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RESEARCH ARTICLE

Subglacial geomorphology of Lystad Bay, Horseshoe Island, Antarctica

Tuba Çınar Pehlivan[1*], Bedri Alpar[2]

ORCID IDs: T.Ç.P. 0009-0004-1284-948X; B.A. 0000-0002-9694-1395

[1] Turkish Navy, Office of Navigation, Hydrography and Oceanography, Istanbul, TÜRKİYE
[2] Institute of Marine Sciences and Management, Istanbul University, 34134, Istanbul, TÜRKİYE

***Corresponding author:** a.tuba.cinar@gmail.com

Abstract

High-resolution swath-bathymetric data were collected via multibeam sonar in Lystad Bay (Horseshoe Island, Antarctica). From 3D high-resolution data, important shallows that pose a danger to sailors have been identified. Successive depressions on the crystalline/volcanic bedrock (active lakes), elongated-streamline glacial landforms and glacial landforms with distinctive shapes in this subglacial margin were recognized, and how they may have developed was explained. Limited oceanographic data support that suspended material transport may also be effective in sediment accumulation. Suggestions have been made for geological and geophysical studies that are expected to be carried out in the future.

Keywords: Hydrography, multibeam, sea floor morphology, drumlins, meltwater corridors

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Introduction

The Antarctic Peninsula, which points toward South America and shares geologic and geomorphic characteristics with it (Figure 1a), is part of a continent sculpted by glaciers and harsh weather (Öztürk 2017). To the west, Marguerite Bay and its neighboring islands, shaped by glaciers in the form of nunataks, horns, arêtes, and moraines, are home to a variety of marine creatures, including krills, seals, whales, and penguins. Horseshoe Island, at the mouth of Bourgeois Fjord, is one of the numerous islands dispersed across the northern region. The only way the island is connected to the sea is via Lystad Bay on its western coast (Matthews

1983). Owing to complex geographic features and inclement weather, precise bathymetry measurement, necessary to obtain comprehensive information about the depth, texture, and geomorphic characteristics of the seafloor, takes a long time in these regions. With the advancement of cutting-edge multibeam echo sounding technology over the last 20 years and the availability of highly accurate GPS tracking, however, seabed morphology has been mapped at a never-before-seen level of detail. The subglacial landforms recognized on the seafloor of Lystad Bay are described in this paper for the first time via swath-bathymetric images we collected during the 2020 expedition.

Materials and Methods

Geomorphological features of the study area

The study region is located in the northeast of Marguerite Bay. Marine geophysical and geological studies by Livingstone *et al.* (2013) revealed a sequence of glacial landforms oriented along the axis of the trough, indicating that streams flowed toward the shelf edge during the previous glaciation. Its inner shelf margin is characterized by ice-molded bedrock, drumlins and subglacial meltwater channels. These geomorphic elements gradually changed into classical drumlins and mega-scale glacial lineations (MSGLs) toward the middle shelf. Marine sediment data from Kilfeather *et al.* (2011) suggest an ice–stream retreat in Marguerite Bay, which is characterized by a rapid and then slower deglaciation phase since the Last Glacial Maximum (LGM). Additionally, the researchers asserted that approximately 9,000 years ago, the retreat quickly moved toward the inner shelf. The ice sheet rapidly thinned near the inner shelf, where the islands are situated, in tandem with this final stage of glacial melt. Among them is Horseshoe Island, with a surface area of 60 km^2 and situated 18 km away from Forbes Glacier's tidewater glacier discharge. Our marine geophysical survey was carried out in Lystad Bay, which is situated to the western side of Horseshoe Island (Figure 1).

Lystad Bay is located in a glacial shelf area characterized by subglacial landforms formed beneath the ice and ice-marginal landforms at the edge of the glacier. In general, the majority of subglacially produced landforms (e.g., lineations and drumlins) are oriented parallel to the former ice-flow direction. In contrast, the majority of ice-marginal landforms (e.g., basement fills, moraines, grounding-zone wedges, etc.) are oriented transverse to the former ice-flow direction (Batchelor *et al.* 2018). Evaluation of previous studies can be found in Menzies and Rose (1989), Dowdeswell *et al.* (2016), Menzies *et al.* (2018), and Batchelor *et al.* (2018). The scope of this paper, however, does not make extensive use of the prior literature.

There are a few published studies in Lystad Bay and Horseshoe Island. The geology of the island is composed of granitic gneisses, gabbro, diorite, and volcanic rocks (see the third figure given by Matthews 1983). Along the northern coastal area of Lystad Bay, the crystalline basement is composed of undifferentiated volcanic rocks and coarse granite rocks. The island, characterized by uneven blocks, various debris deposits, frozen rocks, coastal sediments, and braided beds, is characterized by three key geomorphological regions (Yıldırım 2020). The northern region is mostly covered by a remnant of the nonerosive ice cap. Mount Searle, +537 m above MSL, is composed of volcanic and gabbro tuff. Numerous glacial and periglacial landforms and deposits are present in the central region. The southern region is rough and shaped by glaciers. Breaker Mountain rises to a height of approximately 879 m above MSL and is encased in glaciers. The most prevalent geological features include raised beaches, patterned terrains, moraines and talus cones. The Shoesmith Glacier, which empties mostly into Lystad Bay and partly into Gaul Cove, is located in the middle of Horseshoe Island. The true age of deglaciation on the island is proposed to be 9.4±0.8 ka (Ciner *et al.* 2019).

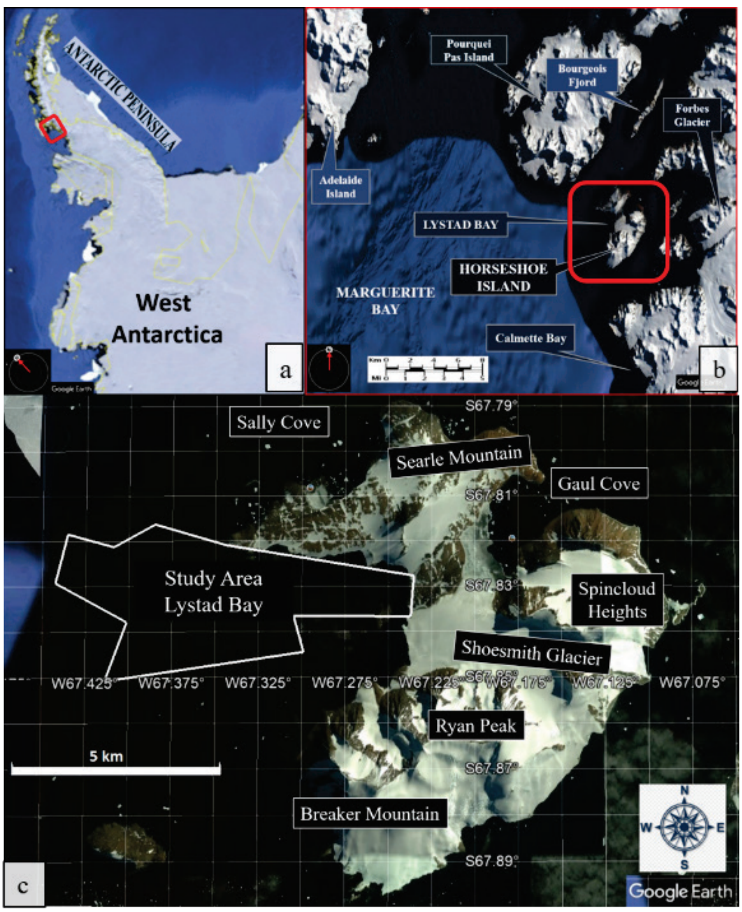

Figure 1. Location map of Lystad Bay and Horseshoe Island (Google Earth)

Data collection and processing
The R2SONIC 2022 model multibeam sonar device, owned by the Turkish Naval Forces Command, Office of Navigation, Hydrography and Oceanography (ONHO), was used to collect high-resolution bathymetry data (R2Sonic LLC 2017). The transducer bandwidth we used was in the range of 170–450 kHz. The beam width is 0.3°x0.6°, and swaths ranging from 10° to 160° depending on the water depth can be selected.

According to the manufacturer, the greatest vertical uncertainties at the 95% confidence level, depending on seabed suitability, range between 0.8 and 2.5 m at a 100 m water depth. The depth of the transducer was adjusted according to the water depth, seafloor slope and ambient noise conditions in the water. The sound speeds were measured via Valeport mini SVP and AML Minos CTD in and around Lystad Bay as 1446–1448 m/s at the sea surface, 1446 m/s at -30 m and 1445 m/s at -50 m. For data collection, the Hysweep collection module of Hypack software was used. Patch tests (roll, pitch and yaw) were applied for calibration. Antarctica rarely experiences longer periods of sea level changes, e.g., storm surges, because of its limited open water, which is primarily encircled by sea ice and glaciers, and its unique wind patterns, which blow offshore. We collected data only when the Beaufort Sea state was less than 3 and used active heave compensation to reduce the influence of waves on depth measurements. Since the operating speed is kept constant at a certain level, there was no need to apply latency correction. Trimble brand primary and secondary GPSs of the multibeam sonar system were used. To improve the accuracy of the positioning data, setting a real-time kinematic system up was not possible because of the geographic conditions and limited expedition time.

For tide, sound speed and transducer corrections, HYPACK's data processing module (MBMAX64) was employed. Hourly tide estimates for Rothera, Adelaide Island, 46 km from Lysad Bay and both locations share the same time zone (UTC -3.00) were applied to compensate for tidal changes, which changed between 0.72 and 1.55 m during the survey. The sound speed corrections were applied according to the measured SVP data. The draft of the transducer was -64 cm and was held constant during all the measurements.

Moreover, the CARIS HIPS&SIPS data processing program was used for the remaining processing phases, such as muting undesirable data and cleaning noise. Every step of the data processing procedure was completed one at a time, line by line, to monitor line intersections. False reflections due to bad weather conditions, steeply sloping seafloor (see the region entitled "muted data" in Figure 2), and ship turns at the ends of the lines were eliminated from the data. To prevent misinterpretation, filter functions have been utilized extensively.

During the studies, as supplementary data, some meteorological (e.g. cloudiness, temperature, wind speed and direction) and oceanographic parameters (e.g. CTD data, water visibility and color) were also measured in and outside Lystad Bay. Water visibility measurements inside (4.5–7.5 m) and outside (3.5–7.5 m) the bay were not particularly helpful since they are closely related to cloudiness. The water color in the bay, however, was green, coded 11-13 on the Forel scale, whereas it was bluish green (code 7-9) outside the bay. Salinity measurements are absolutely crucial in tracking glacial melting and ocean circulation, assessing the stability of ice shelves and understand the potential impacts on marine ecosystems. The oceanographic measurement periods, however, were not long enough due to the adverse environmental conditions and limited working time. Furthermore, no current measurements were taken in Lystad Bay.

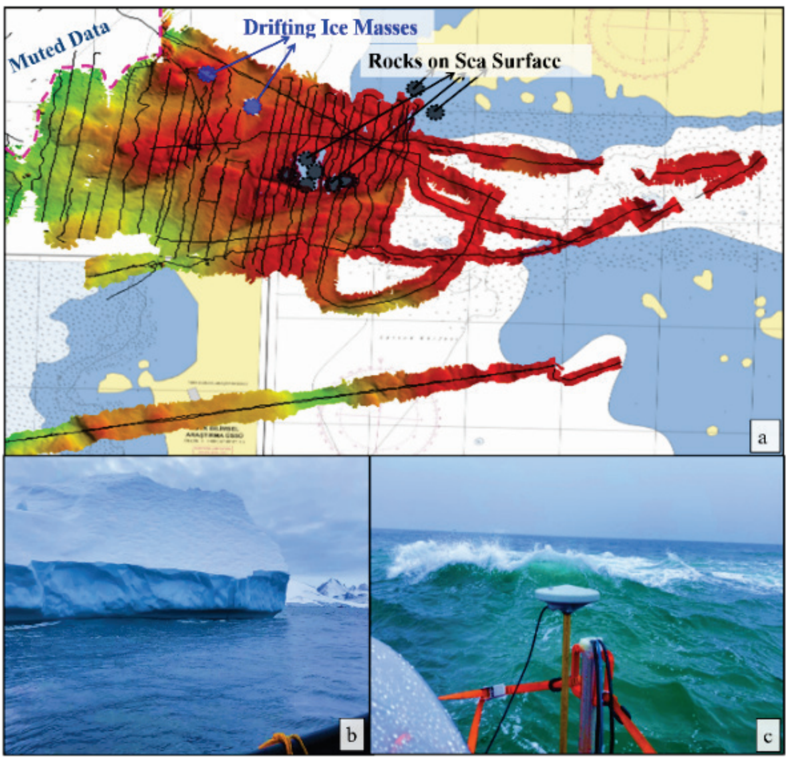

Figure 2. (a) Swath-bathymetric image and survey lines overlaid on the ONHO 2019 chart. Some examples of (b) drifting ice floes (blue dots in Figure a) and (c) rocky ridges barely projecting above the sea surface and are dangerous to shipping (black dots in Figure a).

Hydrographic data were gathered in accordance with IHO C-13 (2011) and S-44 (2022) guidelines. Meteorological measurements were collected in accordance with WMO-8 (2023). Oceanographic data were collected, controlled and interpreted according to the manuals of IOC-UNESCO (1965, 1993 and 2006).

Results

The study area varies in length from 3600 to 5400 m and in breadth from 2100 to 3200 m in Lystad Bay. In a narrow longitudinal region located to the south, additional measurements were also taken (Figure 2). In the research area's western and northwestern borders (top left corner in Figure 2), the water depth increases rapidly. The recordings in those regions remained noisy despite our attempt to take measurements several times and attempt to minimize acoustic losses by using the lowest operational frequencies. Consequently, possible weak bottom signals, which remained below the ambient noise level in those areas, were muted.

Traditional single-beam charts can be inaccurate because of slope and uneven terrain, and they may fail to reflect true depths adequately. Some depth differences were observed between the high-resolution swath-bathymetric soundings and the available classical charts (1:150,000 BA2974; 1:50,000 BA3213) of the United Kingdom Hydrographic Office (UKHO). The soundings in our high-resolution swath data, for example, vary between 25 and 65 m at a shoal marked as 13.1 m on the UKHO charts (Figure 3).

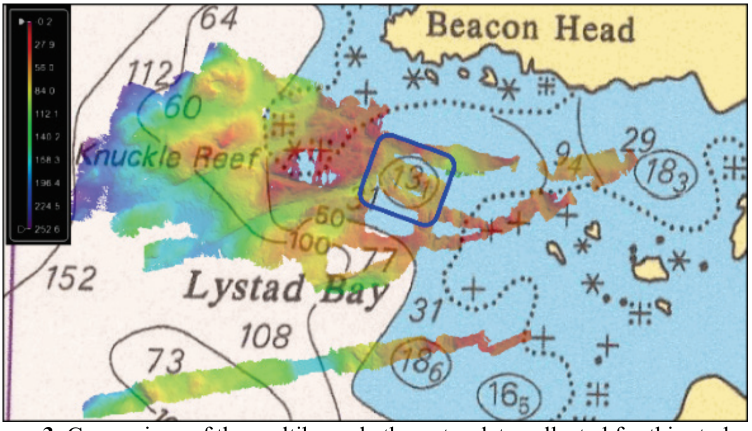

Figure 3. Comparison of the multibeam bathymetry data collected for this study and drawn with 45% transparency to the previously available UKHO chart

For data processing, we used the same steps and parameters applied for the 2019 ONHO data (Figure 4a). Both datasets are compatible with each other (Figure 4a, b) and are directly merged (Figure 5). In general, the seabed morphology seems to be compatible with the land topography, except for some rugged and sharp-looking landforms lying along the littoral zone. A few dominant landforms can be observed on the seafloor, which may be composed of crystalline, metamorphic, and volcanic rocks from the low-lying rocky subdued terrain of the northern margin of Horseshoe Island. These are elongated-streamline glacial landforms, such as semiparallel and cutting channels, and other irregular glacial landforms, such as drumlins (Figure 6).

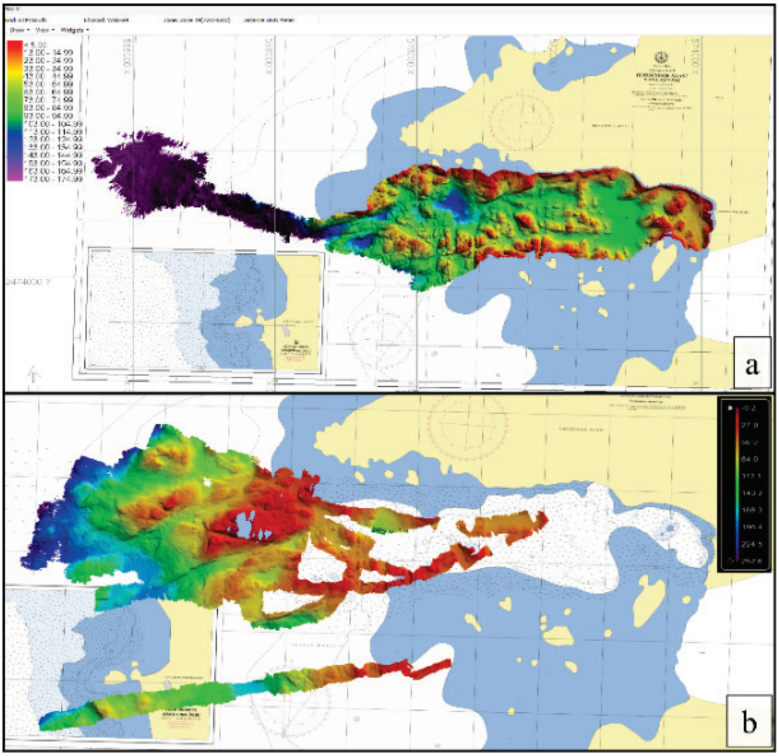

Figure 4. (a) ONHO 2019 data (see Figure 8 in Tükenmez *et al.* 2022),
(b) Swath bathymetric data collected in 2020

The landforms formed by subglacial processes at the ice/bed interface are often streamlined and elongated. The long axes in formations caused by both sedimentation and bedrock erosion are often in the direction of previous ice flows (Dowdeswell *et al.* 2016).

The most distinctive geomorphic features on the seafloor are three channel structures that run N60° and are nearly parallel; two of them can be seen in Figure 7. These channel structures cut across the inner continental shelf, extending toward the deeper ocean. Glaciers eroding the shelf during past glacial periods may have had a U-shaped profile with steeper sides and a flatter bottom.

The channel on the right (Figure 7), a reverse-angle and farther-off view of the one shown in Figure 6, is located along the WSW extension of the formation boundary between two main geological units observed to the north of Lystad Bay: the coarse granite rocks (a member of the Andean Plutonic Suite) and volcanic rocks. The channel on the left (Figure 7a, b) must be cut into the coarse granite rocks under glacial conditions. Moreover, in addition to these two channels, another channel trending N60°E at the southernmost margin (Figure 4a) lies at the extension of the formation boundary between the same volcanic rocks and the Antarctic Peninsula metamorphic complex, which is composed of foliated granitic gneiss and banded gneiss (see the third figure given by Matthews 1983). As a result, the principal geomorphic components regulating the evolution of the landforms found in Lystad Bay are the elongated-streamline glacial landforms that developed on the basement and later matured into underwater channels, which were initially subglacial bed forms.

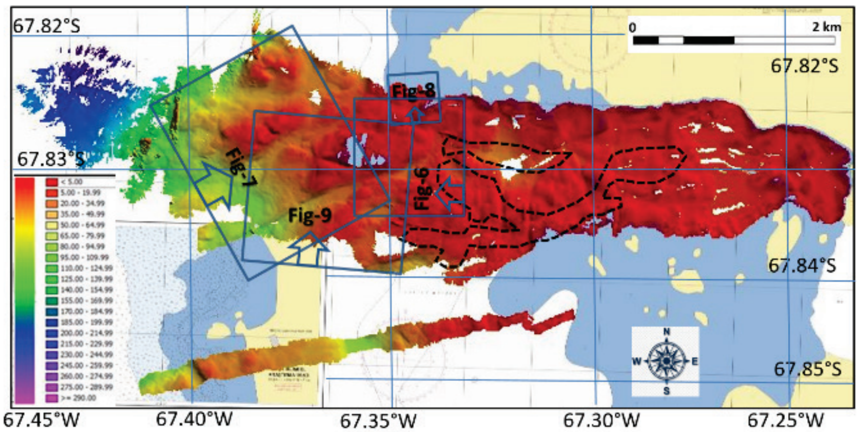

Figure 5. Composed view of swath bathymetry data collected in 2019 and 2020. The data overlaps are indicated by the black dashed line.

For a very long time, experts have been baffled by drumlins, which are irregular glacial landforms. The initial portion of the drumlin, which resembles a whale's head, is predicted to be more inclined when it is present. The drumlin's back portion has a decreasing slope that leads to its tail. Drumlin-like structures are streamlined "teardrop" or "oval" shaped mounds produced in bedrock and are typically thinned downstream. A landscape of blister-like landforms is created when ice sheets flow through a sedimentary bed. These landforms are often oriented aerodynamically in the direction of ice flow, with each ridge having a length ranging from 100 to 1000 m and a relief of approximately 100 m (Clark *et al.* 2009). Two small ridges, similar to towheads, were placed on the U-shaped base of meltwater corridors, with long axes parallel to the corridors (Figure 7b) resembling small drumlins or elongated flutes. On the other hand, the mound-shaped landform near the relatively deeper western parts of Lystad Bay is not classified as a drumlin (blue line in Figure 7b). More regional uplift on the crystalline bedrock of the Andean Plutonic Suite, which was partially fragmented due to erosive and depositional processes along the nearby corridors, may have occurred.

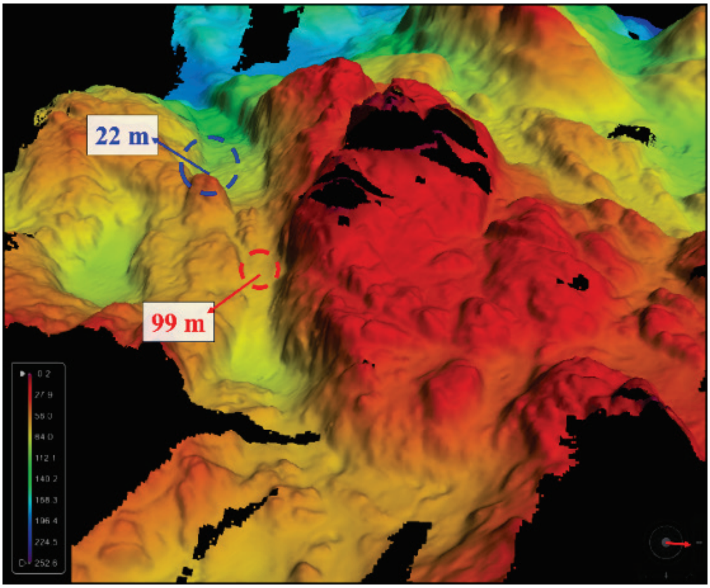

Figure 6. Close-up view of a hillock (-22 m) and a channel lying next to it (-99 m). The image is a x5 exaggeration and is shaded from the E. The red arrow shows N. See Figure 5 for the location.

Another drumlin is positioned among a few tiny mound-shaped highs, which are the secondary geomorphic features most commonly observed near the northern boundary of the study area (Figure 8). The other one is the largest (1.15 × 0.5 km) compared with the others in the study area, and its head exceeds the sea surface in the form of "rock awash", as shown in the dark zones (Figure 9). This may be one of the larger drumlins in Antarctica (see Clark *et al.* 2009) and possibly formed as a result of substantial subglacial flows. Depending on the subglacial processes that produced them, their sizes differ.

Discussion

Owing to modern geophysical techniques, the depth and glacier shelf bottom morphology can now be studied in considerably more detail compared to the period when traditional single-beam acoustical methods were used (Damuth 1978; Parnum *et al.* 2009). Using acoustic data collection and processing techniques, we created a variety of comprehensive swath-bathymetric images along the northern approaches of Lystad Bay, a medium-sized basin on the western edge of Horseshoe Island and the inner shelf area (erosional zone) of Marguerite Bay. First, the shallow marine areas we delineated at high resolution will increase researchers' freedom of movement in future investigations. Furthermore, the description of seabed structures may provide insight into future marine geological and geophysical research. The most characteristic subglacial landforms identified in Lystad Bay can be classified into three categories: a) successive depressions on bedrock (active lakes), b) elongated-streamline glacial landforms (e.g., flutes, cross-shelf troughs, grounding zone wedges) and c) glacial landforms with distinctive shapes (e.g., drumlins, hill–hole pairs, ice-molded bedrock). These structures, which are likely to be found on ice-free continental margins, can help researchers comprehend the direction and force of glacial movement and extract ancient ice flow models (Ottesen and Dowdeswell 2009).

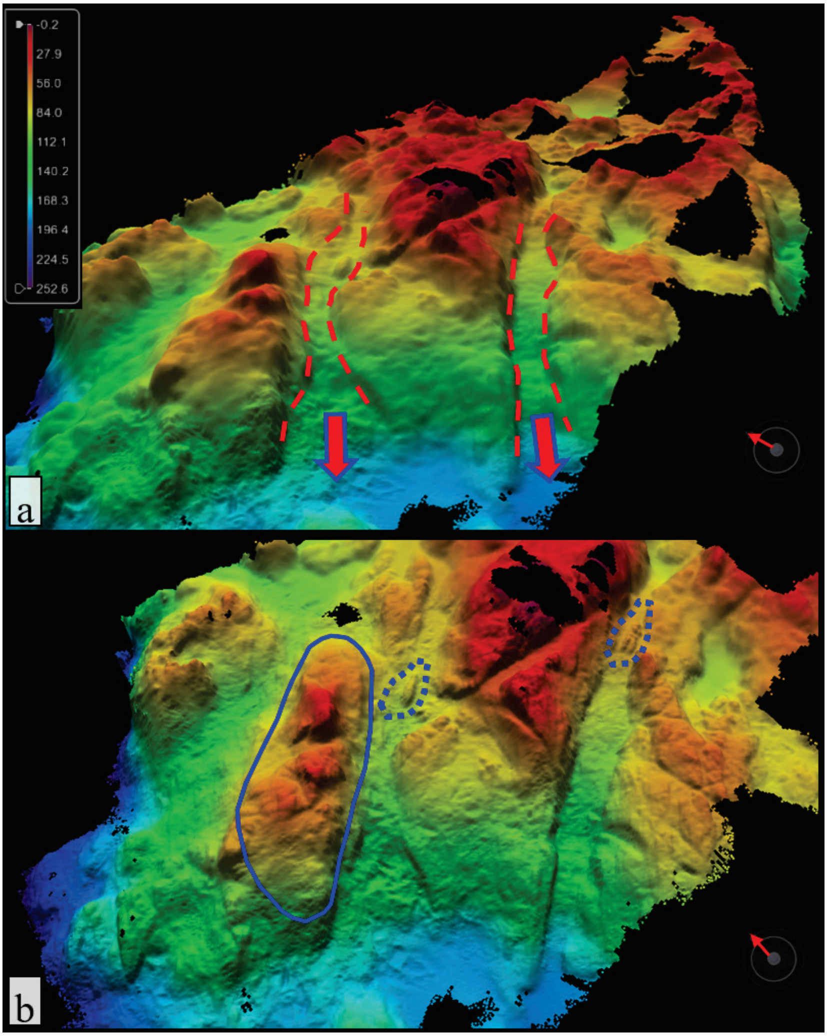

Figure 7. Swath-bathymetric image of N60°E-trending channel structures from the (a) 45° viewpoint and (b) approximate summit viewpoint. The red arrows indicate the meltwater flow direction. The channels contain two flow ridges (dashed lines) that measure approximately 105 by 40 meters. See Figure 5 for the location.

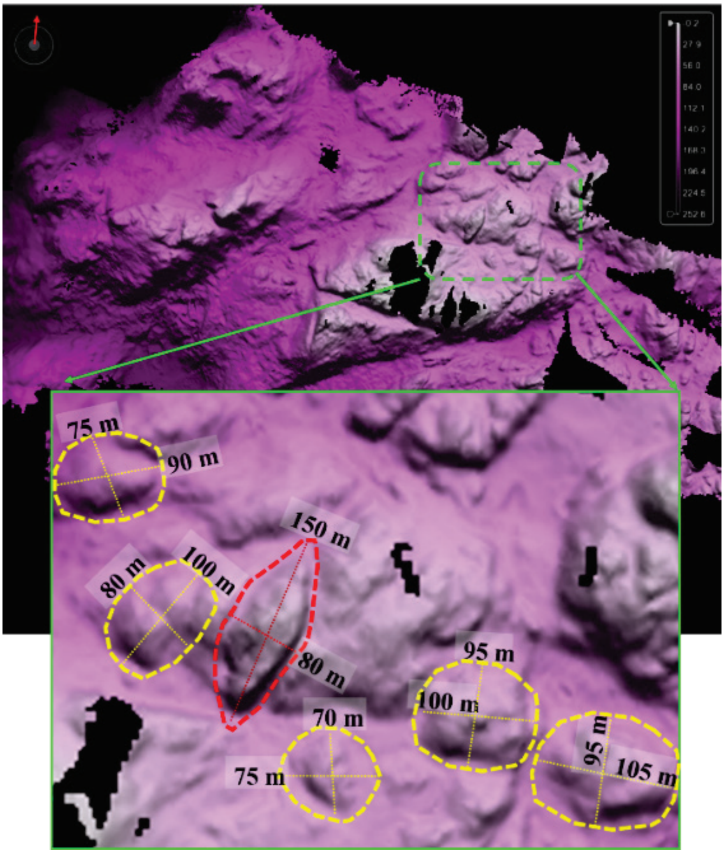

Figure 8. Dimensions of a drumlin (red dashed line) and hummock-shaped mounds (yellow dashed line) at Lystad Bay's northernmost edge. See Figure 5 for the location.

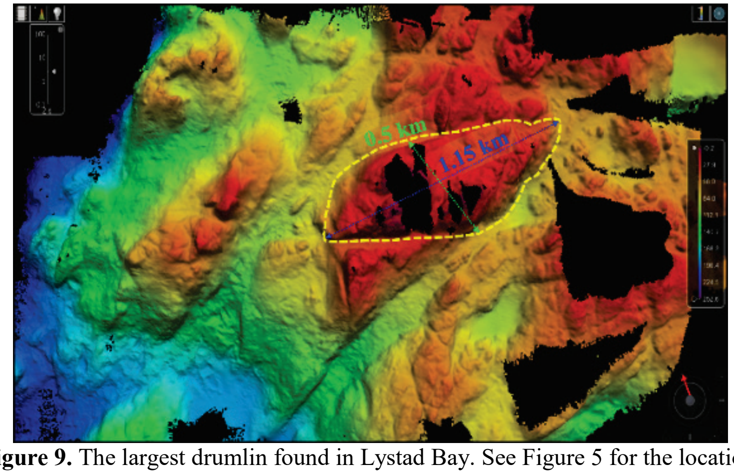

Figure 9. The largest drumlin found in Lystad Bay. See Figure 5 for the location.

A. Successive glacial depressions on bedrock
On the northern edge of Lystad Bay, few seafloor depressions are visible, extending from Horseshoe Island to the open sea (Figures 2-6). Three interpretations of their development are possible:

a. Hill–hole pairs: These pairs are common glaciotectonic landforms created by the movement of glaciers. The deeper areas may be depressions at the bottom caused by the glacier acting like an enormous bulldozer to chisel off the material that formed the higher area (a pair of hills next to it). The depressions are usually filled with sediment.

b. Relic subglacial active lakes on bedrock: The depressions on the seafloor differ in their orientations and shapes (Figure 4a). They are connected in a way that allows water to flow between them. To the south, these depressions are bounded by longitudinal, oval, and asymmetric drumlin-shaped mounds, which are cut by a large channel semiparallel to the northern depressions in question. All these formations, except the depressions to the north, are cut by some N–S extending channels, whose edges can be sharp or larger (possibly ice-marginal landforms). This seafloor morphology reveals the presence of historic glacial lakes that have formed as relict structures in the region.

Subglacial lakes are a defining feature of polar regions and are recognized as archives of past climate conditions. Glacial lakes dynamically, mechanically, and hydrologically interact with the glaciers above them, regulating ice flow, under ice hydrology, sediment transport, and geomorphological activity. The 80% of all subglacial lakes, are stable systems trapped in topographic depressions on solid ground, and they have been studied the most. Owing to their structure, these lakes are either closed systems or their inlets and outlets are approximately balanced. The inner and middle regions of the Antarctic continent have prospective hydrological zones, which are home to stable glacial lakes that have been found in the past 25 years. Other types of lakes exhibit a variety of activities and are dynamic. A portion of them take the shape of water masses that build up in crevices beneath the glacier ice. There are active lakes nearer the glacier border, where surface melting, friction, or the release of geothermal energy cause the lakes' waters to flow successively toward the sea. Drainage and storage events in active lakes are determined by mechanical and hydrological interactions with the overlying ice sheet. The drainage of active lakes on glacier margins causes local depth, whereas filling causes local elevation increases. These formations will eventually form the sea floor as glaciers recede even farther (Livingstone *et al.* 2022).

We might also identify the existence of old glacial lakes arranged in a row inside the study area from this standpoint (Figures 4 and 5). These depression areas are smaller in size than the subglacial lakes that have been reported to exist within the continent. This is explained by the ice surface being steeper as a result of global warming. Our study area is located in one of Antarctica's most sensitive regions to the effects of global warming. The flow toward the ocean between the depression areas observed in the swath-bathymetric images occurred via the meltwater corridors also observed in the images. Although active subglacial lakes in such places are shrinking in size, their activity remains high. The flow between active lakes is short-lived, but discharge drainage is significant. Swath-bathymetric images show the morphological features of active subglacial drainage and meltwater channel systems, which corroborate this interpretation. In this case, unexpected floods caused in the glacier's front section by meltwater entering the cracks in the underice shelf and passing the grounding line (GL), a dynamic hinge point, may also have been effective. As another possibility, these channels might have been formed by former catastrophic outbursts that probably predated the Pleistocene epoch, even though the actual discharge of water from subglacial lakes was rather small (Pattyn 2011).

c. Lakes developed over hill-hole pairs: The older hill-hole pairs that formed during the glacial phase could have later served as the formation site for the landforms delineated as extinct subglacial active lakes that formed during the deglaciation phase. For a better interpretation high-resolution seismic data is needed.

B. Elongated-streamline glacial landforms

The geomorphology of cross-shelf troughs provides valuable insights into past glacial activity and reflects the older influence of water drainage corridors beneath glacial ice on the glacier retreat process. An essential part of glacial systems is the hydrology of the water trapped beneath glacier ice and the meltwater drainage it produces at the ocean's bottom. Before glacier ice transitions to free floating in the ocean, the drainage made on the ground ultimately controls the stability, residence time, and flow of the glacier ice in the transition area. Controlling the movement of sediments beneath the ice and toward the glacier tip is another consequence of meltwater drainage. The subglacial meltwater corridors, which are visible as remnants on the sea floor, are the most significant pieces of evidence supporting this theory. They are 1.2–1.8 km long and 180–270 m wide. The carving depths of meltwater corridors with triangular cross-sectional geometries range from 45 to 120 m. However, they vary along the corridors due to varying bathymetry and geological formations. The subglacial meltwater corridors constitute a drainage system that is compatible with the geomorphology of Lystad Bay and may have been constructed when the ice sheets were substantially thicker.

The meltwater corridors in the study area are a collection of several drainage methods over wide, permanent routes in the paleo-subglacial environment. They are thought to be subglacial landforms connected with erosional and depositional glacial activity following the last glacial maximum (LGM). The ENE-WSW oriented meltwater corridor is wider than the corridor that cuts it obliquely, implying that it contains more sedimentary material. Except for a small-scale hill (or drumlin) observed at the intersection of two meltwater corridors, these channels lack a subaerial braided structure. This may imply that the study area is not mature enough to ensure the formation of such a braided pattern. Similarly, the sea floor of Lystad Bay must have remained permanently under the sea after the glacier retreated (possibly 9000 y BP). Since then, subglacial meltwater landforms have played a significant role in the movement of water masses and sediment on the continental shelf, influencing ocean circulation and marine ecosystems.

When explaining corridor structures in swath-bathymetric pictures, the retreat events of grounding line (GL), the point where a glacier transitions from being grounded on bedrock to floating on water as an ice shelf, must also be considered. Its consequences can be more significant than those of meltwater processes. However, these events should not be examined independently of the canalized drainage and storage processes that rely on them. The distance to the GL is the most important component in determining surface shape. The further away from the GL, the more the morphology will mature.

The distinctive morphological properties of glacial movements in their GLs can take the form of scraping or filling deposits. Glacial expansion also has the potential to crush, abrade, and scour surfaces. This results in a variety of erosional landforms, including the steady formation of GL landforms and valleys. They are under the control of the material coming to the environment in different ways around the GLs, of relatively warm ocean waters and of the effects of turbulence and tides. It is important to understand these processes and the behavior of glaciers on seabeds, both individually and in general, depending on different environmental conditions (e.g., ocean, bathymetry, and iceshelf structuring features). The resulting seafloor structures are named according to their location and formation (Merta 1989). It would not be incorrect to conclude that the subglacial formations shown in swath-bathymetric images are parallel to the general direction of historic ice flow in the region. Given its size, the Lystad basin has the potential to direct ice movement throughout the region. In other words, glacier movements and behaviors that leave imprints on Lystad Bay's crystalline and volcanic bedrock must be consistent with the region's existing regime regulations.

C. Glacial landforms with distinctive shapes

Apart from elongated-streamline glacial landforms produced at the ice–bed interface, some other landforms have distinctive shapes, differentiating their upflow/glacier (stoss) and downflow/glacier (lee) sides. Their origin is mostly attributed to subglacial hydrology, subglacial bed topography and sediment composition (deformation of erosive materials), and glacier movement (dragging and shovelling). Sediment erosion and deposition create elongated landforms with steeper stoss sides and gentler lee sides, sculpting some unique shapes such as drumlins under the great strain of ice. Additionally, subglacial meltwater may have an impact on the movement and deposition of sediment, which may aid in the development of drumlins with unique shapes (Menzies *et al.* 2018). Similarly, recognizable shapes can be seen spreading alone or in small groups on the swath-bathymetric images (Figures 7-9). These hills and drumlins vary in breadth and length from 80 to 500 meters and 180 to 1500 meters, respectively. The diameters of the hills that are more circular in shape range from 75 to 100 m (Figure 7). Drumlins are distinguished by their asymmetrical and curved features within complex subglacial environments, which results in higher-amplitude sonar reflections. The ENE-WSW spreading hills are asymmetrical and are divided by the subglacial meltwater corridors mentioned above (Figure 7). In conclusion, the drumlins in Lystad Bay are placed individually rather than in a specific order. The studied area lacked drumlin swarms or same-directional clusters; this could be attributed to slower and less powerful glacier activities because of the semiclosed nature of Lystad Bay.

The lack of core samples prevents additional and thorough feedback on sediment transportation, its primary means (bottom or suspension), and historical glacial and interglacial climates. The inflow of terrigenous sediment is regulated by changes in the glacial and interglacial climates. During glacial periods, massive amounts of terrigenous material are transported to and deposited in basins. Conversely, during interglacial periods, the absence of continental glaciers and sea ice, combined with high sea levels that submerge the continental shelf, greatly reduces the amount of terrigenous material that reaches deeper basins. There are no discernible patterns of sedimentary deposition in swath-bathymetric maps, with the exception of depression areas (active lakes), implying that fine-grained material in the basin may have been carried in suspension. In fact, our water color measurements, while limited in temporal and spatial scope, support the idea that dissolved material and sediment transfer in water were significant over Lystad Bay. The apparent hue of water is easy to identify and offers information about the water components that contribute to that color (Garaba *et al.* 2015).

From a geological and geophysical perspective, assessing the types of silt, debris, and true seafloor deposits with swath-bathymetric data alone is challenging in the absence of bottom samples. Understanding the thickness distribution of recent seabed sediments is also essential, especially with respect to which side thick deposit hills are found and in which direction the sediments thicken. We can use this knowledge to ascertain the direction of meltwater flow (as well as the retreat of the GL). With seismic reflection data, however, it could have been determined whether these silt accumulations were built-up or construction-related grounding zone wedges caused by the GL push. Internal seismic reflections could easily indicate the forward spread of sediments derived from the subglacial environment. As the GL is a sedimentary environment, the structures formed there reflect the elements of the processes governing such a dynamic environment. Here, the decisive internal reflections are the downlap reflections on the superimposed subunit and the dipping foreset reflections in the forward direction. Apart from determining the drumlin's progression direction, two other features that help describe the extent of glacier deformation are whether the drumlins are stacked deltas and whether they crossover the component they overlie without causing damage or disturbance.

The uneven and incoherent structures perceived as drumlins differ significantly from the appearance of a moraine field, which forms under recessionary conditions and appears consistently on swath-bathymetric images. As a result, the structures delineated in the swath maps, mostly the subglacial channels and drumlins, have to be representative of an environment where glacial retreat is regularly forced. This suggests that the last glacial retreat is most likely to have occurred in the N60° direction, which is currently occupied by the Shoesmith Glacier on Horseshoe Island. Currently, mountains rising to a height of 500 m encircle the Shoesmith Glacier, which stretches in a 1500 m wide channel. High-resolution seismic reflection records are critical for evaluating the age connections between meltwater corridors.

Other well-known glacial landforms in this category, such as fluted moraines, slope fans, and debris flow patterns, were not visible in our swath bathymetric images. In addition to the isolated elongated flutes we interpreted in this paper, fluted moraines represent a larger-scale wavy-surface landscape feature. They have a low profile and are mostly buried under the ice sheet in Antarctica. Slope fans and debris flows are fan-shaped structures that typically form in front of shelf breaks.

D. Glacial landforms somewhat perpendicular to the main ice flow direction
Some ice-marginal landforms that run somewhat perpendicular to the direction of the former glacial flow were observed in the form of mostly eroded grooves and partly elongated ridges or hillocks (moraines or periglacial features) in our images (Figures 4 and 5). This type of landform occurs during general ice-sheet retreat or grounding zone wedges that occur by temporary forward moves after a period of retreat. The infill material, possibly diamictons, may have been eroded from the valley walls and collected as a result of drift and violent movements caused by abrasion processes when the Shoesmith Glacier ice sheet receded. Crevasses can also leave behind similar but small-scale linear depressions in the landscape. Therefore, these randomly stacked deposits are estimated to have experienced only chaotic reflections in the seismic records.

Conclusion

In uncharted parts of the Earth, very few precise bathymetry measurements have been obtained via swath-bathymetric imaging technologies. In this study, the first high-resolution swath-bathymetry measurement in Lystad Bay was obtained. These findings are extremely important for navigational safety in the region and for forthcoming scientific research. For the latter, it should be noted that Lystad Bay is sufficiently shallow to permit ice to remain in contact with the sea bed, possibly until approximately 9000 years BP, meaning that it remained subglacial.

Owing to subsequent global sea level rise, the dynamic environment beneath a glacier drastically changes into a proglacial subaqueous proximal environment once the ice starts to rise from its bed. Lystad Bay subsequently functioned as a proglacial subaqueous proximate environment for a limited period of time. The seafloor landforms scattered throughout the bay show that the ecosystem is dynamic and is influenced mostly by meltwater and sediment transport as well as by physical and chemical oceanographic conditions. However, subglacial landforms and sediments must be assessed not only in terms of area, as we did in this research but also in terms of their third dimension. Therefore, it is highly recommended that high-resolution shallow seismic studies (parametric or chirp subbottom profilers) be carried out in the area in question.

In addition, side-scan sonar (SSS) studies and underwater photography and videography may be helpful in identifying natural features and variations in seabed composition. Considering this perspective, in February 2024, new SSS measurements and video ground-trothing were carried out to determine nearshore interactions along the Lystad Basin (Vardar *et al.* 2024). The southward-flowing meltwater currents reported by researchers at depths of less than 10 m can readily increase turbidity beyond its other sedimentological and biological consequences, which supports the partial decrease in water visibility we observed in Lystad Bay. Unfortunately, the technical characteristics of their system precluded SSS measurements in deeper waters.

Finally, seafloor core samples can provide a plethora of information about potential hazards, compositions, ages, depositional histories, and reconstructions of former environments and habitats.

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Lystad Körfezi tabanı buzul morfolojisi, Horseshoe Adası, Antarktika

Öz

Lystad Körfezi'nde (Horseshoe Adası, Antarktika) çok bimli sonar yöntemiyle derinlik tarama verileri toplanmıştır. İşlenerek oluşturulan 3B yüksek çözünürlüklü verilerden denizcilere tehlike yaratacak önemli sığlıklar belirlenmiştir. Buzul marjinal deniz alanındaki kristalin/volkanik ana kaya üzerinde birbirini takip eden çöküntüler (aktif göller), uzunlamasına-aerodinamik buzul şekilleri ve farklı şekillere sahip buzul şekilleri belirlenmiş ve yorumlanmıştır. Kısıtlı oşinografik veriler çökel birikiminde askıda malzeme taşınmasının da etkili olabileceğini destekler yöndedir. Gelecekte yapılması umulan jeolojik ve jeofizik çalışmalar için öneriler getirilmiştir.

Anahtar kelimeler: Hidrografi, çok ışınlı iskandil, deniz tabanı morfolojisi, buzul tepeleri, eriyik su kanalları

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