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RESEARCH ARTICLE

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Seafloor geomorphology of the Wrigley Gulf shelf, Amundsen Sea, West Antarctica, reveals two different phases of glaciation

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Abstract

Knowledge of the behaviour of marine-based ice sheets during times of climatic warming, such as the last deglaciation, provides important information to understand how ice sheets respond to external forcing. We analysed swath bathymetric and acoustic sub-bottom profiler data from Wrigley Gulf on the western Amundsen Sea shelf, West Antarctica, to identify glacial features and reconstruct past changes in the extent of the West Antarctic Ice Sheet (WAIS) and ice flow directions. Glacial bedforms mapped within a bathymetric cross-shelf trough include features showing cross-cutting and overprinting relationship and indicate changes in ice-flow orientation. Here, we distinguish at least two phases of different ice-flow patterns on the Wrigley Gulf shelf. During the earlier phase, seaward ice stream flow on the inner shelf was deflected towards the east due to the existence of an ice dome on the middle-outer continental shelf. Retreat of grounded ice towards the centre of this dome is indicated by the asymmetric cross profile of recessional moraines mapped on the middle shelf. The later glaciation phase was characterized by fast, NNW-directed ice flow across the shelf along a broad front and subsequent stepwise landward retreat, which is evident from the common occurrence and orientation of mega-scale glaciation lineations and grounding zone wedges on the middle-inner shelf. It is uncertain whether the two phases of glaciation recorded on the seafloor occurred during the last and penultimate glacial periods or at different times of the last glaciation. Reliable chronological constraints from sediment cores and additional geomorphological information are needed to understand the cause of the changes in WAIS dynamics reflected by the two ice-flow phases.

KEYWORDS
bathymetry, Getz ice shelf, glacial geomorphology, ice flow change, West Antarctic ice sheet

1 | INTRODUCTION

Glacial bedforms on the continental shelf of the Amundsen Sea provide important information on the West Antarctic Ice Sheet (WAIS) extent during the last glacial period and documented changes in ice flow and WAIS dynamics during the last deglaciation (e.g., Larter et al., 2014, and references therein). Mapping and detailed morphological analysis helped to understand the dynamical behaviour of the marine-based WAIS under changing environmental forcing and thus can be used to improve ice-sheet models (e.g., Golledge et al., 2012, 2013).

Complex paleo-ice flow patterns recorded on the seafloor require extensive coverage with bathymetric data to allow accurate reconstructions. They are often controlled by regional geology and pre-existing topographic relief (Hogan et al., 2020; Munoz & Wellner, 2018; Rodrigo & Herbstaedt, 2021), complicating the simple offshore flow patterns observed in some regions in West Antarctica, such as the Ross Sea (e.g., Anderson et al., 2002; Wellner et al., 2001). Offshore of the Antarctic Peninsula, glacial geomorphic features have been used to show that ice domes existed between ice streams during past periods of extended ice cover (Campo et al., 2017; Lavoie et al., 2015). To the east and west of the northern Antarctic Peninsula,

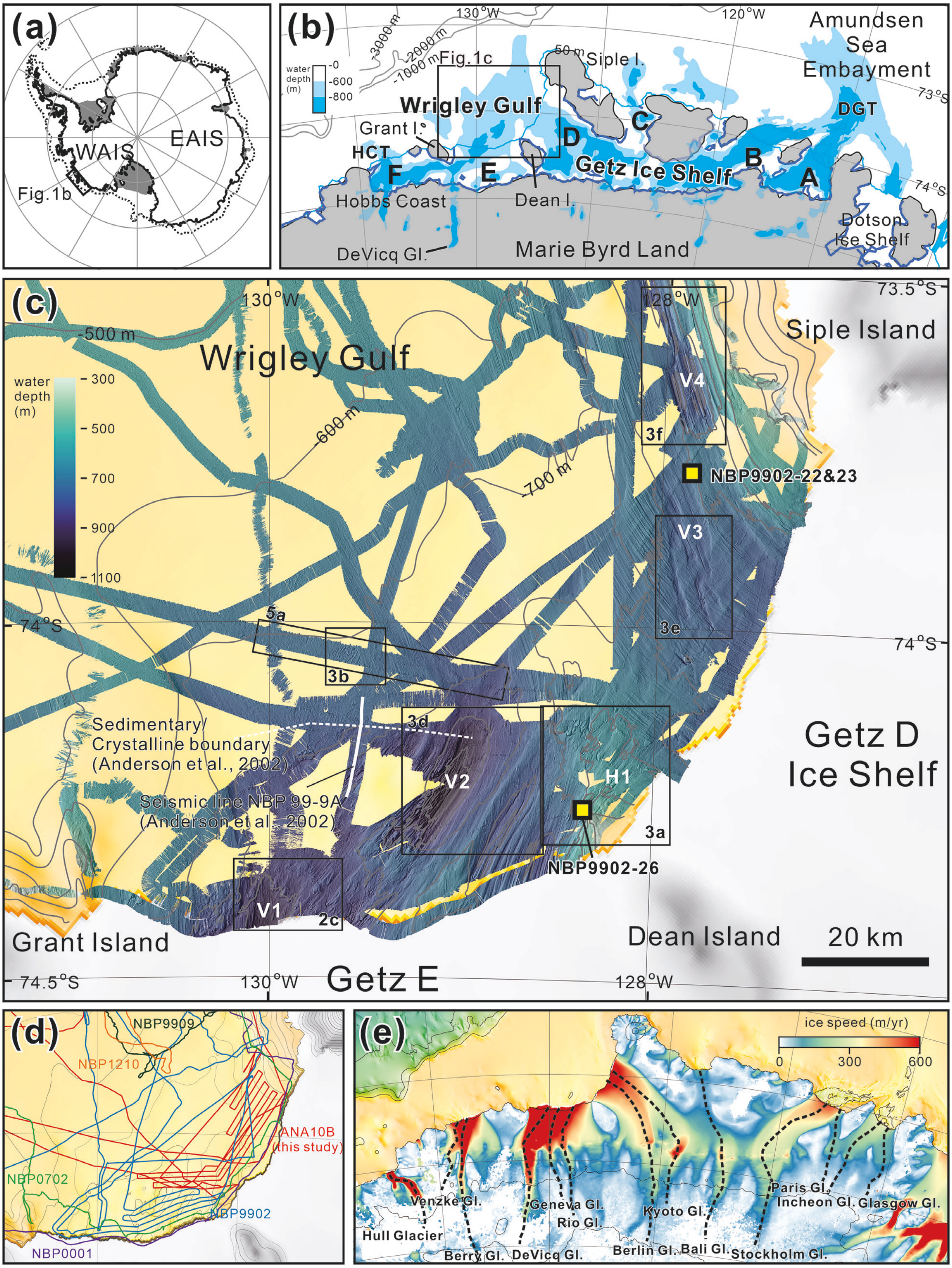

FIGURE 1 Maps showing (a) the location of the Wrigley Gulf study area in the wider context of Antarctica (WAIS = West Antarctic Ice Sheet, EAIS = East Antarctic Ice Sheet), (b) the Getz Ice Shelf region with bathymetry under the ice shelf (Millan et al., 2020) and on the nearby continental shelf (Arndt et al., 2013) including the present grounding line (blue solid line, Rignot et al., 2022) (GDT = Getz-Dotson paleo-ice stream trough, HCT = Hobbs Coast paleo-ice stream trough), (c) the multibeam bathymetry collected on R/V *Araon* cruise ANA10B (this study) and R/V *Nathaniel B. Palmer* cruises NBP9902 (Anderson, 2013), NBP9909 (Bengtson, 2013), NBP0001 (Jacobs, 2013), NBP0702 (Nitsche, 2013), and NBP1210 (Halanych, 2016), (d) the tracklines of these cruises, and (e) the flowlines of outlet glaciers feeding Getz Ice Shelf (The European Space Agency, 2021) and present ice-flow speed (Rignot et al., 2022). Nomenclature of Getz ice shelves A to F in (b) follows Hillenbrand et al. (2013). Yellow rectangles in (c) indicate sites of NBP9902 cores with radiocarbon dates on carbonate material (Anderson et al., 2002), and bathymetric contours in (c) were modified from Arndt et al. (2013) based on the available multibeam bathymetry data.

islands and bathymetric highlands on the middle to outer continental shelf became the centers of ice domes separating fast-flowing ice streams during the Last Glacial Maximum (LGM; ca. 19–23 calibrated [cal.] ka before present [BP]) (Campo et al., 2017; Lavoie et al., 2015). The Wrigley Gulf, which receives ice flow from the Getz Ice Shelf, shares characteristics with the broad, open Ross Sea, where flow is relatively unconstrained, and with areas offshore from smaller drainage basins along both sides of the Antarctic Peninsula, where ice flow patterns are much more irregular and controlled by regional constraints.

Getz Ice Shelf is an elongate ice shelf with a surface area of ∼34 000 km^2 fringing the West Antarctic coast and offshore islands in the western Amundsen Sea (Cochran, Tinto, & Bell, 2020). It overlies deep subglacial troughs oriented parallel and oblique to the coastline (Figure 1; Cochran, Tinto, & Bell, 2020; Millan et al., 2020) and buttresses several outlet glaciers draining the Marie Byrd Land sector of the WAIS (Figure 1e; The European Space Agency, 2021). Ice flow velocity at the calving front of the Getz Ice Shelf is consistently ≤0.6 km/year (e.g., Selley et al., 2021), much lower than the velocity of up to 3 km/year characterizing the calving fronts of the fast-flowing Thwaites Glacier and Pine Island Glacier in the eastern Amundsen Sea Embayment (Rignot et al., 2022). However, ice discharge along the entire Getz Ice Shelf has increased since the 1990s (Selley et al., 2021). Our study area is Wrigley Gulf, an embayment located in front of the Getz D and E ice shelves that lie between Siple Island and Dean Island, and between Dean Island and Grant Island, respectively (Figure 1b). The Getz D Ice Shelf is fed by Berlin and Kyoto glaciers, whilst the Getz E Ice Shelf is fed by ice from the DeVicq, Geneva, and Rio glaciers (Figure 1e; The European Space Agency, 2021).

A cross-shelf bathymetric trough in the Wrigley Gulf area, which is relatively broad on the inner-middle shelf but narrows substantially on the outer shelf, had been previously identified in multibeam bathymetric survey data (Anderson et al., 2001, 2002; Nitsche et al., 2007). Glacial lineations indicate NNW-ward paleo-ice flow on the mid-shelf, but grooves and drumlins close to the Getz E Ice Shelf front indicate N-ward and NE-ward directed paleo-ice flow on the inner shelf (Anderson et al., 2002). These data revealed not only that the Wrigley Gulf trough hosted a paleo-ice stream but also suggested a complex ice drainage pattern on the shelf that may have been accompanied by changes in ice flow. So far, limited bathymetric data and glacial geomorphological information from the Wrigley Gulf shelf, especially from its eastern part, have hindered a detailed understanding of the changes in ice flow pattern and its relative timing.

Previous bathymetric investigations have described the glacial geomorphology on the Amundsen Sea shelf both in the Dotson-Getz paleo-ice stream trough in front of the Dotson, Getz A and Getz B ice shelves to the east of Wrigley Gulf (Graham et al., 2009; Larter et al., 2009) and in the Hobbs Coast paleo-ice stream trough in front of the Getz F Ice Shelf to the west (Klages et al., 2014) (Figure 1b). The record in the Dotson-Getz trough shows an important control of substrate on the bedform imprint. Rough crystalline bedrock on the inner shelf helped to preserve complex bedform variability resulting from multiple episodes of subglacial erosion over time, whereas sedimentary substrate on the middle to outer shelf likely only provides signatures of the last phase of grounded ice stream flow, that is, immediately preceding the last deglaciation (Graham et al., 2009). Subglacial substrate could have played an important role in controlling the formation of glacial bedforms of Wrigley Gulf, too, considering the similarity of the substrate distribution to the Dotson-Getz trough, with crystalline basement being exposed on the inner shelf and sedimentary substrate being present on the middle and outer shelf (Anderson et al., 2002). The inner shelf part of a paleo-ice stream trough extending seaward of the Hobbs Coast is dominated by sedimentary substrate (Klages et al., 2014). On the inner shelf, presence of a large grounding zone wedge indicates a prolonged episode of ice-margin stabilization during WAIS retreat at the end of the LGM (Klages et al., 2014).

Existing bathymetry data from the Amundsen Sea shelf revealed a large number of different glacial bedforms and regional variability in their distribution. Neither the Dotson-Getz trough nor the Hobbs Coast trough, however, exhibit large-scale features suggesting a reorientation of ice flow, such as cross-cutting bedform sets. Indeed, bedforms in both troughs indicate grounded ice retreated in an upstream direction within the major paleo-ice stream trough during the last deglaciation (Graham et al., 2009; Klages et al., 2014). The complex ice-flow dynamics implied in Wrigley Gulf (Anderson et al., 2002) cannot be explained by a similar deglaciation model as in the neighbouring paleo-ice stream troughs and, therefore, consideration of a more complicated (de-)glaciation model is required. Notably, the Wrigley Gulf trough (Anderson et al., 2002; Figure 1b) extends across the continental shelf roughly in a N-S direction, but the deepest depressions on the inner shelf have NE–SW orientation (Figure 1b,c). The mid- and outer shelf parts of Wrigley Gulf trough are relatively shallow and show a rather flat topography, that is, the bathymetry resembles a bank without deepening on the axial part (Figure 1b,c).

In this study, we address how the topographic conditions in the Wrigley Gulf affected the configuration of paleo-ice flow. We also investigate the likelihood that ice dome was present on the shallow middle and outer shelf of the Wrigley Gulf area by reconstructing the directions of grounded ice flow and ice margin retreat from seafloor geomorphology.

The Korea Polar Research Institute conducted a swath bathymetric and acoustic sub-bottom profiler (SBP) survey in Wrigley Gulf in 2020 (Figure 1c,d). Combined with previously reported swath bathymetric data collected by the US Antarctic programme (Anderson et al., 2001; Wellner et al., 2001), these data provide further insight into the past glacial dynamics in the Wrigley Gulf area. Here we aim to (1) identify glacial bedforms preserved on the seafloor using the new swath bathymetric data, (2) infer changes in paleo-ice flow patterns and their relative timing from the mapped bedforms, (3) investigate how glacial evolution is related to the topographic conditions on the Wrigley Gulf shelf, and (4) provide explanations for the observed geomorphology to understand the past WAIS dynamics.

2 | DATA AND METHODS

Marine geophysical data were collected during the R/V *Araon* cruise ANA10B in January 2020. Detailed multibeam bathymetric data were collected using a hull-mounted Kongsberg EM122 multibeam echosounder operated with a frequency of 12 kHz, a resolution of 432 depth points per ping and an opening angle of 130°. Previously

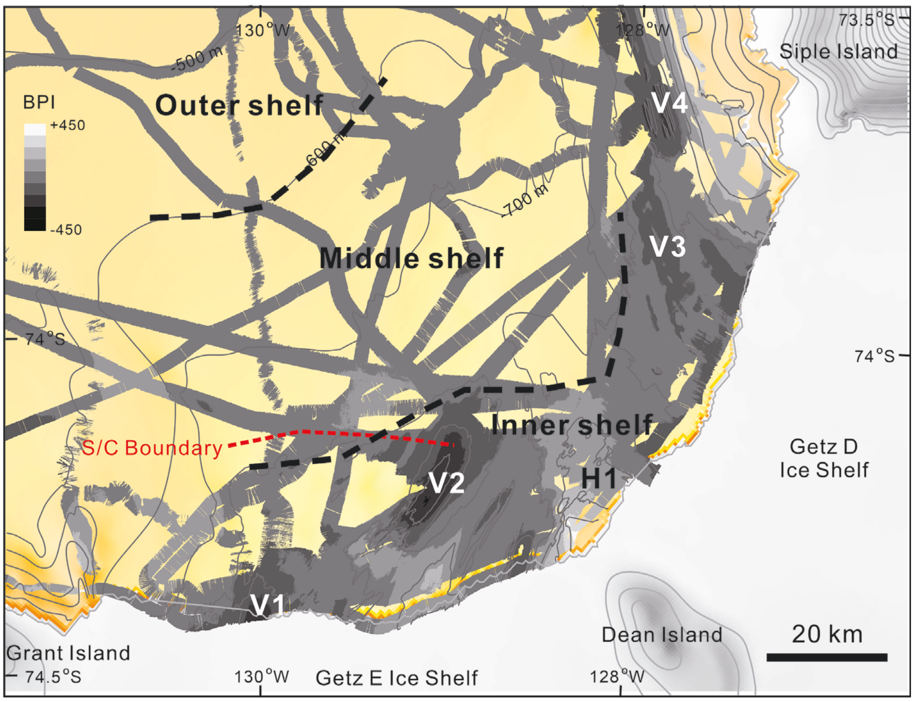

FIGURE 2 Classification of the Wrigley Gulf continental shelf based on the Bathymetric Position Index (BPI) and bathymetry. S/C boundary indicates the sedimentary/crystalline substrate boundary of Anderson et al. (2002).

reported swath bathymetry data of RV/IB *Nathaniel B. Palmer* cruises NBP9902, NBP9909, NBP0001, NBP0702, NBP9909, and NBP1201 were obtained from the Marine Geoscience Data system (http://www.marine-geo.org) (Figure 1d; Anderson, 2013; Bengtson, 2013; Jacobs, 2013; Nitsche, 2013; Halanych, 2016). All the data were processed using CARIS HIPS and SIPS software (http://www.caris.com/products/hips-sips/) and converted to a 20-m grid. Bedforms were manually mapped, and the dimension of bedforms was measured from the swath bathymetry grids in QGIS 3. The SBP data on cruise ANA10B were obtained simultaneously with the swath bathymetry data, using a Kongsberg SBP27 system hull-mounted on R/V *Araon*. Operating frequencies and vertical resolution are 2–9 kHz and 0.2 ms. SBP data were visualized using SBP27 operating software (KM SBP v. 1.4.8) provided by Kongsberg.

We used the 'Bathymetric Position Index' (BPI) analysis tool in the Benthic Terrain Modeler for ArcGIS 10.4 to classify seafloor terrain. The BPI was modified from the Topographic Position Index and represents bathymetric characteristics in their regional context by comparing the depth of defined cells to the neighbourhood cells (McKenzie et al., 2022, 2023; Walbridge et al., 2018). The mean elevation of the neighbourhood was calculated with the defined radius (inner:outer = 100:1000) from the bathymetry grid data (20 × 20 m), and standard deviation datasets were defined as ridge (positive, >0) or valley (negative, <0).

3 | RESULTS AND INTERPRETATIONS

3.1 | Bathymetry and substrate

The swath bathymetry data confirm that, in general, Wrigley Gulf has an over-deepened inner shelf and a shallow outer shelf (Anderson et al., 2002), but the detailed bathymetry is more varied. We divided the continental shelf of the study area into inner, middle, and outer shelf sections based on bathymetry and seafloor roughness (Figure 2). We set the inner/middle shelf boundary roughly based on BPI values of −50. It corresponds to ~800 m water depth in the western part and at ~700 m water depth in the eastern part of Wrigley Gulf. The BPI values of middle/outer shelf are indistinguishable, so we set the middle/outer shelf boundary at ~600 m water depth. The inner shelf is characterized by a rugged seafloor surface characterized by depressions/basins with negative BPI values (<−50), which we refer to as 'valleys' (without any genetic implications), and bathymetric highs with positive BPI values (> +50), while the seafloor on the middle-outer shelf is relatively flat with BPI values mostly between −50 and 50 (Figure 2). The western part of the inner shelf exhibits two broad valleys with water depths of >1000 m (V1 and V2 in Figure 1c) trending N-S and NE–SW, respectively. A bathymetric high protruding NW of Dean Island (H1) separates the western inner shelf from the eastern inner shelf (Figure 2). The eastern inner shelf part of Wrigley Gulf is shallower than 800 m and characterized by a group of N- to NNW-ward directed, narrow, low-relief valleys that are up to 30–50 m deep, ~1–3 km wide (6 km as a group) and ~20 km long (V3 in Figure 1c). A NNW–SSE trending valley (up to 800 m water depth) extends along the western coast of Siple Island towards the shelf edge (V4 in Figure 1c).

The SBP data from the Wrigley Gulf continental shelf show that unlithified sediments are rare and restricted to limited areas, such as the deepest parts of the observed valleys, with their thickness reaching not more than 2 m. The SBP data could not be used to analyse the internal structure of the sub-seafloor on the inner shelf because it was acoustically impenetrable, likely indicating lithified strata.

3.2 | Glacial geomorphology of the seafloor

We identified subglacial bedforms across the Wrigley Gulf area (Figure 3) largely based on criteria given by Graham et al. (2009) for glacial bedforms observed in the Dotson-Getz trough area on the western Amundsen Sea Embayment shelf and present the resulting map in Figure 4.

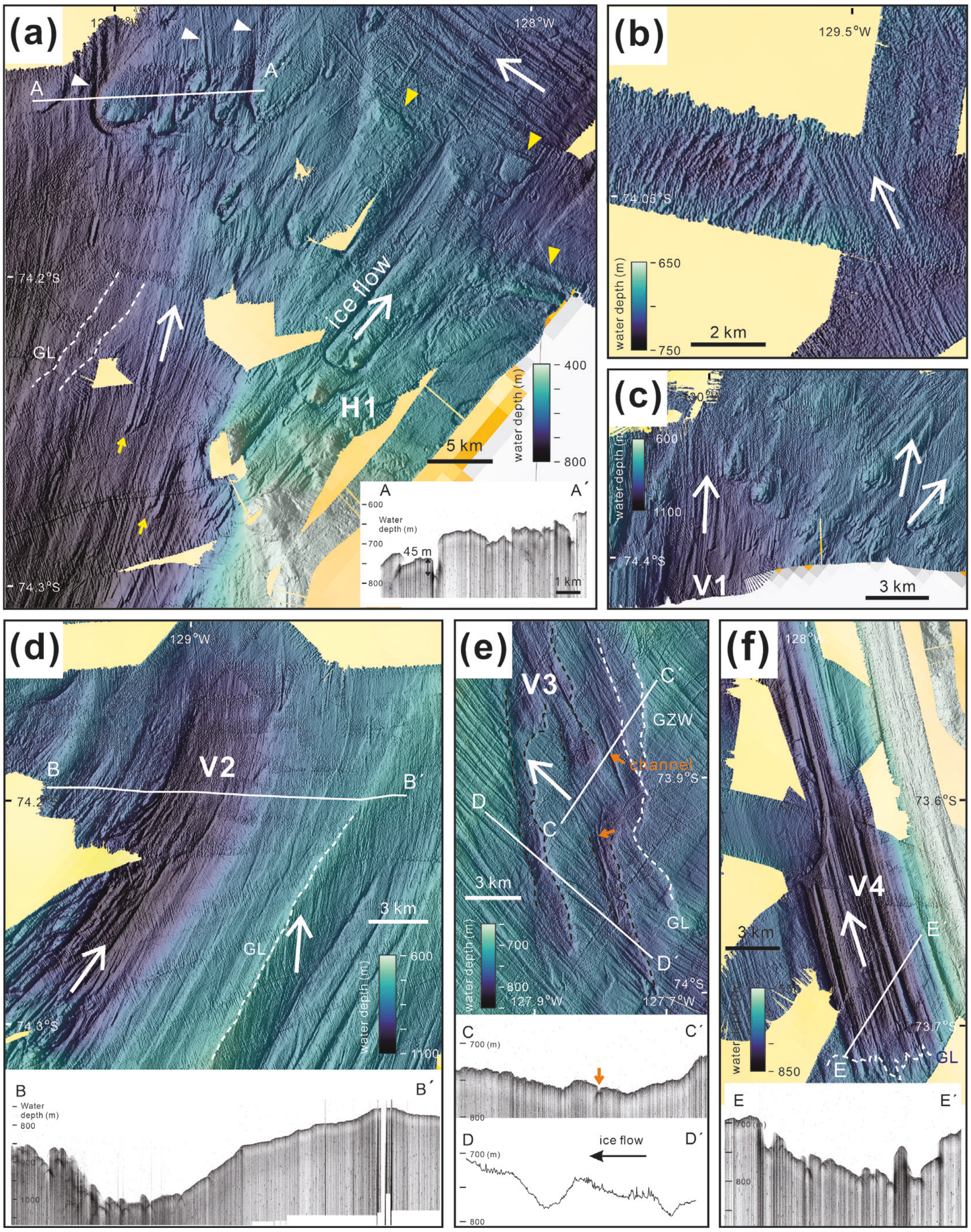

FIGURE 3 Multibeam bathymetric images of glacial features on the Wrigley Gulf continental shelf with sub-bottom profiler (SBP) images. Locations of the featured areas are shown in Figure 1c. All images are oriented with north to the top. Thick white arrows indicate paleo-ice flow direction. GL = grounding line features. GZW = grounding zone wedge. (a) Drumlinoid features on bathymetric high H1 overprinted (white triangles) or eroded (yellow triangles) by glacial lineations of different orientations. (b) Transverse ridges overprinted by glacial lineations on the western middle shelf. (c) Glacial features on the western innermost shelf. Drumlinoid features and glacial lineations in valley V1 indicate northward ice flow. To the east of V1, drumlinoid features and glacial lineations formed by NE-ward ice flow are overprinted by glacial lineations formed by N-ward ice flow. (d) Drumlinoid features indicating NE-ward ice flow in valley V2 on the western inner shelf and glacial lineations formed by N-ward ice flow to the east of V2. (e) Glacial features around a group of small valleys V3 (black dashed line) on the eastern inner shelf showing mega-scale glacial lineations, a GZW, and channels. (f) Groove-ridges developed in the easternmost valley V4.

3.2.1 | Drumlinoid features

Description

Elongated groove-ridges associated with teardrop-shaped heads at upstream end are the most prominent features on the seafloor high H1 and the western inner shelf (Figure 4). Here we use the term 'drumlinoid features' for all elongated bedforms with teardrop-shaped heads. The top of bathymetric high H1 is dominated by drumlinoid features with moats (ca. 5–45 m deeper than the surrounding seafloor) around tear-drop shaped heads of up to ~1.5 km width (Figure 3a). The tails of these features are up to ~5 km long and extend into parallel lineations further downstream. Drumlinoid features in the north-western part of valley V2 (Anderson et al., 2002; Figure 3d) are much narrower (up to ~0.3 km wide) and shorter (up to

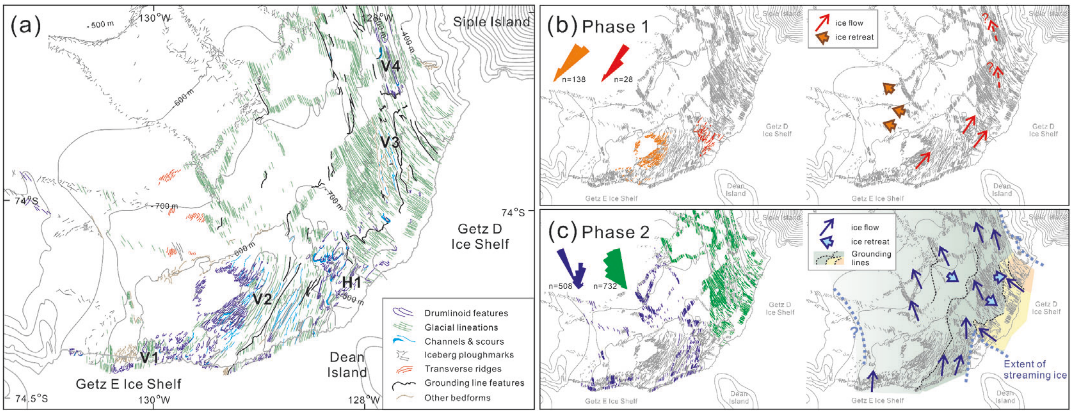

FIGURE 4 Interpretation of seafloor geomorphology of Wrigley Gulf. (a) Geomorphological map showing identified glacial features. (b) Left: orientation of paleo-ice flow of glaciation phase 1 indicated by streamlined bedforms in V2 (orange) and H1 (red) regions. Right: inferred ice-flow and retreat directions of glaciation phase 1. (c) Left: orientation of paleo-ice flow of glaciation phase 2 indicated by streamlined bedforms from western (blue) and eastern (green) Wrigley Gulf. Right: inferred ice-flow and retreat directions of glaciation phase 2.

~2.5 km long) than those on H1. Although less common, drumlinoid bedforms also occur in other parts of the study area. For example, directly to the SW of H1, several elongated ridges with heads of up to ~0.3 km width and long tapering tails of ~4 km length occur on seafloor covered with highly elongated (>10:1) lineations (yellow arrows in Figure 3a).

Interpretation

Drumlins are formed beneath an actively flowing glacier and are elongated along the ice flow direction and have steep stoss and gentle lee sides (Bell et al., 2016). Many drumlinoid features were reported from paleo-ice stream troughs on the Antarctic continental shelf, especially at the transition between crystalline bedrock and sedimentary substrate (e.g., Graham et al., 2009; Shipp, Anderson, & Domack, 1999; Wellner et al., 2001; Wellner, Heroy, & Anderson, 2006). Drumlinoid features on bathymetric high H1 shows NE–SW elongated groove-ridges with teardrop-shaped heads at their south-western end. The morphology and orientation of the drumlinoid features indicate that grounded ice flowed NE-ward across H1 in the past (Figure 4b). Drumlinoid bedforms in the NW part of valley V2 (Anderson et al., 2002; Figure 3d) also indicate NE-ward paleo-ice flow (Figure 4b). Smaller drumlinoid features to the SW of H1 (yellow arrows in Figure 3a), however, were produced by NNE-ward ice flow. Drumlinoid features in valley V1 indicate N-ward ice flow (Figure 3c).

3.2.2 | Glacial lineations

Description

Streamlined, elongated sets of parallel grooves/ridges are common features on the middle and inner shelf seafloor in Wrigley Gulf. In this study, we did not distinguish lineations developed on sedimentary substrate from those developed on crystalline bedrock and grouped them together as 'glacial lineations' (Figure 4a). Highly elongated lineations are most common at 600–800 m water depth (Figure 4a), where they are usually characterized by length:width ratios higher than 15:1. Most of them have heights of <10 m and lengths of several to tens of kilometers. The lineations in the Wrigley Gulf area are usually well preserved and unmodified, except for overprinting by iceberg ploughmarks in shallow parts of the shelf (see Section 3.2.5). Glacial lineations formed on crystalline basement (e.g., in valley V2; Anderson et al., 2002) tend to have smaller dimensions.

Interpretation

The highly elongated ridges and grooves are interpreted as mega-scale glacial lineations (MSGLs). On the West Antarctic continental shelf, MSGLs are common in areas of sedimentary substrate (e.g., Graham et al., 2009; Klages et al., 2017; Ó Cofaigh, Livingstone, & Dowdeswell, 2016; Wellner et al., 2001). MSGLs are landforms typically moulded into subglacial sediments beneath fast-flowing grounded ice, with lengths as much as tens of kilometers, amplitudes of a few meters, and wavelengths of tens to a few hundred meters (e.g., Bell et al., 2016; Clark, 1993; Ó Cofaigh et al., 2005). We use the term 'MSGLs' for the highly elongated lineations with length:width ratios higher than 15:1. They include glacial lineations for which an origin by moulding into a sedimentary substrate is unlikely or unclear, similar to what has been observed on the inner shelf part of Filchner trough in the Weddell Sea embayment (Larter et al., 2012). The paleo-flow orientation of the MSGLs in Wrigley Gulf points to dominance of NNW-ward ice streaming at a width of ~90 km during the last glaciation (Figure 4c). In the eastern part of the study area, the paleo-ice flow direction indicated by the MSGLs gradually changed into a more westward direction during grounded ice retreat (Figure 4a). The paleo-ice flow direction on the innermost shelf in front of the Getz D Ice Shelf is similar to the present-day ice shelf flow (Rignot et al., 2022). Groove ridges in valley V4 were formed by NNW-ward ice flow west of Siple Island.

3.2.3 | Grounding line features

Description

MSGLs in Wrigley Gulf commonly superimpose the surfaces of ramp or wedge-shaped sedimentary bodies with a steep seaward flank and terminate at their crests (Figure 3e). The crestlines of the sediment wedges commonly are sinuous, but linear ('GL' in Figure 3a,d) and zigzag-shaped crestlines (Figure 3f) are also observed. The heights of the wedge-shaped bodies are usually less than 20 m.

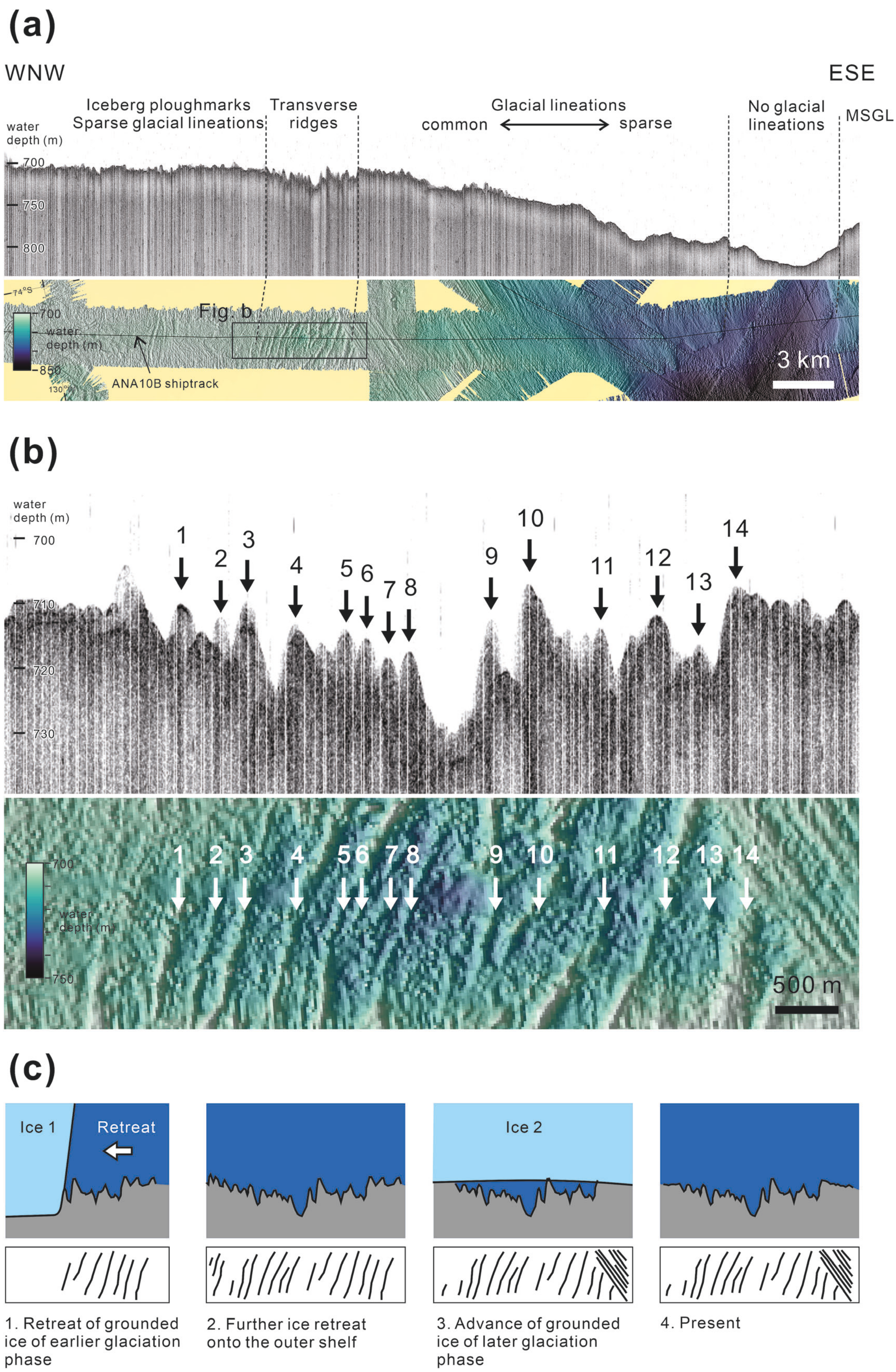

FIGURE 5 (a) Sub-bottom profile across (upper panel) and multibeam bathymetric image of (lower panel) the area with transverse ridges on the western middle shelf of Wrigley Gulf. (b) Detailed view. (c) Schematic diagram illustrating the formation and preservation of the transverse ridges.

Interpretation

The wedge-shaped sedimentary bodies with MSGLs on the surfaces are interpreted as grounding zone wedges (GZWs). GZWs are ramp-shaped sedimentary deposits which form through the delivery of deforming subglacial sediment to the grounding line during stillstands or minor re-advances of the ice margin (Batchelor & Dowdeswell, 2015;

Dowdeswell et al., 2008). They usually have an asymmetric strike profile with an upstream dipping back-slope that has MSGLs on top (e.g., Dowdeswell et al., 2008; Ó Cofaigh et al., 2005). The <20 m high GZWs on the eastern inner shelf of Wrigley Gulf are much smaller than the ~80 m high GZW on the inner shelf part of the Hobbs Coast trough further west (Klages et al., 2014). They resemble small GZWs that were produced during relatively short-lived grounding line stillstands or re-advances during general retreat (e.g., Ottesen et al., 2022; Simkins et al., 2017). In eastern Wrigley Gulf, the orientations of MSGLs and GZW crestlines indicate NW-ward ice flow and S- to SE-ward back-stepping of grounded ice during its retreat (Figure 4). The NE–SW striking linear ridges observed on the western part of the inner shelf probably mark paleo-grounding line positions, too. We assume these were also formed by the accumulation of subglacial sediment at the grounding line, when retreat was temporarily halted ('GL' in Figure 3a,d).

3.2.4 | Transverse ridges

Description

Sets of small, closely spaced, NE–SW oriented ridges are observed on the middle shelf of the western part of the study area between 650 m and 800 m water depth on a seafloor that is deepening landward (Figure 3b; 'Transverse ridges' in Figures 4 and 5a). The ridges are curvilinear, subparallel to each other and have heights of ~5–20 m, with the distance between their crests ranging from ~200 to 500 m. Most transverse ridges generally appear symmetric in bathymetric cross-profiles obtained from the multibeam and acoustic sub-bottom profiler data, but at least two ridges (#4 and #10) are asymmetric, with their steeper flanks facing WNW (Figure 5b).

Interpretation

The morphology and dimension of the ridges are similar to those of recessional moraines that are common in shallow shelf settings. These moraines are regularly formed at the grounding line when grounded ice retreats relatively slowly (e.g., Dowdeswell et al., 2008; Shipp, Wellner, & Anderson, 2002; Simkins, Greenwood, & Anderson, 2018). In Wrigley Gulf, the transverse ridges are only observed in spatially restricted areas, where MSGLs and iceberg ploughmarks are sparse (Figure 4), implying that they would have been erased by any later subglacial erosion, and that these recessional moraines probably had been more widespread in the past. Transverse ridges are overridden by MSGLs formed by NW-ward ice flow (Figure 3b), suggesting grounded ice retreat was followed by renewed grounding-line advance. The deep bathymetry of the area with the transverse ridges (Figure 5a) suggests that the moraines there avoided erosion by later ice flow because the transverse ridges were formed at a water depth greater than the depth where ice was able to ground during its re-advance (Figure 5c). Considering that recessional moraines often display steep stoss sides and gentle lee sides (Klages et al., 2016; Winkelmann et al., 2010), we conclude that in western Wrigley Gulf grounded ice retreated WNW-ward onto the shallower, outer shelf after an earlier glaciation phase before grounded ice re-advanced N-ward during a later glaciation phase.

3.2.5 | Iceberg ploughmarks

Description

Randomly oriented, curvilinear narrow furrows with associated berms of <5 km in length, <250 m in width and <10 m in height are observed on the outer and middle shelf of Wrigley Gulf. These features are the most common features on seafloor shallower than 700 m water depth, and cross-cut all the other bedforms described above.

Interpretation

Iceberg ploughmarks are erosional features cut into the seafloor by the grounding and movement of iceberg keels. Ploughmarks are typically arcuate features cut into older features by turbation of seafloor sediments (e.g., Shipp, Wellner, & Anderson, 2002). The maximum water depth of ~700 m for the iceberg ploughmarks in Wrigley Gulf is similar to the maximum ploughmark depth of 700–750 m reported for the Dotson-Getz Trough in the western Amundsen Sea Embayment (Graham et al., 2009). Due to the extensive presence of iceberg ploughmarks on the outer shelf, the maximum seaward extent of grounded ice on the outer shelf of Wrigley Gulf during the last (and possibly earlier) glacial periods is uncertain.

4 | DISCUSSION

4.1 | Changes in paleo-ice flow directions

Previously reported multibeam bathymetric data imply multiple different paleo-ice flow directions on the western Wrigley Gulf shelf (cf., Anderson et al., 2001). However, due to the lack of data showing the exact relations between glacial bedforms, it was not clear whether their formation was contemporaneous or time-transgressive, and which features were formed first, if they were formed at different times. Our new bathymetric data clearly show that paleo-ice flow directions changed in Wrigley Gulf. Based on our findings, we distinguish two phases of different ice-flow patterns and refer to the earlier as 'glaciation phase 1', and to the later as 'glaciation phase 2'.

The most striking example is found around bathymetric high H1, where drumlinoid bedforms are either overprinted (white triangles in Figure 3a) or eroded (yellow triangles in Figure 3a) by MSGLs of different orientations. The drumlinoid features were formed by NE-ward ice flow during glaciation phase 1, while the MSGLs indicate convergence of NW-ward ice flow from the eastern part and N- to NNE-ward ice flow from the western part during glaciation phase 2. The southern part of H1 would have been located between the two paleo-ice stream branches, largely protected from subglacial erosion by its position on the lee side of Dean Island, which would have preserved previously formed glacial bedforms in the area by preventing erosion during the phase 2 ice flow (Figures 3a and 4c). This scenario is similar to that of an inter-ice stream ridge identified on a shallow mid-shelf bank north of Burke Island in the eastern Amundsen Sea Embayment, where the bathymetric high of the island split ice streaming in central Pine Island trough to the west from ice streaming in Cosgrove-Abbot trough to the east. This allowed local formation of an ice body comprising slow-flowing to stagnant ice (Klages et al., 2013, 2015). The flow direction of grounded ice on the Wrigley Gulf shelf at the time when the grounding line had retreated close to the present ice margin was comparable to the modern flow directions of the Getz D and E ice shelves and major glaciers feeding into them (Figure 1e; Rignot et al., 2022).

In the western inner shelf region, drumlinoid features and grooves/ridges formed by an earlier, NE-ward grounded ice advance were overprinted by glacial lineations formed by later N-ward ice flow (Figure 3c,d). Bedforms preserved on the floor of valley V2 suggest occupation by NE-ward flowing ice during glaciation phase that was more than 1000 m thick. Notably, drumlinoid features are observed only on the north-western flank of V2. Rugged seafloor surface on the north-western flank is in contrast to the smooth seafloor surface on the south-eastern flank (SBP image in Figure 3d). We infer that basement on the south-eastern flank of V2 is covered by lithified sediments with glacial lineations on top that indicate N-S directed ice flow (Figure 3d). We suggest that grounded ice streamed N-ward across the NE–SW oriented valley during the later glaciation phase 2. During its retreat, the grounding line around the valley V2 would have been located at the south-eastern flank as indicated by grounding line features (e.g., 'GL' in Figure 3d), probably due to instability of marine-based ice sheet on a reverse bed slope of north-western flank (Jamieson et al., 2012). This would have favoured the deposition of glacial sediment on the south-eastern flank of the valley. We interpret that the grounding line would have already retreated landward of V2 before glacial sediment could fill the valley.

In contrast to the western inner shelf, glacial features indicating ice flow directions during an earlier glaciation phase are not observed from the eastern part of the inner shelf, which is almost entirely covered by MSGLs with NW-SE orientation (Figures 3e and 4a). Thus, it is likely that glacial bedforms produced by former ice flow, if present, were obliterated by grounded ice flow during glaciation phase 2. Glacial lineations in easternmost valley V4 reveal a dominance of NNW-ward ice flow and do not indicate a switch in ice flow orientation (Figures 3f and 4a).

On the middle shelf, the seafloor is mostly covered by NW-ward directed MSGLs associated with GZWs of phase 2 glaciation. Analysis of bedform directions indicates that grounded ice emanating from the Getz E and Getz D regions merged to form a NNW-ward flowing ice stream that reached a width of up to 90 km when the grounded ice had advanced onto the middle-outer shelf (Figure 4c). During the course of upstream grounding line retreat following the maximum ice extent, the paleo-ice stream separated again into a NW-ward flowing branch emanating from the Getz D region and an N- to NE- ward flowing branch emanating from the Getz E region.

Directions of ice advance and retreat during glaciation phases 1 and 2 are summarized in Figure 4b,c, respectively. It remains a possibility that glacial features interpreted as a result of phase 1 glaciation might actually have formed during multiple different glaciations. However, we prefer the interpretation that they were formed during the same glaciation based on the continuity of inferred ice flow directions. Specifically, there is a lack of bedform evidence for changing ice-flow directions, such as cross-cutting relationships between features, whose formation we attribute to the phase 1 glaciation.

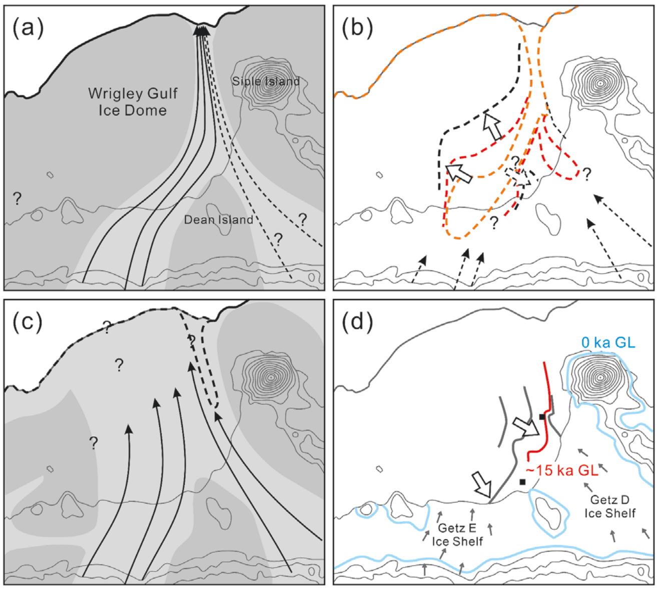

FIGURE 6 Glacial history model for the Wrigley Gulf area based on glacial features on the continental shelf. GL = grounding line. Thick solid/dashed lines indicate identified/inferred GLs, respectively. Arrows indicate the ice-flow directions. White arrows indicate the retreat directions. Question marks indicate inferred ice conditions that are not supported by geomorphological evidences. Areas occupied by streaming ice/stagnant ice are shown in light grey/dark grey, respectively. (a) Advance of grounded ice during the glaciation phase 1. (b) Retreat of the phase 1 grounded ice onto middle-outer shelf. The orange/red/black dashed grounding lines were drawn based on bathymetric contours of 800/700/600 m, respectively. (c) Advance of a wide ice stream during the glaciation phase 2. (d) Retreat of phase 2 grounded ice. GL retreat directions are illustrated by large open arrows, and former GL locations are identified by the position of GZWs. Solid squares indicate the locations of NBP 9902 cores with ^{14}C dates on carbonate material (Anderson et al., 2002). Small arrows on Getz D and Getz E ice shelves indicate present-day ice-flow directions (Rignot et al., 2022). Light blue line indicates the present grounding line (Rignot et al., 2022).

4.2 | Glacial history of the Wrigley Gulf shelf

4.2.1 | Glaciation phase 1

During the glaciation phase 1, ice stream flowed NE-ward on the inner shelf of Wrigley Gulf, and the ice grounded on the seafloor at water depths exceeding 1000 m. Ice on the western inner shelf, probably a seaward extension of today's DeVicq, Geneva, and Rio outlet glaciers, deflected to the east, probably towards the easternmost valley V4 (Figures 4b and 6a). There was probably a convergence of this ice stream with ice emanating from the Getz D area during phase 1, but any evidence for the latter ice stream branch is lost due to thick glacial sediment cover deposited during the later glaciation phase 2. The eastward deflection of the phase 1 ice flow on the inner shelf implies that N-ward flow was inhibited, probably by largely stagnant to slow-flowing grounded ice on the shallow, middle-outer continental shelf (Wrigley Gulf Ice Dome in Figure 6a). This is comparable to the LGM conditions on the eastern and western Antarctic Peninsula shelves where ice domes delineated by ice stream systems were present on the middle-outer continental shelf (Campo et al., 2017; Graham & Smith, 2012; Lavoie et al., 2015).

Transverse ridges interpreted as recessional moraines on the western middle shelf of Wrigley Gulf (Figures 3b and 4) mark the position of the grounded ice margin during initial retreat at the end of phase 1. Their existence also suggests that the grounding line of the ice stream flowing to the east of the dome had already further retreated onto the present-day inner shelf position during the formation of the recessional moraines. Ice retreat tends to occur much more rapidly over a deep trough than over the shallow banks on either side of a trough during the initial deglaciation due to a lack of pinning points to stabilize the grounding line, as shown in the calving bay re-entrant model (Leventer et al., 2006). The physical configuration of Wrigley Gulf would have favoured the initial deglaciation along the deep bathymetry on the inner shelf that had hosted the grounded ice stream during phase 1 (Figure 6b). This is similar to the trough-to-bank retreat during post-LGM deglaciation recorded in the western Ross Sea, where the ice retreat onto the shallow banks is documented by recessional moraines around them (Greenwood et al., 2018; Halberstadt et al., 2016; Shipp, Anderson, & Domack, 1999; Simkins, Greenwood, & Anderson, 2018). We assume that the grounding line positions within the Wrigley Gulf trough retreated roughly perpendicular to the bathymetry contours at 800, 700, and 600 m water depths, implying that the SE margin of the Wrigley Gulf Ice Dome would have retreated towards the NW, that is, the outer shelf direction (Figure 6b). This is supported by the asymmetric cross profiles of several of the recessional moraines on the middle shelf (Figure 5). It is uncertain, however, whether the seafloor cleared of grounded ice was either overlain by open ocean water or covered by an ice shelf.

4.2.2 | Glaciation phase 2

The phase 2 glaciation was characterized by a NNW-ward flowing ice stream, up to ~90 km wide (Figure 4c). This contrasts with the narrow and confined, NE-ward flowing ice stream of phase 1 (Figure 6c). Recessional moraines formed at the ice margin during the retreat of phase 1 ice are preserved at a water depth greater than the grounding depth of phase 2 ice (Figure 5). This implies that grounding depth of phase 2 ice was shallower than that of retreating phase 1 ice in the middle shelf of western Wrigley Gulf. Evidence for the presence of stagnant ice on the middle-outer shelf is absent for phase 2. Reconstruction of paleo-ice flow directions during this time indicates that the wide paleo-ice stream was fed by merged ice emanating from both the Getz E and the Getz D areas (Figure 4c).

The distribution of GZWs indicates that at the end of phase 2 ice retreated SE-ward in the eastern part of the study area (Figures 4c and 6d). In the western part of the Wrigley Gulf shelf, the grounded ice seems to have retreated earlier than in the eastern part, probably due to the large water depth of the western inner shelf.

Radiocarbon dates on calcareous shells and bryozoans from sediment cores recovered on the eastern inner shelf of Wrigley Gulf (for core locations, see Figure 1c) are ~15.6 cal. ka BP at site NBP9902-PC26 and ~14.3 cal. ka BP at sites NBP9902-TC22 and -TC23 (Anderson et al., 2002; Larter et al., 2014). These ages indicates that the retreat of grounded ice there must have occurred prior to ~15 cal. ka BP (Figure 6d).

4.2.3 | Multiple glacial cycles or a single glacial cycle?

The submarine glacial bedforms preserved on the seafloor of Wrigley Gulf show at least two phases of glaciation in this sector of the Amundsen Sea continental shelf, with different patterns of ice flow and retreat. It is uncertain, however, whether these two phases occurred during different glacial periods or the same glacial period.

One possibility is that phase 2 corresponds to the most recent glacial period, the LGM, while phase 1 represents the penultimate glacial period. Evidence for ice flow during phase 1 is mostly observed on the inner shelf, especially in the V2 and H1 areas (Figure 4b). Seismic profiles from the Wrigley Gulf area had previously revealed crystalline basement rocks on the western inner shelf and an offlapping wedge of sedimentary strata on the outer shelf (Figure 1c; Anderson et al., 2002). The crystalline basement on the western inner shelf is characterized by a rugged seafloor surface and parabolic returns in sub-bottom profiles (Figures 2 and 3). We infer the substrate of V2 and H1 areas is composed of crystalline basement and hard sedimentary bedrocks based on the seismic profiles (Anderson et al., 2002), seafloor roughness, and sub-bottom profiles. On the inner shelf part of Dotson-Getz Trough of the western Amundsen Sea Embayment, glacial features on the hard, bedrock-floored inner shelf record multiple imprints of past ice flow (Graham et al., 2009). Considering the similarities in the seafloor substrate with the Dotson-Getz Trough region, the glacial bedforms on the Wrigley Gulf shelf attributed to phase 1 may be the results of glaciations older than the last glaciation.

Another possibility is that the two glaciation phases represent the evolutionary changes in WAIS behaviour since the last glaciation. This hypothesis assumes a continued thinning during deglaciation and that the waning and retreat of the phase 1 ice dome on the middle-outer shelf triggered the change in ice-flow orientation that was reorganized to form the widespread NNW-ward ice-flow of phase 2. It is consistent with the implication that the phase 2 ice was slightly thinner than the retreating phase 1 ice, inferred from the preservation of recessional moraines on the western middle shelf (Figure 5c).

Additional age constraints provided by sediment records from the Wrigley Gulf continental shelf, especially for glaciation phase 1, are needed to determine which hypothesis is correct. Also, more detailed multibeam bathymetric data from the western middle shelf, where the retreat of ice at the end of phase 1 and ice advance during phase 2 are recorded, would help reveal the relationship between the two glaciation phases. Further research on the glacial history of Wrigley Gulf will help understand the environmental forcing that caused the difference in ice streaming and ice retreat between the two glaciation phases and predict the future WAIS behaviour during times of climate warming.

5 | CONCLUSIONS

- Glacial bedforms on the continental shelf of Wrigley Gulf in the western Amundsen Sea indicate two phases of glaciation.
- Phase 1 glaciation was mainly controlled by topography and was characterized by confined ice streaming on the inner shelf and presence of an ice dome on the relatively shallow and rather flat middle-outer shelf. Drumlinoid bedforms and glacial lineations

formed during the phase 1 glaciation on the western and central inner shelf indicate ice-stream flow in a NE-ward direction. Asymmetric cross profiles of several recessional moraines on the middle shelf indicate retreat of grounded ice towards the outer shelf.

- A NNW-ward flowing, ~90 km wide ice stream occupied the Wrigley Gulf continental shelf during phase 2 glaciation and the subsequent deglaciation. Mega-scale glacial lineations and grounding zone wedges on the middle-inner shelf show that ice retreat occurred earlier in the western part than in the eastern part of the study area, and the grounded ice retreated southeastward in the eastern part. Previously reported radiocarbon dates indicate that the grounded WAIS retreated from the eastern inner shelf prior to ~15 cal. ka BP.
- It remains unclear if the phase 1 and 2 glaciations represent two different glacial periods or two different phases of the same glacial period. Further age constraints from sediment cores and more detailed geomorphological mapping of the western middle shelf are needed to understand the changing WAIS dynamics during the two glaciation phases.

AUTHOR CONTRIBUTIONS

Jae Il Lee: Conceptualization; writing-initial draft. **Claus-Dieter Hillenbrand**: Conceptualization; writing—reviewing and editing. **Julia S. Wellner**: Conceptualization; writing—reviewing and editing. **Hyoung Jun Kim**: Data collection; data processing. **Hyun Hee Rhee**: Data processing. **Kyu—Chul Yoo**: Funding acquisition. **Sunghan Kim**: Data collection. **Min Kyung Lee**: Writing—reviewing and editing.

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DATA AVAILABILITY STATEMENT

The multibeam bathymetry and shiptrack data are available at Korea Polar Research Data Centre (https://doi.org/10.22663/KOPRI-KPDC-00002188.2).

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