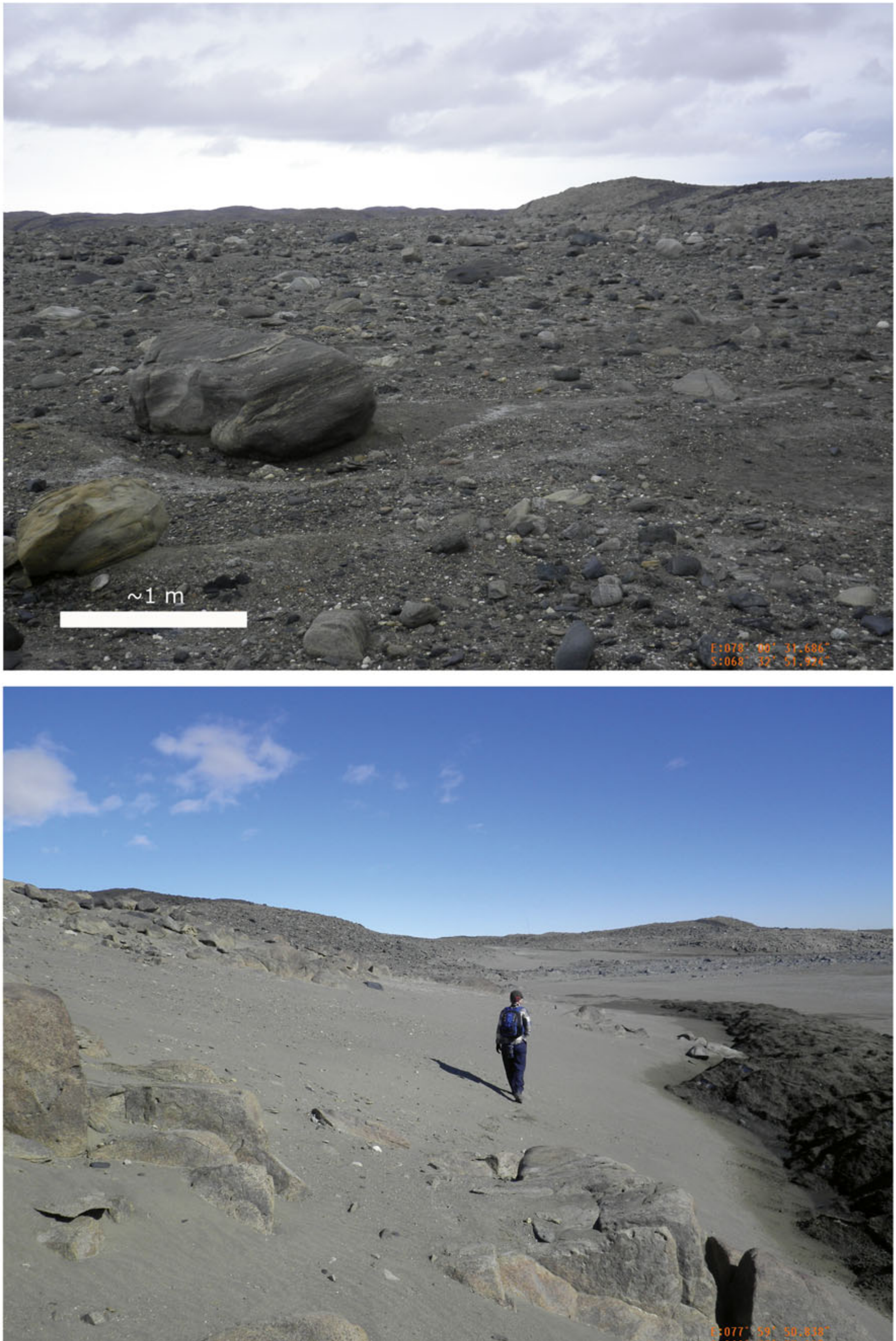

a.

b.

Figure 12. Aeolian features in western Vestfold Hills. **a.** Boulder with wind scour (dominant wind left to right). **b.** Lee-side dune accumulating sand downwind of a bedrock ridge (dominant wind left to right).

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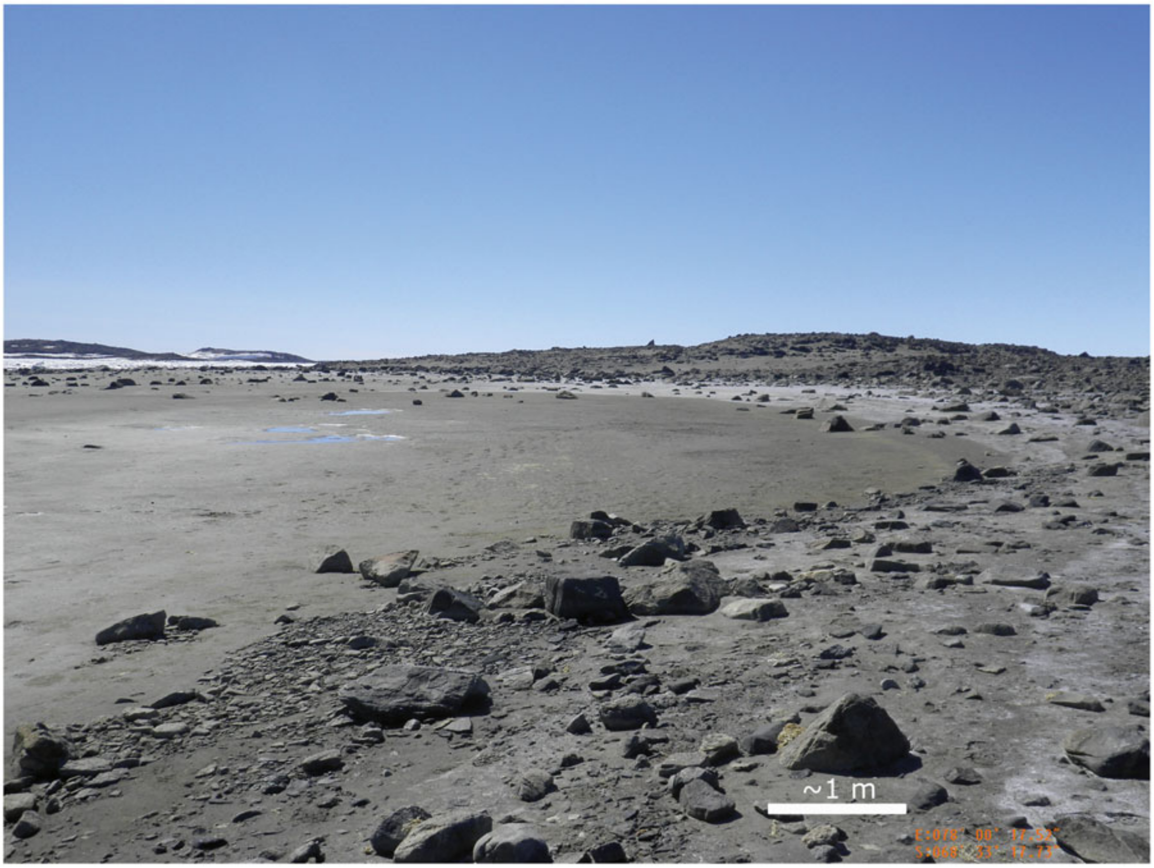

Figure 13. Intertidal sand sheet.

5) Growth or insertion of infauna into some sediments, causing bioturbation during inundation;
6) Freezing on of boulders and thrusting by sea ice in the intertidal zone, mixing boulders with marine sediment that would otherwise overlie glacial deposits.

The height and duration of inundation of the presently terrestrial field area by seawater during the Holocene have been constrained by field evidence and relative sea-level models (Zwartz *et al.* 1998, Hodgson *et al.* 2016). The data and models show relative sea level at 20 m below modern sea level at or prior to 13 500 a BP (Fig. 11). Sea level rose rapidly between 9678 and 9411 a BP, reaching > 8.8 m above sea level from 9411 a BP until at least 7564 a BP. Relative sea level then fell slowly to ~6200 a BP then steadily until the present. This resulted in at least several thousand years when much of the study area was inundated by seawater, which is reflected in the geomorphology, texture and fossil content of some areas of Dingle Sand.

Discussion

In the study area, valley fills typically have Dingle Sand at the surface, forming flat-topped ridges dissected by depressions (Fig. 6). The presence of up to 1.4 m of gravelly sand, diamicton and erratics indicates a primary glacial origin for Dingle Sand. Post-depositional modification by terrestrial and marine geomorphic processes resulted in some characteristics not typically seen in glacial deposits. Small overflow channels drain larger depressions that fill with water from melting snowbanks; no ice marginal channels (*sensu* Atkins & Dickinson 2007) were observed in the field area. This discontinuous distribution of Dingle Sand is most readily explained if the valley fills originated as ablation till that accumulated on top of and between stagnant ice bodies, as occurs elsewhere in the Vestfold Hills in the present day (Fitzsimons 1990, 1997). Debris on top of ice bodies would then redistribute, perhaps even causing topographic inversion, so that present-day depressions represent former high points of stagnant ice masses (Figs 8 & 16a,b). Some areas of Dingle Valley show groups of small depressions that are elongated north-east to south-west, approximately normal to the direction of ice motion indicated by striae (Fig. 6a; Adamson & Pickard 1983). These depressions developed when well-defined debris bands in the ice formed controlled moraine ridges (*sensu* Evans 2009) parallel to the retreating ice margin (Fitzsimons 1990, 1997).

Sediment deposition at the modern Vestfold Hills ice margin produces ice-cored mounds that could develop into inverted topography during ice ablation as sediment reworks via debris flows and meltwater streams (Fig. 16a,b; Fitzsimons 1997). These processes modify slope deposits, removing sediment cover from many bedrock areas. This probably happened in our study area, but the present state of the valley fills suggests that outwash streams were relatively small.

Large, arcuate ridges visible on multibeam and LIDAR data are likely to have experienced wave action while forming part of the shorelines of lakes or intertidal lagoons. Heidemann Valley exhibits three ridges crossing it at right angles to the valley axis (Fig. 9a). The most inland ridge complex has crest elevations of +9.6 to +10.7 m, the intermediate ridge has crest elevations

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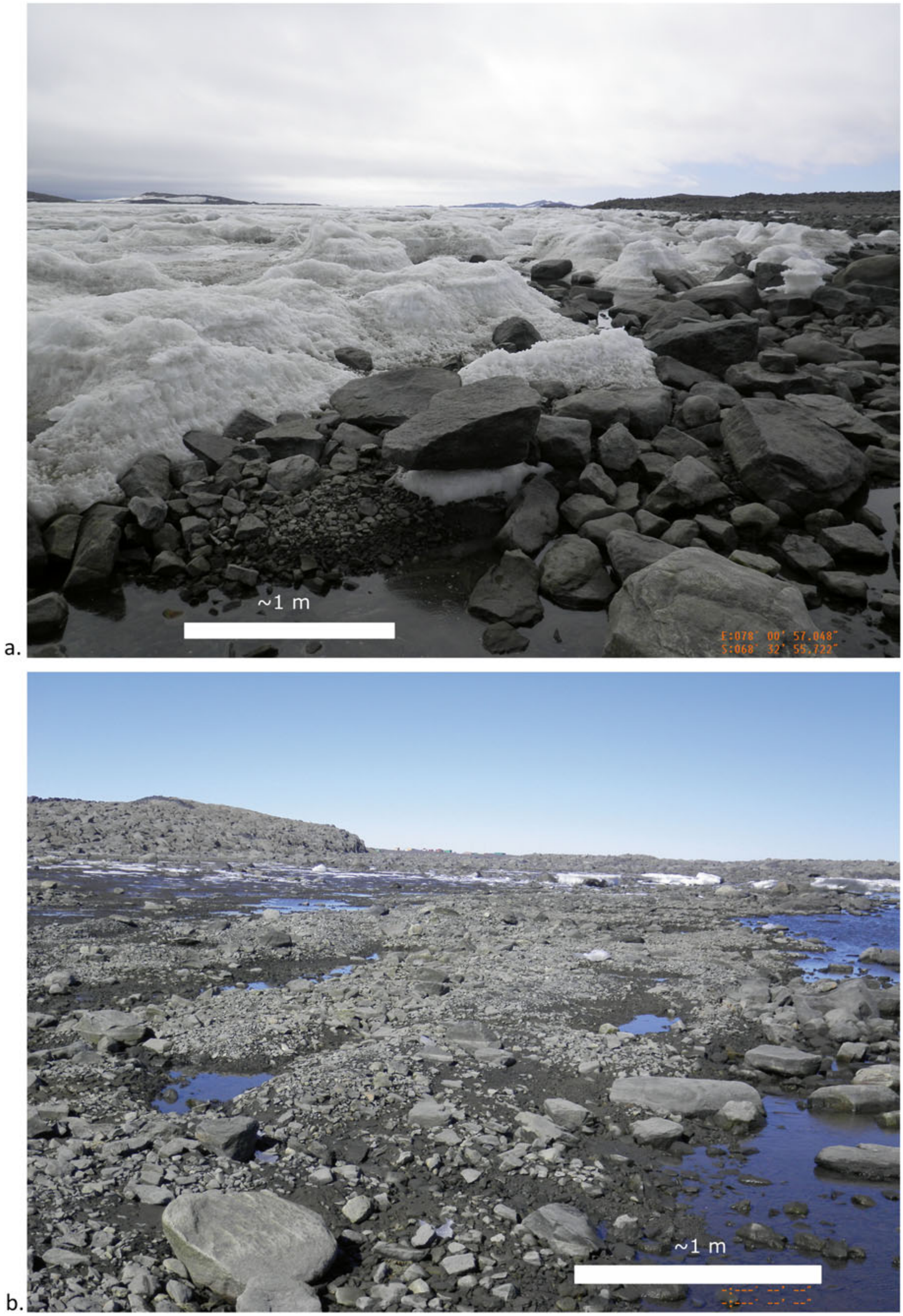

Figure 14. Sea ice thrusting in the intertidal zone on south-west- to west-facing shores. **a.** Sea ice in the intertidal zone lifting and stacking boulders from the bed. **b.** Intertidal zone surface after sea-ice thrusting.

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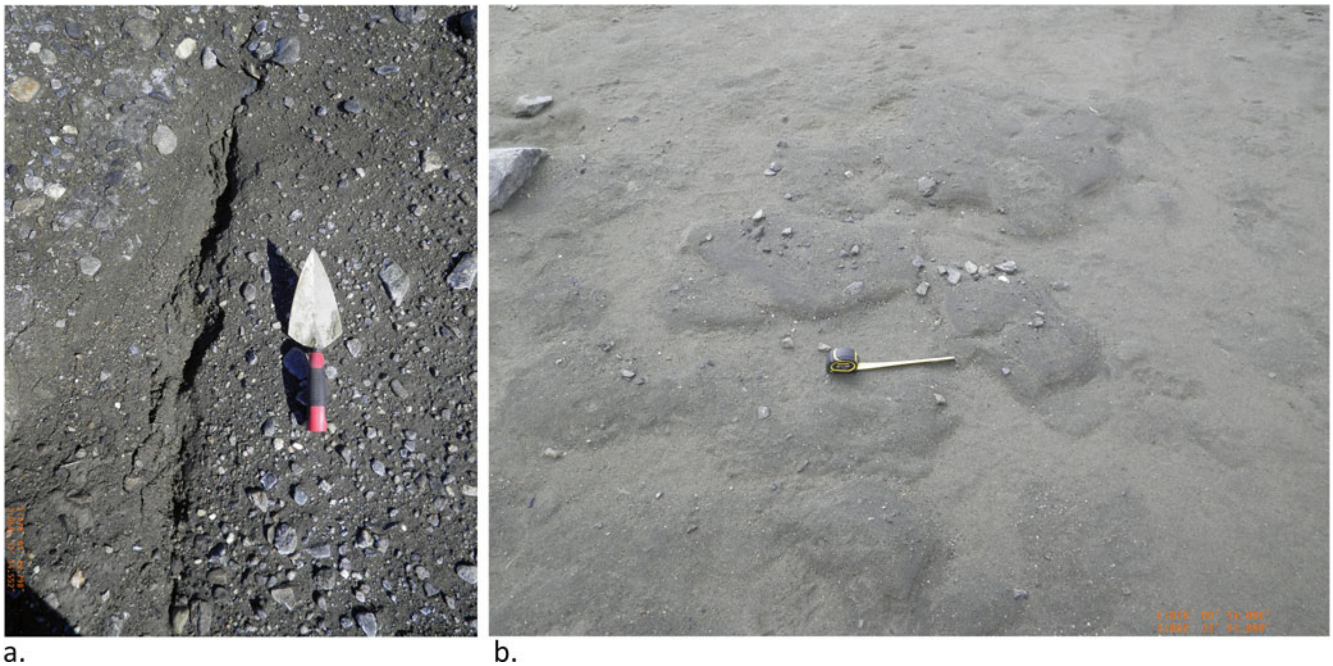

Figure 15. Ground-ice features in Dingle Sand. **a.** Ground-ice crack. Trowel is 30 cm long. **b.** Domes formed over ground-ice lenses in the intertidal zone. Tape is extended 20 cm.

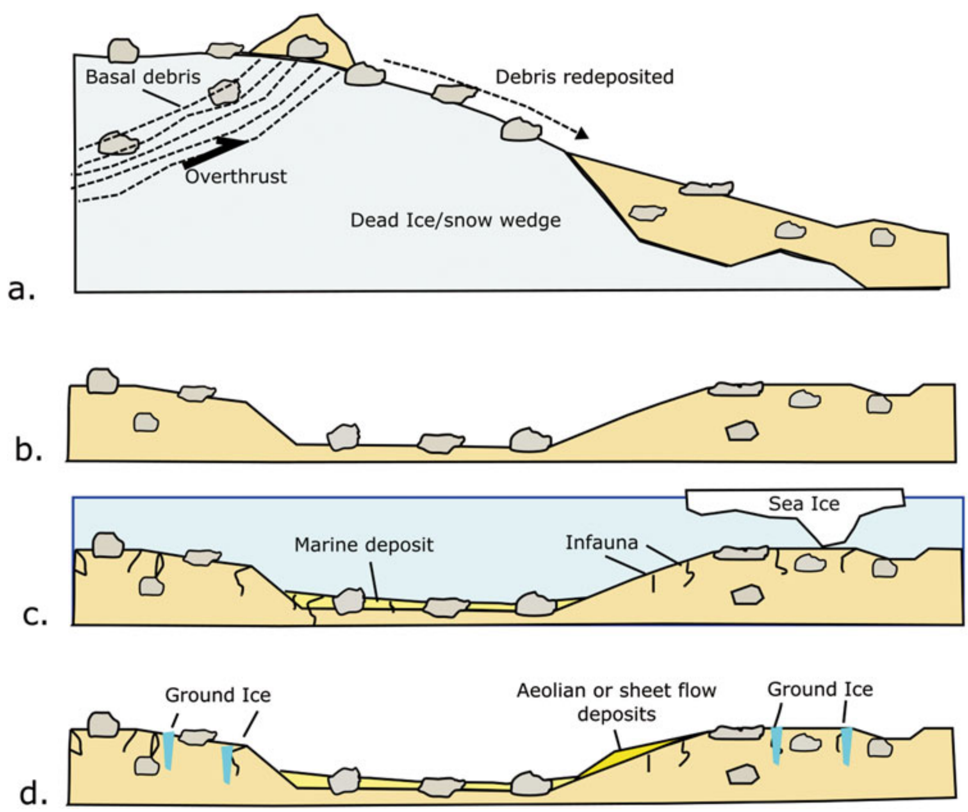

Figure 16. Evolution of Dingle Sand. **a.** Deposition of Dingle Sand as a Type A moraine of Fitzsimons (1997). Basal, debris-rich ice thrusts over dead ice or a snow wedge. Debris is released and reworked down the ice face to form a ridge. **b.** Complete ablation leaves ridges where debris accumulated and depressions where debris-poor dead ice or a snow wedge occurred. The deposits are gravelly, silty sand with boulders. **c.** Marine transgression deposits marine sands and muds and allows bioturbation by infauna in areas below ~10 m above present sea level. Some scouring by sea ice occurs. **d.** Isostatic rebound produces some coastal-zone reworking and deposition, with disturbance by the formation of ground ice. The surface is reworked by wind and meltwater from snowbanks.

between +8.8 and +9.8 m and the ridge adjacent to the modern beach has crest elevations between +7.3 and +8.0 m (Fig. 9b). Field observations of isolation lake basins (Zwartz *et al.* 1998) coupled with glacial isostatic adjustment models (Hodgson *et al.* 2016) can be used to indicate when these ridges and basins were modified by wave action. Ridges and basins in Abatus Bay, between -9.5 and -6.0 m above sea level, would have been flooded by seawater ~9.5–14.0 ka BP. The range of ages suggested by glacial isostatic-adjusted (GIA) models (Fig. 11; Hodgson *et al.* 2016) includes one global model suggesting that inundation could have occurred ~18 ka BP; however, this seems too early given other evidence for deglaciation ~14 ka BP (White *et al.* 2020). Dating of Dingle Sand from Abatus Bay would better constrain GIA models (Hodgson *et al.* 2016). Features in Heidemann and Dingle valleys at +6 to +10 m above sea level were probably inundated by seawater ~6.2 ka BP.

The relative sea-level history of the area also constrains the ages of marine fossils within Dingle Sand. Marine fossils, almost always fragmentary, are common in glacially transported sediment down-ice of marine inlets at the Vestfold Hills (Gore *et al.* 1994), but the near-surface Dingle Sand also hosts fossils (particularly *L. elliptica*) in life position that are relatively undamaged (Figs 5 & 16c). Fossils in life position are confined to elevations < 10 m above sea level. *Laternula elliptica* burrows into the upper parts of muddy sand beds from just below the grounding zone of sea ice to 700 m below sea level; radiocarbon dating these fossils from the upper parts of Dingle Sand formerly inundated by seawater can only provide minimum ages for the sediment. As isostatic rebound led to shallowing of the seawater inundating Dingle Sand, grounding sea ice was able to crush and disrupt many of the shells that were in life position, leading to their fragmentation and redistribution (Fig. 16c,d). These two processes - crushing and transport by glacial ice or crushing by tidal sea ice - account for the fragmentary occurrence of most fossil material in Dingle Sand. The depositional mechanisms and post-depositional modification of Dingle Sand have implications for dating these sediments. Marine fossils in Dingle Sand below the peak Holocene sea-level high-stand will bracket the ages of inundation and emergence of the location from the sea. Dating Dingle Sand deposited below present sea level could help constrain GIA models of deglaciation (Hodgson *et al.* 2016). Dating the deposition of Dingle Sand might also be possible via optical dating of sediments above the marine limit of 9–10 m above sea level, giving a more direct date for deglaciation (e.g. Gore *et al.* 2001).

Conclusions

Dingle Sand is a distinct, mappable unit of poorly sorted, gravelly, silty sand with boulders found in valleys and on bedrock ridges in western Vestfold Hills, which continues below sea level. High-resolution topographic and grain size data are consistent with Dingle Sand forming as ablation till during retreat of ice from north-west to south-east during deglaciation. Post-depositional modification of the sediments by wind, sea ice and processes associated with marine transgression and regression have modified the sediment texture and in places allowed emplacement of marine infauna in life position. Regional studies of deglaciation indicate that Dingle Sand was probably deposited 14–11 ka BP, but direct dating has not yet been possible, with the fossil material dated so far representing glacial reworking of older fossils or colonization during post-deglaciation marine inundation. Underlying Vestfold Beds is a finer-grained glacial diamicton of probably Plio-Pleistocene age, which in turn overlies the early Pliocene Sørsdal Formation, which has a type locality on Marine Plain. Vestfold Beds are thicker and more extensive than Dingle Sands, possibly reflecting multiple episodes of sediment accumulation and redistribution. In Dingle Sand, Vestfold Beds and Sørsdal Formation, the Vestfold Hills provide a record of complex interactions between ice volume, subaerial exposure and marine inundation over at least the last 4.5 Ma.

Author contributions. PEO'B - concepts and approach, fieldwork, data analysis, manuscript preparation; DBG - concepts and approach, fieldwork, manuscript preparation; BF - concepts and approach, fieldwork.

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Competing interests. The authors declare none.

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