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ORIGINAL RESEARCH PAPER

Seafloor deposits and deformations in shallow marine areas of a paleo-glacial area revealed by side-scan sonar data: a case study from Horseshoe Island, Western Antarctica

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Abstract

Advances in marine geophysical imaging, including high-resolution side-scan sonar and multibeam bathymetry integrated with ground-truthing methods (e.g., sediment sampling and underwater video observations), have substantially enhanced our ability to map submerged glacial landforms and reconstruct past ice-sheet dynamics. These techniques provide critical insights into ice-flow patterns, subglacial erosion, and sediment deposition—key processes for understanding both paleo-glaciation and the response of modern ice sheets to climate change. Despite these advances, nearshore environments, which preserve key evidence of past ice-sheet and ice-marginal processes, remain understudied in many regions of Antarctica. To address this gap, we present the first high-resolution geophysical and ground-truthing dataset from the western coast of Horseshoe Island (Western Antarctic Peninsula). This dataset integrates side-scan sonar imagery with underwater video observations to map nearshore erosional and depositional landforms at unprecedented resolution. The identified landforms provide new insights into past ice-flow dynamics and subglacial processes, thereby helping to constrain ice-sheet reconstructions and improve predictions of future change. Distinct morphological boundaries and erosion patterns indicate that meltwater streams have significantly influenced the seafloor, particularly at depths greater than 10 m, reflecting glacial–marine and ice-marginal environmental conditions in the recent past. Within a limited area, geophysical evidence reveals subglacially formed seafloor features, including remnants of a paleo-lake and its associated paleoshoreline, pointing to former subglacial hydrological activity. The orientation of meltwater channels and streamlined glacial landforms indicates a dominant southward paleo–ice flow. This interpretation is supported by greater seafloor incision and deeper bathymetry in the southern sector of the island compared to its western margin. Collectively, these observations advance reconstructions of ice-sheet dynamics by elucidating the role of subglacial and ice-marginal processes in shaping nearshore submarine geomorphology. The integration of high-resolution marine geophysical data with ground-truthing observations provides critical empirical constraints for numerical ice-sheet models and contributes to refining projections of Antarctica's future contribution to global sea-level rise.

Keywords Western Antarctica · Ice movements · Seafloor characterization · Glacial morphology · Nearshore dynamics

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Introduction

During the Quaternary, the geomorphology of terrestrial and marine environments at mid- to high latitudes has been strongly influenced by the advance and retreat of ice sheets during repeated glacial–interglacial cycles, particularly during stadial periods (Svendsen et al. 1999; Dyke et al. 2002). These oscillations resulted in the formation of a wide range of subglacial, ice-marginal, and glacimarine landforms. While glacial records on land are often modified or removed by subsequent erosion, weathering, and

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human activity, submarine glacial landforms can in many cases remain well preserved on continental shelves, slopes, and basin floors, although their preservation may be locally modified by post-glacial marine processes, particularly in dynamic nearshore environments (Solheim 1991; Shipp et al. 1999; Dowdeswell et al. 2002; Ottesen et al. 2005; Larter et al. 2012).

The growing body of research on submarine glacial geomorphology has been facilitated by advances in marine geophysical imaging techniques. Early studies relied primarily on single-beam echosounders to document large-scale seafloor morphology (Damuth 1978). Subsequent developments in side-scan sonar (SSS), multibeam echosounders, and shallow seismic reflection systems have enabled detailed mapping of seafloor textures, landforms, and sedimentary structures, as well as the identification of buried glacial features (Dowdeswell et al. 2006). These techniques have significantly improved reconstructions of past ice-sheet behavior, including ice-flow directions, grounding-line positions, and sediment transport pathways.

Side-scan sonar (SSS) is a particularly effective tool for high-resolution imaging of seafloor morphology and surficial sediment variability over large areas. Variations in acoustic backscatter intensity reflect differences in sediment grain size, roughness, and substrate composition, allowing for qualitative classification of seafloor sediment types and geomorphic features (Richardson et al. 2001; Briggs et al. 2001; Goff et al. 2004; Ferrini and Flood 2006; Buscombe 2017). Although backscatter strength is influenced by multiple factors—such as incidence angle, seabed roughness, and acoustic impedance contrasts—systematic patterns in acoustic response provide valuable insights into sedimentary processes when supported by ground-truth observations (Hamilton 1980; Jackson et al. 1986; Jackson and Briggs 1992).

Despite extensive research on deep-water and shelf-scale glacial geomorphology, shallow nearshore marine environments remain comparatively understudied, particularly in Antarctica. These settings are highly dynamic, influenced by iceberg scouring, meltwater discharge, tides, waves, and coastal currents, which can obscure or modify glacial landform preservation. As a result, the sedimentary and geomorphic signatures of ice–ocean interaction in nearshore zones are often poorly constrained, even though these areas are highly sensitive to environmental change and play a critical role in linking terrestrial glacial processes with marine sedimentation. This study presents the first high-resolution investigation of seafloor morphology and sediment distribution in the nearshore zone (0–50 m water depth) along the western coast of Horseshoe Island, located in Marguerite Bay, Western Antarctic Peninsula (Fig. 1). By integrating side-scan sonar imagery with underwater video observations, this work aims to (i) characterize surficial seafloor sediments based on acoustic backscatter patterns, (ii) identify erosional and depositional landforms related to glacial, subglacial meltwater, and post-glacial processes, and (iii) infer dominant paleo–ice-flow and sediment-transport directions in a shallow marine, glacier-influenced setting. The results provide new insights into nearshore glacial geomorphology and offer a spatial framework for interpreting ice-marginal dynamics in coastal Antarctic environments.

Study area

The study area is located offshore of the western coast of Horseshoe Island, within the Marguerite Bay archipelago in the south-central sector of the Antarctic Peninsula (Fig. 1a–b). Marguerite Bay represents a key glaciated embayment of the Western Antarctic Peninsula, where ice-sheet advance and retreat during the Late Quaternary have strongly shaped both terrestrial and submarine landscapes. During the Last Glacial Maximum (LGM; ~ 20 ka), grounded ice extended from the Antarctic Peninsula mainland across Marguerite Bay to the continental shelf break (Bentley et al. 2011).

Deglaciation of the region occurred in multiple stages, as constrained by radiocarbon dating and marine geophysical evidence (Ó Cofaigh et al. 2008). Two major phases of ice retreat have been identified: an initial retreat shortly after ~ 14.2 ka, followed by a second phase after ~ 10.6 ka. These episodes resulted in progressive ungrounding of the ice sheet from the outer shelf toward the inner bay. By approximately 9.5 ka, the inner regions of Marguerite Bay, including the Horseshoe Island area, were largely ice-free, coinciding with post-glacial marine transgression (Çiner et al. 2019).

Lystad Bay, located immediately offshore of the western margin of Horseshoe Island, constitutes the primary focus of this study. The bay was initially charted in 1960 using single-beam echosounder data acquired by the Royal Navy, and no comprehensive high-resolution surveys were conducted for several decades. More recently, multibeam echosounder surveys carried out during the Turkish Antarctic Expedition III have provided improved bathymetric coverage of the bay (Tükenmez et al. 2022). Comparison of these modern datasets with British Admiralty nautical charts (BA2974 and BA3213) reveals notable discrepancies in water depths and coastline geometry, highlighting the need for updated, high-resolution seafloor mapping and geomorphological interpretation in the area.

The nearshore zone investigated in this study extends from the coastline to approximately 50 m water depth and encompasses a range of geomorphic settings, including shallow rocky substrates, sediment-covered basins, and steep bathymetric gradients toward the southern offshore

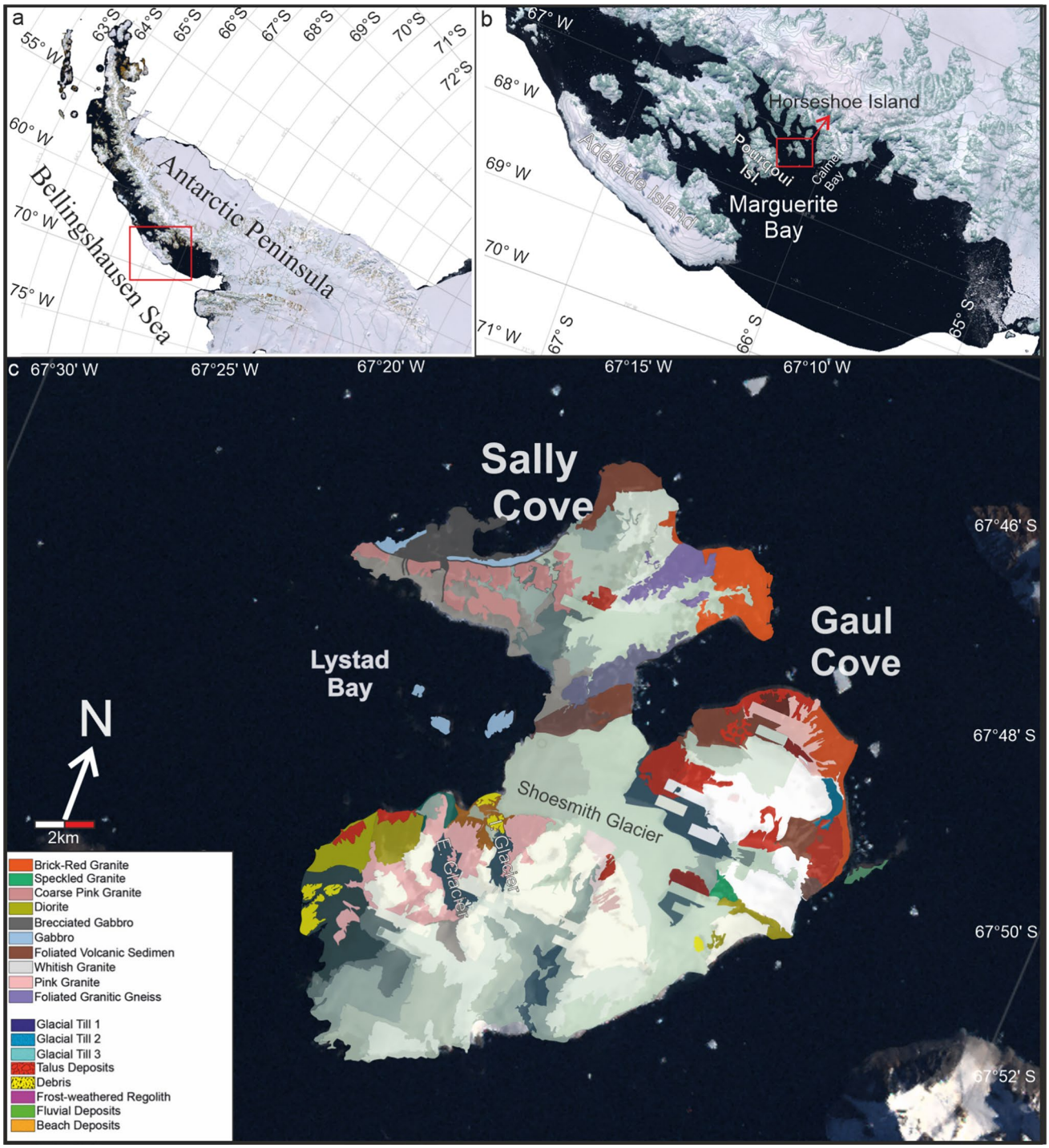


Fig. 1 Location and geological context of the study area. (**a**) Location of the study area within West Antarctica. (**b**) Regional map showing Marguerite Bay and the location of Horseshoe Island. (**c**) Geological and geomorphological map of Horseshoe Island and its surroundings (after Matthews 1983; Yıldırım, 2020; abbreviations: E = Erinç, I = İzbirak). Boxes shown in panels (**a**) and (**b**) indicate the regions enlarged and presented in panels (**b**) and (**c**), respectively

sector. These shallow marine environments are directly influenced by local glacial systems, seasonal meltwater discharge, iceberg activity, and coastal hydrodynamics. As such, they represent a transitional zone where subglacial, ice-marginal, and post-glacial marine processes interact and leave distinctive imprints on seafloor morphology and sediment distribution.

By focusing on this poorly documented nearshore environment, the present study provides essential context for interpreting the spatial variability of seafloor deposits and deformation features around Horseshoe Island and contributes to a more comprehensive understanding of Late Quaternary glacial dynamics in Marguerite Bay.

Onshore geology and morphology

Horseshoe Island is the third largest island within the Marguerite Bay archipelago (Fig. 1b), covering an area of approximately 60 km^2. Nearly 66% of the island is presently covered by glaciers or semi-perennial snow and ice, reflecting the continued influence of glacial and periglacial processes on its landscape. The island is characterized by two prominent topographic highs: Mount Breaker (879 m above sea level) and Mount Searle (537 m above sea level). A glacier-free saddle at approximately 80 m above sea level separates the northern and southern sectors of the island and hosts a gently sloping plateau measuring roughly 500 × 750 m. This plateau contains five freshwater lakes, which are interpreted to reflect recent periglacial activity and seasonal meltwater accumulation.

The southern part of Horseshoe Island is dominated by three major outlet glaciers—Shoesmith, Erinç, and İzbirak—which drain ice from the interior toward the surrounding marine environment. These glaciers play a key role in delivering meltwater and sediment to the nearshore zone and are therefore directly linked to the submarine depositional and erosional features investigated in this study.

The bedrock geology of Horseshoe Island is predominantly igneous in composition. Mafic lithologies include gabbros and undifferentiated volcanic rocks, while felsic intrusive units comprise granites of varying color (white, pink, brick-red, and mottled varieties) as well as diorite (Matthews 1983; Yıldırım, 2020). These lithologies are crosscut by dense swarms of basaltic dykes, which form linear, erosion-resistant ridges. The orientation and resistance of these dyke systems exert a strong structural control on surface drainage patterns, slope development, and localized glacial erosion.

Quaternary deposits mapped across the island record a complex history of glacial advance, retreat, and post-glacial modification. These deposits include frost-shattered bedrock, regolith, till preserved within morainal ridges, erratic boulders, debris-covered ice, talus accumulations, and both active and relict fluvial sediments (Yıldırım, 2020). Many of these features reflect deposition during periods of ice-sheet occupation, followed by reworking by periglacial weathering and meltwater processes during deglaciation.

Despite the relatively detailed understanding of onshore geology and geomorphology, the nearshore and submarine extensions of these glacial systems around Horseshoe Island remain poorly documented. The continuity between terrestrial glacial landforms and their submerged counterparts is largely unresolved. By integrating onshore geological context with high-resolution marine geophysical observations, this study aims to bridge this gap and provide a coherent interpretation of how bedrock structure, glacial dynamics, and sediment supply from land influence seafloor morphology and sedimentation in the adjacent shallow marine environment.

Material and method

Side-scan sonar data acquisition

Side-scan sonar (SSS) data were collected in February 2024 using a DeepVision DE3468D Dual CHIRP Digital SSS system operating at 340 and 680 kHz. To ensure optimal imaging of seafloor morphology and surficial sedimentary features, a frequency of 340 kHz was selected for the survey, balancing spatial resolution and signal penetration in shallow marine environments. At this frequency, the acoustic wavelength is approximately 4 mm, yielding a theoretical along-track resolution of ~ 1.5 cm based on a horizontal beam width of 0.9°.

The sonar system was towed from a 3 m inflatable Zodiac vessel at an average speed of 1–1.5 knots. Survey lines were planned to maximize seafloor coverage while accounting for coastal morphology and operational constraints imposed by sea ice. The maximum swath range was set to 150 m per side, resulting in a total swath width of up to 300 m under favorable conditions. In total, approximately 80 km of SSS profiles (Fig. 2) were acquired, covering an area of ~ 16 km^2 within Lystad Bay and extending toward the southwestern sector of Horseshoe Island (Fig. 2). Environmental conditions during data acquisition included air temperatures of approximately − 4 °C, seawater temperatures near − 1 °C, and average wave heights of ~ 0.5 m.

Data processing and acoustic mosaic generation

SSS data processing was conducted in three main stages using SonarWiz software (Pratomo et al. 2018). First, raw sonar files were converted into the XTF format to ensure compatibility with processing and visualization tools. During the main processing stage, radiometric calibration was applied to normalize signal amplitudes and reduce system-related and geometric variations in backscatter intensity. Subsequently, individual sonar swaths were merged to generate georeferenced acoustic mosaics, allowing continuous visualization of seafloor textures across the survey area.

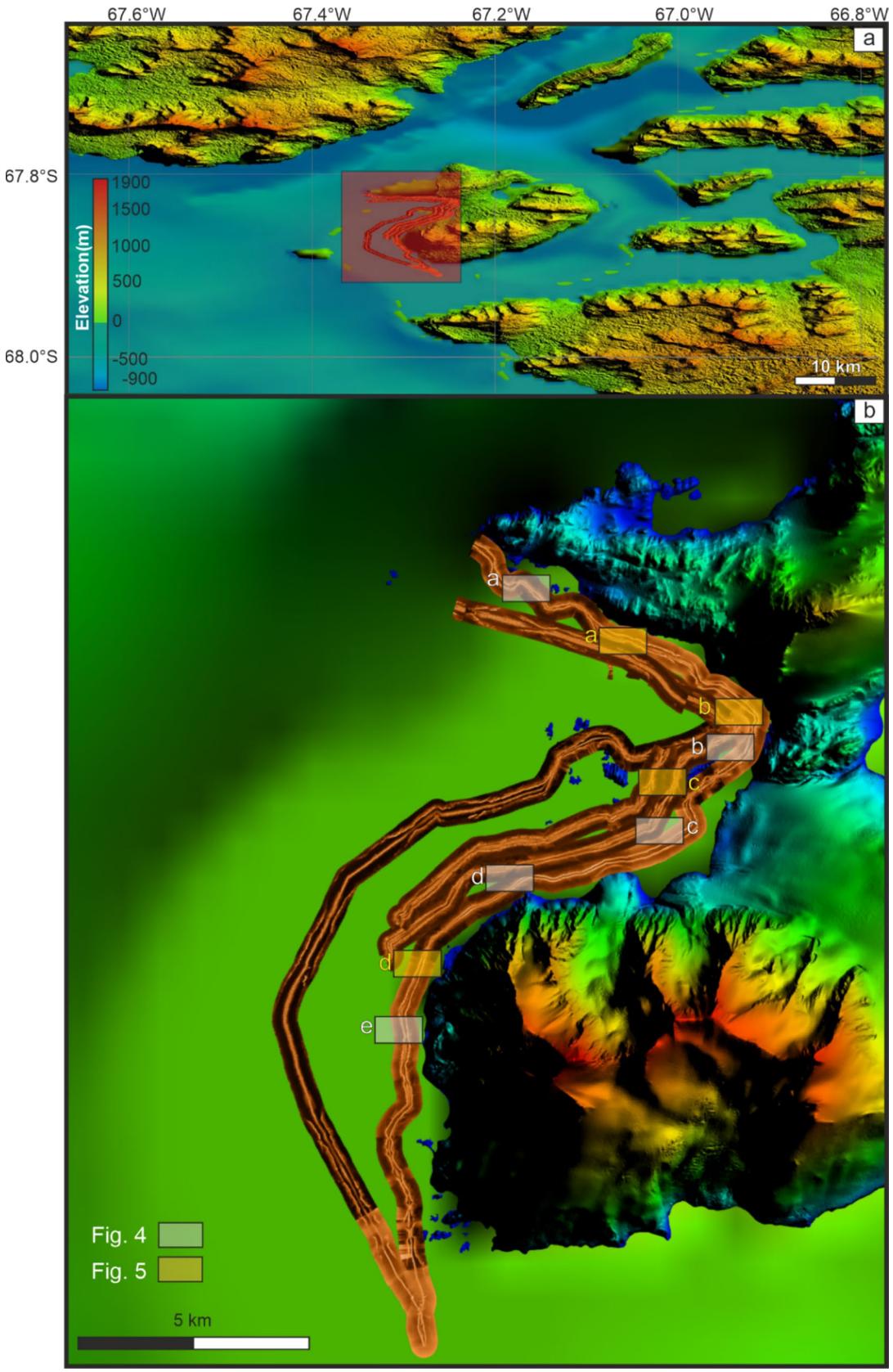


Fig. 2 (**a**) Side-scan sonar survey track lines acquired in the study area. Topographic data are derived from ASTER GDEM v2, and bathymetric data are from the ETOPO1 global relief model. (**b**) Enlarged view of the red boxed area showing the locations of representative sonogram examples presented in Figs. 4 and 5

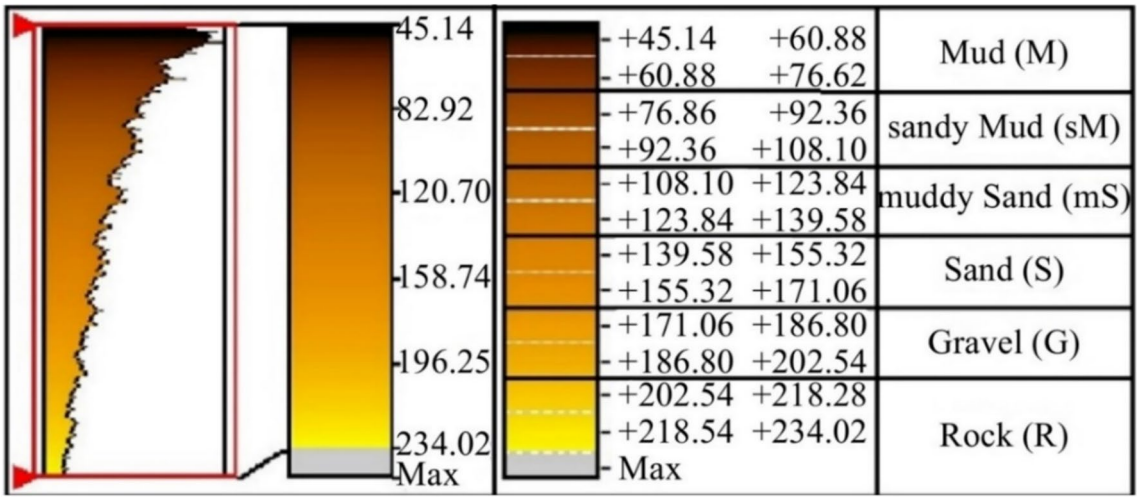


Fig. 3 Acoustic seafloor classification based on backscatter intensity values derived from side-scan sonar data (Özgan et al. 2024). Different acoustic facies reflect variations in sediment texture and seabed roughness

Table 1 Acoustic backscatter intensity variations and the outcrop features of the seafloor formations, Barnhardt et al. (1998)

Map unit	Acoustic reflection intensity	Outcrops features
Mud (M)	Weak	Smooth flat
sandy Mud (sM)	Weak	Smooth flat
muddy Sand (mS)	Medium	Smooth flat
Sand (S)	Medium	Smooth flat
Gravel (G)	Strong	Low relief often covered with ripples or boulders
Rock (R)	Strong	High relief, fractures common

Post-processing steps focused on improving data quality through noise reduction, artifact removal, and manual editing. These procedures enhanced the clarity of acoustic contrasts and facilitated the identification of sedimentary units and geomorphic features. Areas affected by excessive noise, shadowing, or poor signal quality were excluded from interpretation to minimize uncertainty.

Acoustic sediment classification and feature mapping

Interpretation of acoustic backscatter patterns was based on the premise that variations in backscatter intensity reflect differences in sediment grain size, surface roughness, and substrate hardness (Hamilton 1980; Jackson et al. 1986; Jackson and Briggs 1992). Seafloor sediment classification followed the framework proposed by Barnhardt et al. (1998), which relates qualitative backscatter strength to dominant sediment types.

Backscatter intensities were classified into six sedimentary units: Mud (M), Sandy Mud (sM), Muddy Sand (mS), Sand (S), Gravel (G), and Rock (R). These units were delineated based on relative acoustic brightness, texture, and continuity observed in the mosaics (Fig. 3; Table 1). It is acknowledged that backscatter intensity is influenced by multiple interacting factors; therefore, sediment classifications are interpreted as dominant surface conditions rather than definitive lithological compositions.

Geomorphic features, including erosional boundaries, depositional ridges, morainic features, and linear to curvilinear grooves, were mapped manually from the acoustic mosaics. Feature identification was based on changes in backscatter intensity, seafloor texture, feature geometry, and spatial context. Erosional boundaries were defined as sharp transitions between high-backscatter, rough surfaces and adjacent smoother, lower-backscatter areas, interpreted to represent zones of sediment removal or scouring. Morphological boundaries were identified where changes in seafloor relief or texture occurred without clear evidence of active erosion. Although this distinction involves interpretative judgment, consistent criteria were applied across the dataset to ensure internal reproducibility.

Ground-truthing using underwater video observations

To support acoustic interpretations, underwater video observations were collected using a QYSEA FIFISH V6 remotely operated underwater vehicle (ROV) at six representative locations across the study area. The ROV is equipped with a 4K UHD camera (30 fps) and dual adjustable LED lights (4,000 lumens each), enabling high-quality imaging of seafloor sediments and structures. Video surveys were conducted as close to the seafloor as operationally feasible to maximize visibility of grain size, block distribution, and sediment fabric.

Operational challenges included strong near-bottom currents, high biological productivity in cold saline waters, and reduced battery efficiency at low temperatures. Despite these limitations, the video data provided qualitative validation of acoustic facies, particularly in distinguishing rocky substrates from coarse- and fine-grained sedimentary units. Video observations were used to confirm general sediment types and surface characteristics rather than to provide quantitative sedimentological measurements.

Limitations and uncertainty

Several limitations affect the interpretation of SSS data in shallow marine environments. High-frequency acoustic signals attenuate rapidly in fine-grained, highly porous sediments, potentially reducing backscatter strength and obscuring subtle features. Steep or irregular seafloor topography can generate acoustic shadow zones, leading to incomplete imaging. Additionally, backscatter intensity reflects a combination of sediment properties—including grain size, roughness, porosity, and composition—making unique attribution to a single sediment type uncertain without physical samples.

Interpretation of geomorphic features from acoustic imagery inherently involves subjective judgment. To minimize bias, interpretations were guided by established classification schemes and supported by ground-truth video observations and comparisons with previously published studies. The resulting maps and interpretations should therefore be considered semi-quantitative representations of surficial seafloor conditions and geomorphic patterns.

Results

The analysis conducted in this study revealed the key erosional and morphological boundaries of the seafloor, as well as the distribution of sediments based on grain size across the investigated area. Side-scan sonar data were instrumental in distinguishing variations in seafloor texture and sediment composition. The locations of representative acoustic backscatter patterns are provided in Fig. 3, while detailed examples of these backscatter responses are illustrated in Figs. 4 and 5. These figures highlight the spatial heterogeneity of the seabed and the distinct acoustic signatures associated with different sediment types and geomorphological features.

Erosional and morphological boundaries identified from backscatter data

Side-scan sonar (SSS) data reveal pronounced spatial variability in seafloor morphology across the study area. Distinct acoustic contrasts delineate zones of differing surface roughness and sediment cover, allowing the identification of erosional and morphological boundaries (Fig. 4). Greyscale representations of the sonograms enhance these contrasts, particularly at transitions between acoustically smooth, low-backscatter areas and rougher, high-backscatter surfaces.

In the nearshore zones along the northwestern coast, linear to curvilinear high-backscatter features are observed adjacent to the shoreline (Fig. 4a). These features display westward-oriented trends and are characterized by sharp acoustic boundaries. In the north-central sector of the study area, erosional and morphological boundaries exhibit dominant east–west to southeast-oriented patterns (Fig. 4b). These boundaries locally overprint earlier seafloor textures, indicating multiple phases of seabed modification.

In the western offshore sector of Horseshoe Island, a limited number of narrow, elongated linear depressions were detected (Fig. 4c). These features range from approximately 2 to 10 m in width and extend for several tens of meters. Their acoustic signature is defined by alternating high- and low-backscatter stripes aligned parallel to feature axes. Further south, erosional trends shift toward west–southwest orientations and become more laterally extensive, coinciding with broader zones of seafloor scour (Fig. 4d-e).

Bathymetric gradients increase markedly toward the southern part of the study area. Seafloor depths of approximately 120–140 m are observed in this region, accompanied by abrupt changes in relief and steep seabed slopes. South of these zones, bathymetry exceeds 140 m toward offshore areas, beyond the effective swath range of the SSS system.

Acoustic characterization of surficial seafloor sediments

Acoustic backscatter intensity patterns indicate systematic variations in surficial sediment distribution across the study area (Fig. 5). In the northwestern nearshore sector, very high backscatter returns correspond to large blocky substrates. Individual blocks reach dimensions of up to ~ 19 m in length, ~ 6 m in width, and ~ 8 m in height. Block size decreases progressively eastward, accompanied by an increase in acoustically smoother areas indicative of finer sediment cover.

A sedimentary ridge with west-facing geometry is evident in the northwestern part of Lystad Bay (Fig. 5a). West of this ridge, a laterally extensive low-backscatter unit dominates the acoustic record. This unit exhibits relatively

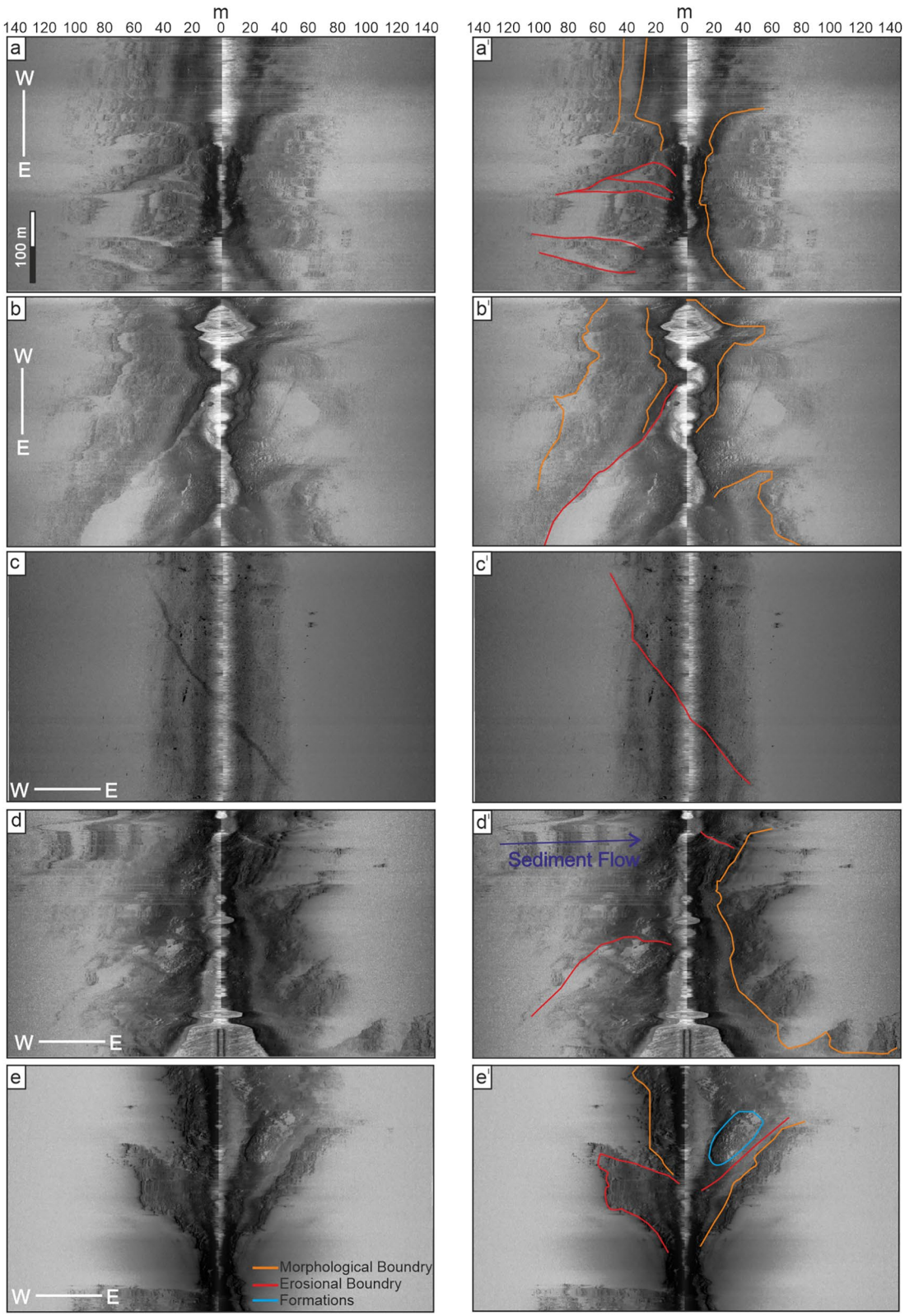


Fig. 4 Interpreted and non-interpreted side-scan sonar sonogram examples illustrating erosional and morphological boundaries within the study area. Erosional boundaries are identified by sharp truncations, scoured surfaces, and abrupt changes in backscatter intensity, whereas morphological boundaries are defined by gradual transitions related to seabed relief and depositional landforms. Locations of the examples are shown in Fig. 3b. A detailed explanation of the criteria used to distinguish erosional and morphological boundaries is provided in the Methods section

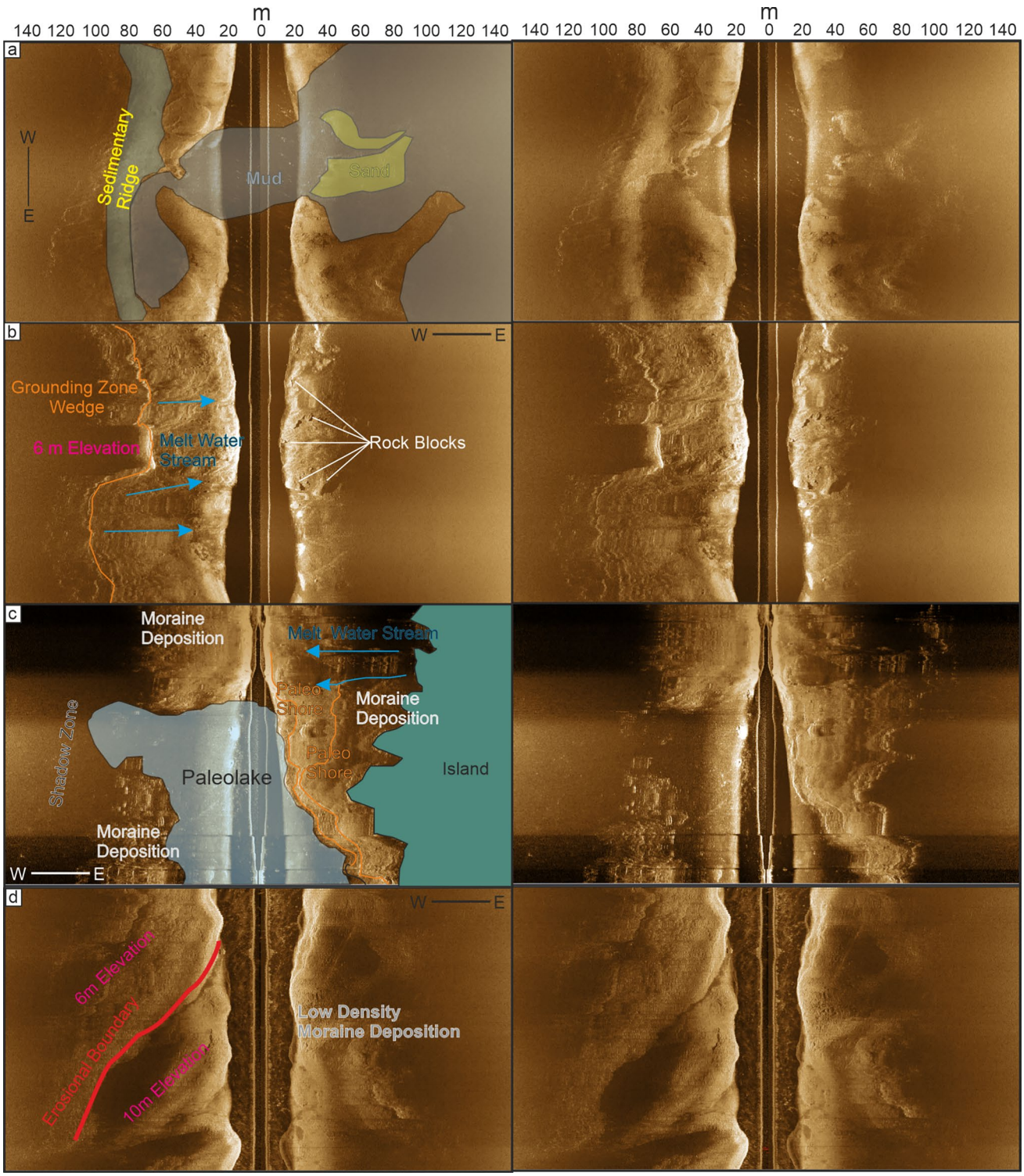


Fig. 5 Side-scan sonar sonogram examples showing depositional characteristics, seabed morphological features, and inferred sediment transport directions. Both interpreted and non-interpreted sonograms are presented to allow independent assessment of acoustic signatures. Dark tones represent acoustic shadows cast by elevated seafloor features. The length of these shadows suggests an estimated vertical relief for the mapped geomorphic structures. Locations of the examples are shown in Fig. 3b

uniform texture, although localized patches of moderate to high backscatter are embedded within it, producing heterogeneous acoustic patterns.

In the eastern sector of the bay, clusters of large, high-backscatter blocks are associated with a wedge-shaped morphological feature (Fig. 5b). Adjacent to this feature, linear sedimentary textures display consistent westward-aligned acoustic trends. In the central part of Lystad Bay, a discrete area of very low backscatter intensity is observed between the coastline and small offshore islands (Fig. 5c). Two laterally continuous linear features with contrasting depths occur to the west of this zone.

An area of low backscatter intensity deposition is found in a limited area, characterized as a paleo-lake, at the Lystad Bay, located between the coast and the small islands (Fig. 5c). To the west of this area, there are two paleo-shorelines at different depths. moraine deposits with an orientation facing the basin center were identified both to the west of the island and to the east of the small islands. Sediment reflections indicating sediment flux towards the center were also observed in these areas.

The erosion in this location becomes more profound as one moves southward on the island. Moderate to low backscatter intensity were observed, and the density of moraine deposits decreases (Fig. 5d). Moderate to high backscatter intensity are dispersed over a large area on the western edge of this location. Abrupt and steep bathymetric gradients occur from the seabed up to the southern and western extremities of the island.

Toward the southern sector of the study area, acoustic patterns change notably. Moderate- to low-backscatter units become more widespread, while the density of blocky high-backscatter features decreases (Fig. 5d). Moderate- to high-backscatter patches are dispersed along the western margin of this sector. Steep bathymetric gradients are common toward the southern and western edges of the survey area.

Ground truthing of reflections via video captures

Underwater video observations provide direct visual evidence of seafloor surface characteristics and support acoustic interpretations (Fig. 6). In nearshore areas at depths of approximately 3–5 m in the northwestern sector, the seafloor is dominated by large angular to subangular white granite blocks. At depths of 5–10 m toward the west, pink granite blocks are prevalent, and fine-grained sediments begin to partially infill spaces between blocks.

In the northern inner parts of the study area, block size decreases with increasing depth. At approximately 15–20 m water depth, blocky substrates transition to predominantly fine-grained sediment cover. In the southern sector, seafloor areas at depths of ~ 15–25 m are largely composed of fine-grained sediments with sparse, isolated small clasts. Beyond ~ 25 m depth in the southern part of the study area, the seabed is consistently covered by fine-grained sediments with minimal coarse material.

The combined SSS and video datasets document a clear spatial organization of seafloor morphology and sediment distribution across the study area. High-backscatter, block-dominated substrates are concentrated in shallow nearshore regions, particularly along the northwestern coast. Low-backscatter, fine-grained sedimentary units become increasingly dominant toward deeper and more southerly sectors. Linear and curvilinear acoustic features define distinct morphological boundaries and sedimentary textures, while bathymetric gradients exert a strong control on feature distribution and acoustic visibility.

Discussion

Interpretation of nearshore glacial landforms in a shallow marine setting

The nearshore seafloor of western Horseshoe Island preserves a diverse assemblage of sedimentary and morphological features that reflect the interaction of glacial, subglacial, and post-glacial marine processes. Unlike deeper shelf environments, where glacial landforms are often laterally continuous and well preserved, nearshore zones are subject to intense reworking by iceberg grounding, wave action, tides, and meltwater discharge. These processes complicate the preservation and interpretation of glacial signatures and contribute to the heterogeneous acoustic patterns observed in this study.

The mapped erosional and morphological boundaries identified from SSS data are interpreted as zones where contrasts in substrate roughness and sediment cover reflect differing dominant processes rather than discrete chronological events. High-backscatter rough surfaces likely correspond to exposed bedrock or coarse-grained substrates, whereas adjacent low-backscatter areas reflect finer-grained sediment accumulation. Similar acoustic expressions of nearshore glacial modification have been documented in other Antarctic and Arctic coastal settings (Solheim 1991; Ottesen et al. 2005; Batchelor et al. 2018), supporting the interpretation that such boundaries represent the spatial imprint of variable glacial and marine influence rather than sharply defined depositional limits.

Grounding-zone wedge and ice-marginal retreat

The wedge-shaped, acoustically high-backscatter feature identified in the eastern part of Lystad Bay is interpreted

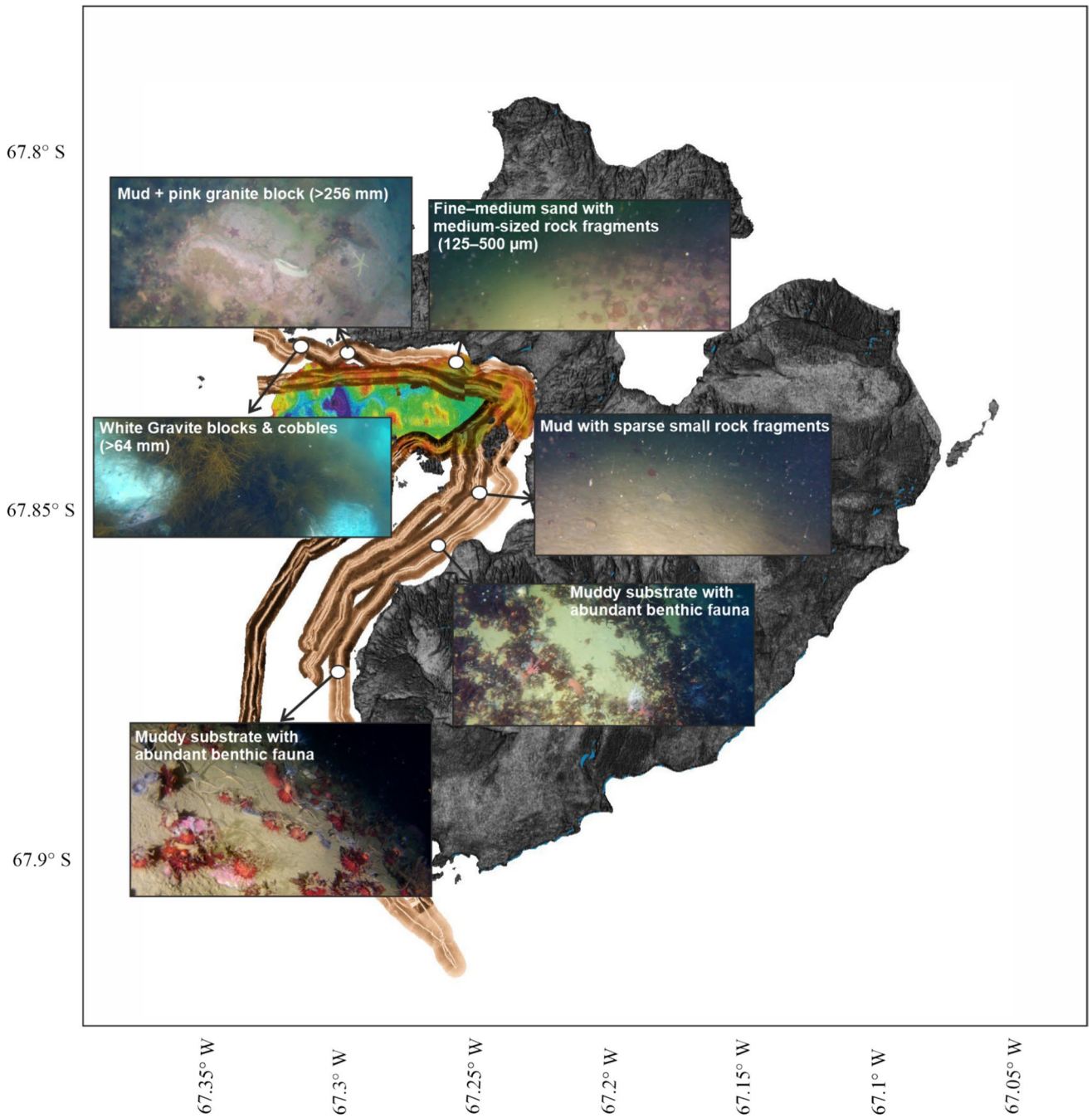


Fig. 6 Video capture images used for ground-truthing of acoustic interpretations. Annotated frames highlight observed seabed elements including block-sized clasts, coarse gravel, fine-grained muddy substrates, and benthic organisms, allowing direct comparison with acoustic facies interpretations

as a grounding-zone wedge (GZW, Fig. 7a), representing a former stable position of the grounding line during ice-sheet retreat. GZWs form through subglacial sediment delivery and progradation at the ice–ocean interface and are widely documented along Antarctic continental shelves (Dowdeswell and Siegert 1999; Batchelor and Dowdeswell 2014). The orientation of iceberg ploughmarks differs from the alignment of the grounding zone wedge identified in the study area (Fig. 7a). While grounding-zone wedges typically record the former flow direction of grounded ice and the stabilization of the grounding line during ice-sheet retreat, the orientation of iceberg ploughmarks reflects the drift pathways of free-floating icebergs after calving. Consequently, ploughmark trajectories are primarily controlled by oceanographic processes such as prevailing currents, tidal circulation, and wind forcing rather than by the

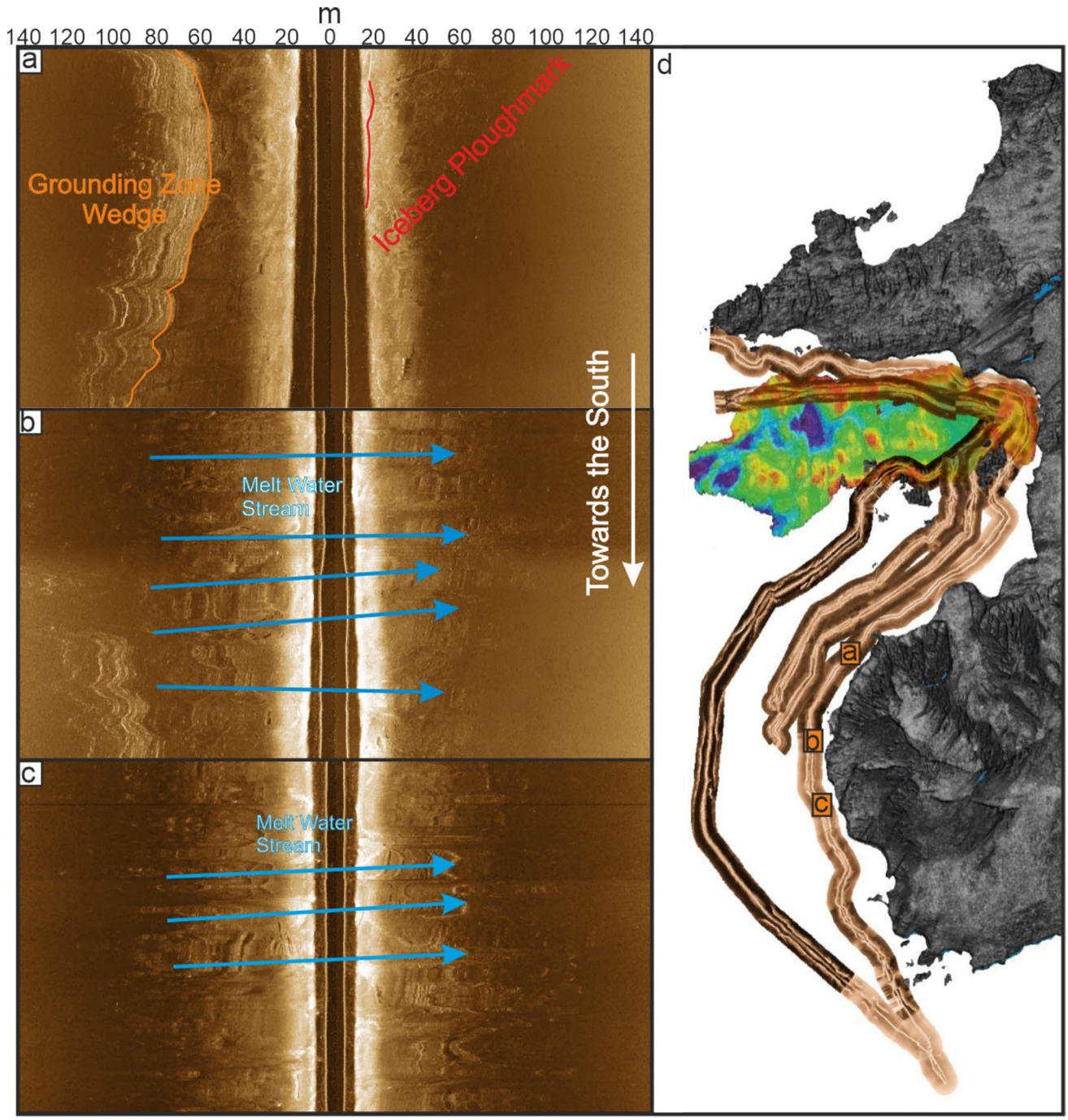


Fig. 7 Representative examples illustrating the general ice-flow pattern within the study area

direction of grounded ice flow. This difference suggests that iceberg transport in the area was influenced by regional ocean circulation, resulting in ploughmark orientations that deviate from the inferred ice-flow direction indicated by the grounding-zone wedge morphology.

Downstream of this feature, closely spaced ridges and sedimentary textures suggest episodic retreat of the ice margin rather than continuous ungrounding. The spatial association of these features is consistent with previously described assemblages that record transitions from grounded ice to ice-marginal and glaciomarine environments (Shipp et al. 1999; Ó Cofaigh et al. 2002; Bart et al. 2017). However, in the absence of sediment cores or seismic profiles, the temporal resolution of these retreat phases cannot be constrained, and interpretations are therefore limited to relative spatial relationships.

Distinguishing ice-flow and meltwater-related features

One of the key challenges in nearshore glacial geomorphology is distinguishing between landforms produced directly by grounded ice movement and those generated or modified by subglacial or ice-marginal meltwater flow (Fig. 7b, c). In this study, linear and streamlined acoustic features were grouped based on their geometry, orientation, and spatial relationship to bathymetry and sedimentary units. While ice-flow-related features typically exhibit broader, more laterally continuous morphologies aligned with regional slope and ice drainage pathways, meltwater-related features are generally narrower, more localized, and preferentially incised into softer substrates.

Given the resolution and surficial nature of the SSS data, these two process signatures cannot always be unambiguously separated. Therefore, the flow directions presented in this study are interpreted as composite indicators of dominant sediment-transport and erosional pathways influenced by both grounded ice and meltwater processes. Similar interpretative approaches have been adopted in other glacial marine studies where physical sampling or subsurface imaging was unavailable (e.g., Dowdeswell et al. 2006; Greenwood et al. 2021). Importantly, the flow directions should be considered qualitative rather than quantitative reconstructions of paleo-ice dynamics.

Interpretation of the low-backscatter basin as a potential paleo-lake

A discrete, low-backscatter basin identified in the central part of Lystad Bay is interpreted as a potential paleo-lake feature. This interpretation is based on the presence of laterally continuous fine-grained sedimentary units, subdued acoustic textures, and the occurrence of linear features resembling former shoreline positions at different depths. Similar acoustic signatures have been associated with subglacial or ice-dammed lakes in other glaciated regions (Ó Cofaigh et al. 2008; Batchelor et al. 2018).

Nevertheless, it is emphasized that this interpretation is necessarily tentative. Without sedimentological cores, chronological control, or subsurface seismic data, the origin of the fine-grained sediments cannot be definitively attributed to lacustrine deposition. Alternative explanations, including localized low-energy marine sedimentation or meltwater plume deposition, cannot be excluded. The paleo-lake interpretation should therefore be viewed as a working hypothesis that highlights the need for future targeted investigations, rather than as a conclusive reconstruction.

Implications for nearshore glacial dynamics and sedimentation

The spatial patterns documented in this study suggest a general southward-directed dominant flow, with secondary westward components influenced by local bathymetry and coastline geometry. Increased seafloor incision and deeper bathymetry toward the southern sector of Horseshoe Island indicate a concentration of erosional energy in this region, likely reflecting the combined influence of ice drainage pathways and meltwater focusing (Fig. 8).

The observed fining trend toward deeper and southern parts of the study area is broadly consistent with glacial–marine sedimentation models. However, the persistence of coarse-grained and blocky substrates in nearshore zones highlights the importance of local sediment supply from adjacent glaciers and bedrock sources (Fig. 9). These findings underscore the complexity of sediment redistribution in shallow Antarctic marine environments and caution against direct extrapolation of deep-shelf models to nearshore settings.

Limitations and directions for future work

This study is based on surficial acoustic data and qualitative ground-truth observations, which inherently limit the ability to constrain depositional processes and timing. High-resolution shallow seismic profiling would allow differentiation between erosional surfaces and sedimentary infill, particularly within the proposed paleo-lake basin. In addition, sediment coring and grain-size analyses would provide critical validation of acoustic interpretations and enable chronological reconstruction of glacial retreat and marine transgression.

Despite these limitations, the present dataset represents the first systematic characterization of nearshore seafloor deposits and deformation features around Horseshoe Island. It provides a valuable baseline for future studies aimed at integrating nearshore geomorphology into broader reconstructions of Antarctic ice-sheet dynamics.

Conclusions

This study presents the first high-resolution characterization of nearshore seafloor deposits and deformation features around the western coast of Horseshoe Island, Marguerite Bay, based on side-scan sonar (SSS) data integrated with underwater video observations. The combined dataset documents pronounced spatial variability in seafloor morphology and surficial sediment distribution within a shallow Antarctic marine environment.

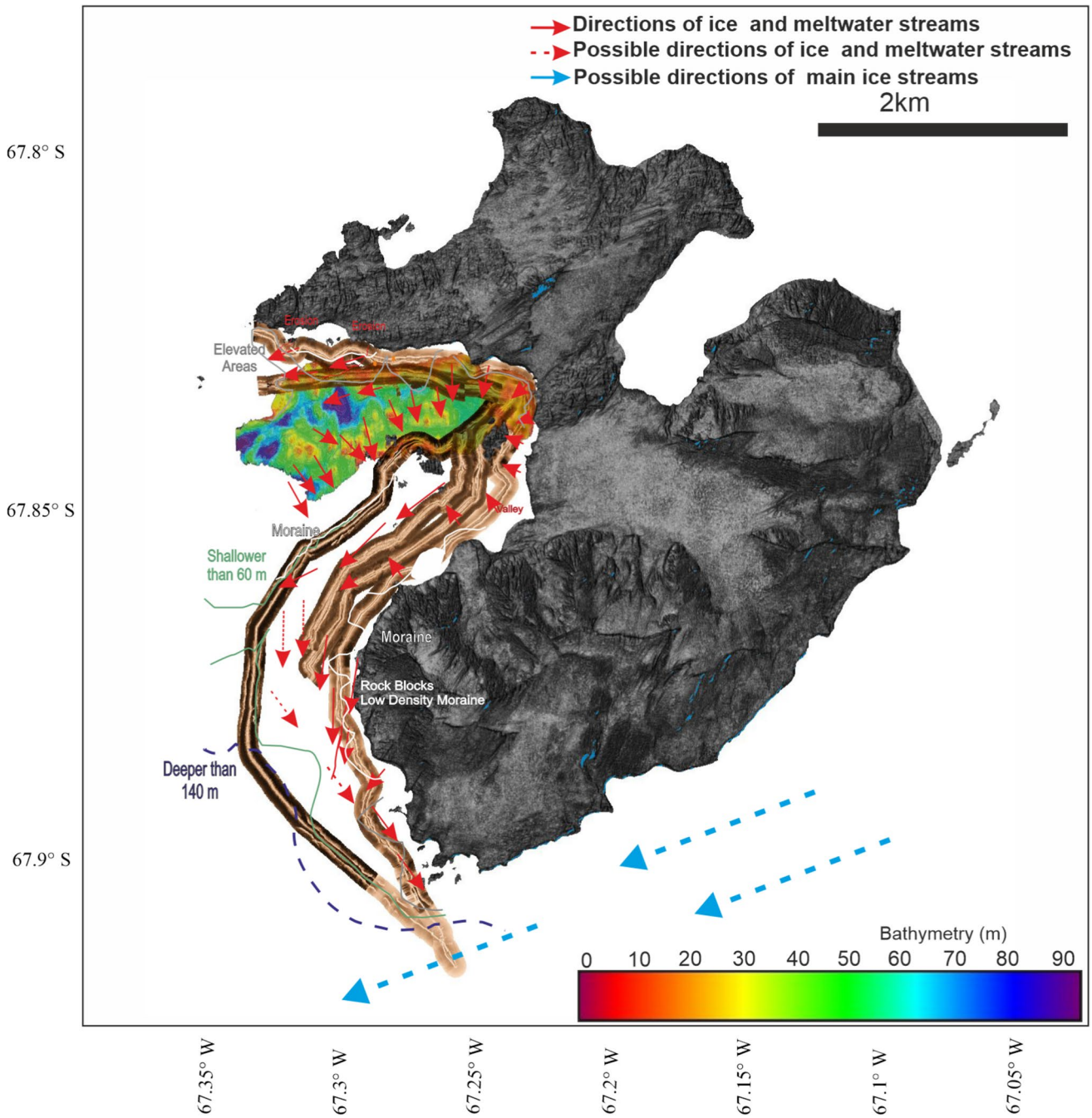


Fig. 8 Reconstructed ice-flow and meltwater stream directions across the study area based on bathymetric and geomorphological evidence. Distinct symbology is used to differentiate depth contours, flow-direction arrows, and inferred ice and meltwater pathways. Ice-flow and meltwater directions are shown together to emphasize their spatial association; however, their differing geomorphic expressions are discussed in the text. Bathymetric data are derived from (Tükenmez et al. 2022), and selected high-resolution bathymetric close-ups are provided as insets to highlight key flow-related features

High-backscatter, block-dominated substrates are primarily confined to shallow nearshore areas, while low-backscatter, fine-grained sedimentary units become increasingly dominant toward deeper and southern sectors. Linear and curvilinear acoustic features define erosional and morphological boundaries that reflect contrasts in substrate roughness and sediment cover rather than discrete depositional events. These patterns highlight the complex interplay between glacial erosion, meltwater discharge, and post-glacial marine reworking in shaping nearshore seabed morphology.

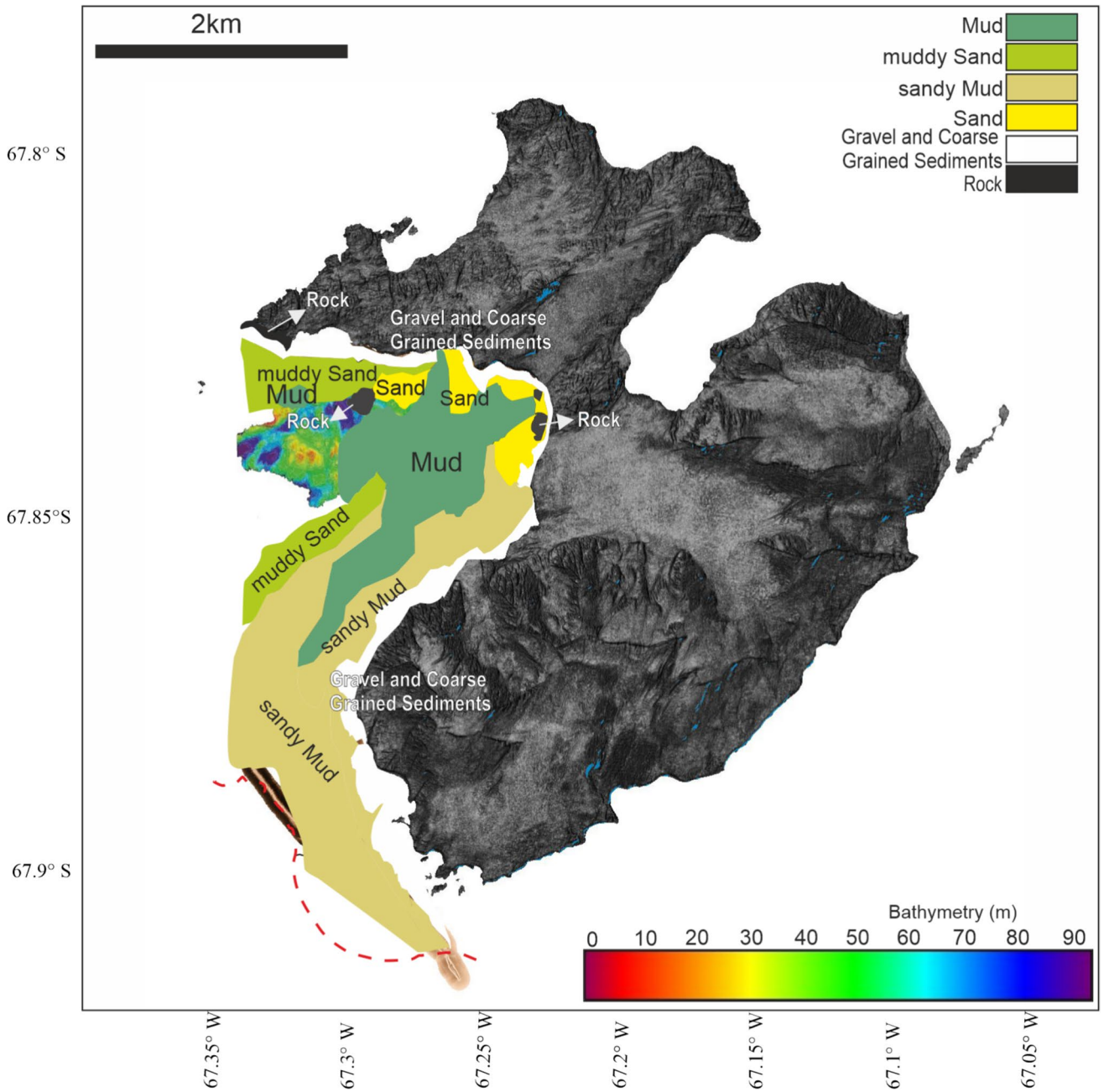


Fig. 9 Sea floor sediment grain size distribution for the study area revealed from acoustic data and video captures Seafloor sediment grain-size distribution map of the study area derived from integrated acoustic backscatter data and video observations.The legend explains both bathymetric shading and sedimentological classifications

A wedge-shaped sedimentary feature identified in the eastern part of Lystad Bay is interpreted as a grounding-zone wedge, indicating a former stable position of the ice margin during retreat. Additional sedimentary textures and ridges suggest episodic ice-marginal retreat, although the timing and duration of these phases cannot be constrained without chronological data. A low-backscatter basin in the central study area is tentatively interpreted as a potential paleo-lake feature; however, this interpretation remains speculative and requires further validation through sediment coring and subsurface imaging.

Overall, the results demonstrate that nearshore environments preserve valuable but complex records of glacial dynamics that differ markedly from those of deeper continental shelf settings. The findings emphasize the importance of integrating high-resolution acoustic mapping with targeted ground-truthing to improve reconstructions of Late Quaternary ice-sheet behavior in Antarctic coastal regions.

Future studies incorporating shallow seismic profiling, sedimentological analyses, and geochronological data will be essential to refine these interpretations and fully resolve the depositional history of the Horseshoe Island nearshore zone.

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Author contribution D.V. (corresponding author) conceptualized the study, conducted data analysis, and wrote the main manuscript text. K.E. contributed to the interpretation of side-scan sonar data and glacial geomorphology. O.Ö. prepared and processed figures and participated in sedimentological data compilation. C.G. assisted with data acquisition and reviewed the geological interpretations. All authors reviewed and edited the manuscript and approved the final version.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The author declares there are no conflict or competing interests.

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