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Key Points:

- Thin fine-grained turbidites record Late Pliocene–Pleistocene history of dense shelf water outflow to the deep ocean in the Ross Sea
- Frequency of Antarctic Bottom Water production through Hillary Canyon declines from 3.3 Ma to early Pleistocene due to expanding ice sheet
- Gaps in our turbidite record correspond to anomalously warm interglacials suggesting cessation of Antarctic Bottom Water production

Supporting Information:

Supporting Information may be found in the online version of this article.

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Plio–Pleistocene Antarctic Bottom Water Production in the Ross Sea Reconstructed From Hillary Canyon Levee Turbidites

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Abstract Dense shelf water (DSW) formed on Antarctica's continental shelves is a significant precursor for Antarctic Bottom Water (AABW), a critical component of global overturning circulation. We hypothesize that DSW cascades off the central Ross Sea shelf generated density currents that entrained sediment as they flowed down Hillary Canyon, resulting in turbidite deposits on adjacent levees. International Ocean Discovery Program Expedition 374 drilled two sites on the Hillary Canyon levee: Site U1525 at the base of the continental slope and Site U1524 on the rise. The more proximal Site U1525 yielded ~160 m of Pleistocene sediment, and the more distal Site U1524 recovered ~270 m of Late Pliocene to Pleistocene deposits. Within the muddy successions are distinct mm-scale silty layers interpreted as turbidites. We identified >3,300 turbidites at Site U1524 and >1,300 at Site U1525. At Site U1524, many outflow events occurred between the ~3.3 and 2.1 Ma interval, except for a gap at ~3.17 Ma, and declined through the Pleistocene. Between 2.1 and ~1 Ma, turbidite frequency was similar at both sites. At ~1 Ma, turbidite deposition ceased at both sites and then resumed at Site U1525 at ~0.9 Ma. Longer-term variability in AABW outflow through Hillary Canyon was influenced by ice sheet extent and continental shelf area, whereas the shorter-term cessations in outflow are interpreted to correspond to anomalously warm interglacials.

1. Introduction

Antarctic Bottom Water (AABW) constitutes the lower limb of the global overturning circulation, as it is the coldest (<1°C), densest (>28.27 km/m³ neutral density), and deepest (>1,900 m) water mass in the ocean (Amblas & Dowdeswell, 2018; Gordon, 1991; Jacobs et al., 1970; Orsi, 2002; Orsi et al., 1999). The formation of modern AABW results from denser shelf water production in coastal polynyas around Antarctica, which mixes with warmer Circumpolar Deep Water (CDW) near the shelf edge (Baines & Condie, 1998; Orsi et al., 1999; Rintoul, 2018; Silvano et al., 2020). Previous studies have examined the history of AABW formation over longer timescales and in response to climatic and ice dynamics in the Miocene to Pleistocene (e.g., Elderfield et al., 2012; Hall et al., 2001; Huang et al., 2017; Li et al., 2023). However, understanding of AABW formation during the Late Pliocene–Pleistocene is limited. Therefore, investigating physical records of AABW outflow during past warm periods is essential for expanding understanding of current and future warming scenarios.

In the present-day Ross Sea, sea ice formation is influenced by strong katabatic winds, resulting in coastal polynyas (Baines & Condie, 1998; Jacobs et al., 1970; Zhang et al., 2024). This phenomenon fosters continuous sea ice formation, thereby increasing seawater salinity via brine rejection. This denser and saltier water mass is termed dense shelf water (DSW; Jacobs et al., 1985; Orsi & Wiederwohl, 2009), which we adopt herein to include all dense water masses originating over the continental shelf and within ice cavities, including high-salinity shelf water and ice-shelf waters, because physical paleo-records are unable to discern water mass origin. These dense shelf waters sink, flowing across and beyond the continental shelf. Under certain circumstances, DSW cascades over the continental shelf edge, forming a density current steered by bathymetry and by the geostrophically adjusted east-west flowing Antarctic Slope Current (ASC) (Baines & Condie, 1998; Gales et al., 2021; Kim et al., 2023; Thompson et al., 2018, 2020). During export and cascading, DSW can resuspend and entrain

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unconsolidated fine-grained sediment at the shelf edge and transport it downslope (Gales et al., 2021). This suspended sediment increases the density of the DSW plume, leading to the formation of a sediment-laden density current with properties similar to dilute (very low concentration) turbidity currents (Backhaus et al., 1997; Baines & Condie, 1998; Gales et al., 2021; Ivanov et al., 2004; Jacobs et al., 1970). The uppermost portion of these DSW-driven turbidity currents spills out of the confined channel via flow stripping processes (Piper & Normark, 1983), resulting in the accumulation of sediment on adjacent overbanks (e.g., Straub & Mohrig, 2008). Thus, the resultant deposits, referred to as “turbidites” hereafter, serve as an archive of these interconnected oceanographic and sedimentary processes (Baines & Condie, 1998).

International Ocean Discovery Program (IODP) Expedition 374 drilled Sites U1524 and U1525 (Figure 1a) in the overbank of Hillary Canyon. Site U1525 is ~60 km northeast of the continental shelf edge near the base of the continental slope, while Site U1524 is ~87 km northeast of Site U1525, on the continental rise. Site locations allow evaluation of the interplay between oceanic influences and West Antarctic Ice Sheet (WAIS) history during the Late Pliocene to Pleistocene (3.3–0 Ma) from the shelf edge to the continental rise. Earth's overall cooling trend since the middle Pliocene influenced marine-based WAIS stability and the factors that control DSW-AABW production.

In this study, we propose that DSW cascading at the shelf edge and upper reaches of Hillary Canyon led to the development of sediment-laden density currents that evolved into dilute turbidity currents at the base-of-slope and continental rise (Figure 1b). The observed thin (<1 cm) turbidites within the mud-dominated successions at IODP Sites U1524 and U1525 record the history of AABW formation in the Ross Sea since ~3.3 Ma. Our analysis focuses on sedimentological characterization, including grain size, thickness, timing, and frequency of these turbidites at locations proximal and distal to the shelf edge. Our sedimentological observations are used to constrain a numerical model that estimates the range of concentrations and velocities of these density currents. We interpret our results in the context of the last 3.3 Myr of ice sheet history, oceanic forcings (e.g., ASC), and other depositional processes in the Ross Sea during a time of progressive global cooling.

1.1. Modern Physical Oceanography of the Ross Sea

The Ross Sea is a major producer of DSW in the modern Southern Ocean (Orsi, 2002; Orsi & Wiederwohl, 2009; Orsi et al., 1999; Zhang et al., 2024). Its large ice shelf, highly productive polynya, and deep and wide glacially carved continental shelf, enables the accumulation and export of large DSW volumes (Amblas & Dowdeswell, 2018; Gordon et al., 2004; Ivanov et al., 2004). In the Ross Sea (Figure 1), the continental shelf averages ~240 km wide (maximum: ~400 km) and comprises an area of $\sim 3.84 \times 10^5 \text{ km}^2$, with ~63% of its shelf deeper than the mean Antarctic shelf depth (460 m; Amblas & Dowdeswell, 2018). This morphology reflects repeated ice-stream occupation of cross-shelf troughs, which eroded the inner-middle shelf, promoting outer-shelf progradation, and focused sediment delivery to the adjacent trough-mouth fan and canyon (De Santis et al., 1995; Gales et al., 2021). Seaward of the central Ross Sea, the Hillary Canyon is the principal conduit for cascading DSW and shelfward intrusions of CDW, with modern observations showing energetic near-bottom dense flows at the canyon head, capable of resuspending and transporting fine sediment downslope (Arosio & Amblas, 2025; Gales et al., 2021).

Three main water masses interact in the Ross Sea: Antarctic Surface Water (AASW), CDW, and AABW (e.g., Bergamasco et al., 2002; Morrison et al., 2020; Orsi & Wiederwohl, 2009; Whitworth et al., 1998). CDW, carried eastward at mid depths by the Antarctic Circumpolar Current, partially recirculates into the Ross Gyre (Bergamasco et al., 2002; Orsi & Wiederwohl, 2009; Whitworth et al., 1998), supplying relatively warm, salty water to the shelf via bathymetric depressions and Hillary Canyon (Arosio & Amblas, 2025; Gales et al., 2021; Gordon et al., 2009). Near the shelf break, mixing and cooling result in modified CDW (mCDW; Orsi & Wiederwohl, 2009; Morrison et al., 2020). The Antarctic Slope Front, aligned with the westward-flowing ASC, regulates landward modified Circumpolar Deep Water (mCDW) intrusion and the offshore export of DSW (Baines, 2009; Bergamasco et al., 2002; Budillon et al., 2011; Jacobs, 1991; Thompson et al., 2018, 2020; Whitworth et al., 1998).

Once on the shelf, mCDW supplies heat and salt to shelf waters, contributing to the formation of DSW (Baines & Condie, 1998; Gordon et al., 2004; Morrison et al., 2020). DSW, with a density $> 28.27 \text{ kg/m}^3$, moves north across the shelf via cross-shelf troughs, interacting with shelf-edge waters, the Antarctic Slope Front and ASC, before being funneled into the Hillary Canyon as AABW (Arosio & Amblas, 2025; Baines & Condie, 1998; Budillon

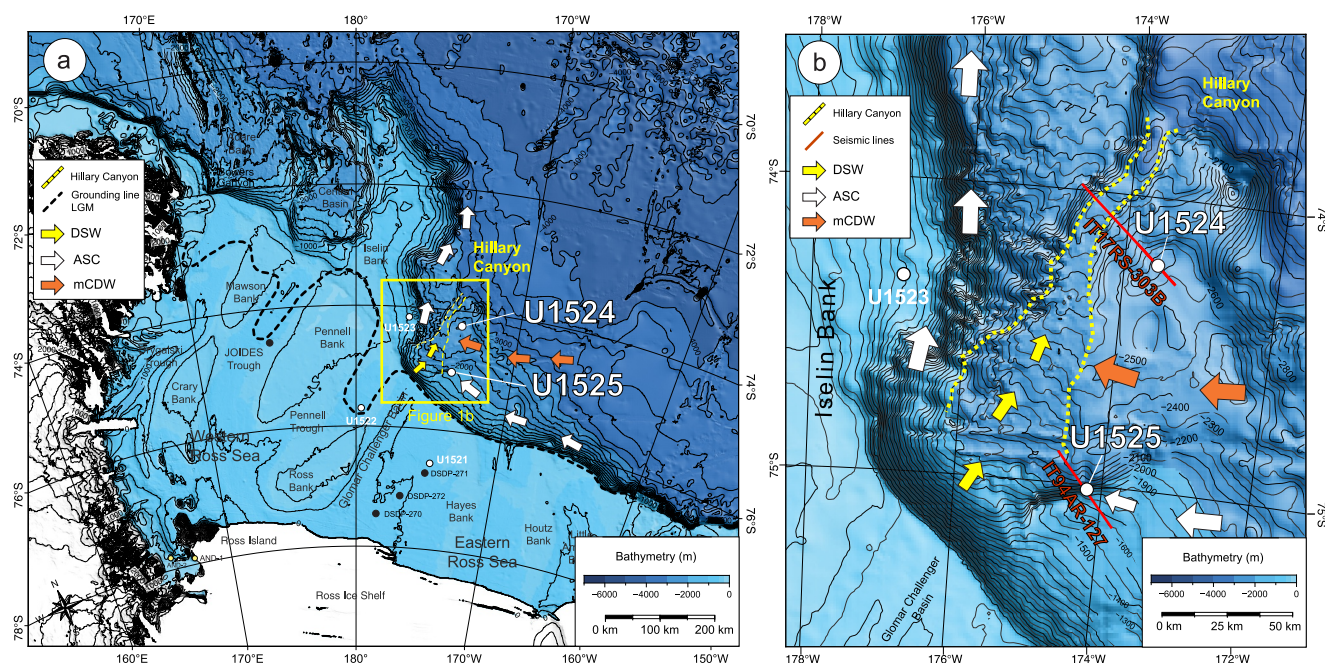


Figure 1. (a) Study area in the Ross Sea. Yellow box shows the location of (b). Bathymetric data is International Bathymetric Chart of the Southern Ocean (IBCSO v2; Dorschel et al., 2022). Sites U1524 and U1525 and other International Ocean Discovery Program Expedition 374 sites (white dots), Deep Sea Drilling Project (black dots) Leg 28 sites (black dots), and Antarctic Geological Drilling Project drill cores (yellow dots). Dashed black line is the grounding line at the Last Glacial Maximum for reference (Halberstadt et al., 2016) (b) Detailed view of Hillary Canyon (outlined in yellow dashed lines in “a”) and Sites U1524 and U1525. Dense shelf water (yellow arrows) flowing downslope in the Hillary Canyon and along the central and western Ross Sea shelf slope, contributing to deep waters. The Antarctic Slope Current (white arrows) carries surface waters westward along the continental shelf break. This along-slope flow also regulates modified Circumpolar Deep Water (orange arrows) transport onto the continental shelf. Location of seismic lines IT94AR-127 (U1525; Figure 2a) and IT17RS-303B (U1524; Figure 2b) shown here. Ross Sea basemap modified from Kim et al. (2023).

et al., 2011; Gales et al., 2021; Gill, 1973; Orsi & Wiederwohl, 2009; Thompson et al., 2018; Withworth & Orsi, 2006; Whitworth et al., 1998; Zhang et al., 2024).

1.2. Plio-Pleistocene Paleoclimatic and Ross Sea Paleoceanographic Evolution

The Pliocene (5.33–2.58 Ma) records a major reorganization of the climate system, transitioning from the warm early Pliocene (~5–3.6 Ma), when global mean temperatures were ~3–4°C above present and atmospheric CO₂ was near modern levels (CenCO2PIP, 2023), toward progressively cooler conditions culminating in Northern Hemisphere glaciation near 2.7 Ma (Dowsett et al., 2013; Haywood & Valdes, 2004; Lisiecki & Raymo, 2005; R. M. McKay, Naish, Carter, et al., 2012; Woodard et al., 2014). Antarctic-proximal records show that this cooling was spatially heterogeneous, characterized by repeated marine ice-sheet advance and retreat, particularly in West Antarctica, superimposed on long-term Late Pliocene cooling (Gohl et al., 2021; R. M. McKay, Naish, Carter, et al., 2012; Naish et al., 2009). Geologically constrained ice-sheet simulations spanning 4.5–2.6 Ma indicate that both the WAIS and EAIS remained highly dynamic throughout the Pliocene, contributing up to ~25 m of glacial–interglacial sea-level variability, with prolonged grounding-line retreat during the mid-Pliocene preceding peak Northern Hemisphere warmth (Halberstadt et al., 2024).

The mid-Piacenzian Warm Period (mPWP; 3.264–3.025 Ma) represents the best-studied interval of sustained Pliocene warmth, with global mean temperatures ~2–3°C above present under broadly modern boundary conditions (Dowsett et al., 2013; Haywood et al., 2016; IPCC, 2023). Far-field sea-level reconstructions indicate highstands of ~10–20 m above present, requiring substantial Antarctic Ice Sheet mass loss in addition to reduced Northern Hemisphere ice (Grant et al., 2019; Miller et al., 2020; Naish & Wilson, 2009). Ice-proximal sedimentary, seismic, and geochemical records from the Ross Sea, Amundsen Sea, Wilkes Land, and Prydz Bay document repeated retreat of the WAIS and marine-based sectors of the EAIS during Pliocene warm intervals, followed by stepwise ice expansion toward near-modern configurations during Late Pliocene cooling (Gohl et al., 2021; R. M. McKay, Naish, Carter, et al., 2012; Passchier et al., 2025; Rahaman et al., 2025). These

Antarctic margin records align with Southern Ocean-wide proxy evidence for enhanced deep-ocean ventilation and strengthened AABW formation beginning in the Late Pliocene to earliest Pleistocene, coincident with Northern Hemisphere glaciation and large-scale reorganization of ocean overturning circulation (Yi et al., 2023). Together, these observations are consistent with coupled ice-sheet–climate simulations suggesting that modest subsurface ocean warming ($\leq 1.5^{\circ}\text{C}$) was sufficient to trigger marine ice-sheet retreat via ocean–ice interactions, even in the absence of major changes in large-scale ocean heat transport (Halberstadt et al., 2024; Haywood & Valdes, 2004; Weiffenbach et al., 2024).

In the Ross Sea sector, multiple proxy records indicate that Pliocene warmth was associated with weakened ASC flow and enhanced incursions of mCDW onto the continental shelf. For example, planktic foraminiferal assemblages at IODP Site U1523 document repeated incursions of subtropical and temperate taxa during the late early to mid-Pliocene, indicating reduced sea-ice cover and warmer-than-present shelf conditions during superinterglacials (Seidenstein et al., 2024). Seafloor morphology and contourite stratigraphy from the Iselin Bank–Hillary Canyon region further support reduced bottom-current vigor during Pliocene warm intervals, followed by progressive strengthening of slope circulation into the Pleistocene (Conte et al., 2021). Together, these records suggest that Pliocene Antarctic warmth involved reorganization of shelf–slope exchange that favored episodic mCDW inflow and dynamic ice retreat, whereas Late Pliocene cooling marks the establishment of more persistent cold-shelf conditions, enhanced DSW formation, and the precursor circulation state to Pleistocene AABW production (R. M. McKay, Naish, Carter, et al., 2012; Rahaman et al., 2025).

Between ~ 2 and 1 Ma, sediments from ANDRILL AND-1B record repeated advance and retreat of marine-based ice in the Ross Embayment, predominantly paced by obliquity (~ 40 kyr), reflecting dynamic Early Pleistocene WAIS behavior (R. M. McKay, Naish, Powell, et al., 2012; Naish et al., 2009). Marine Isotope Stage (MIS) 31 (~ 1.07 Ma) represents the most pronounced ice-retreat event preserved in AND-1B and is characterized by open-marine conditions and reduced ice influence on the continental shelf (Elderfield et al., 2012; R. M. McKay, Naish, Powell, et al., 2012). MIS 31 is widely recognized as an anomalously warm and prolonged interglacial, with Ross Sea sea-surface temperatures estimated to be ~ 3 – 5°C above present and substantial retreat, or partial collapse, of marine-based WAIS sectors inferred from geological and modeling studies (Beltran et al., 2020; Bollen et al., 2022; R. M. McKay, Naish, Powell, et al., 2012; Naish et al., 2009; Pollard & DeConto, 2009; Scherer et al., 2008; Warnock et al., 2022). Following MIS 31, AND-1B contains a ~ 200 kyr hiatus overlapping much of the Mid-Pleistocene Transition (MPT; ~ 1.2 – 0.8 Ma), reflecting grounding-line advance and erosion rather than reduced climate variability (R. M. McKay, Naish, Powell, et al., 2012). Across the MPT, global climate evolved toward larger ice volumes and longer glacial cycles, with stepwise ice expansion in the Ross Sea recorded by repeated diamict deposition prior to renewed Pleistocene glacial–interglacial oscillations (Berger & Jansen, 1994; Clark et al., 2006; Lisiecki & Raymo, 2005, 2007; R. M. McKay, Naish, Carter, et al., 2012, 2019). In contrast, deeper-water sites drilled during IODP Expedition 374 on the continental slope and rise are less affected by grounding-line erosion and more likely to preserve stratigraphically continuous records of ice-proximal sediment delivery and oceanographic variability through the Pleistocene, providing a shelf–slope perspective on Antarctic cryosphere–ocean interactions (Bollen et al., 2022; Jaeger & Koppes, 2016; King et al., 2022).

Despite extensive Antarctic-proximal constraints on ice-sheet extent since the Pliocene, the oceanographic response in terms of Ross Sea dense-water export remains difficult to evaluate from direct, ice-proximal archives. Far-field ventilation reconstructions and global sea-level/ice-volume syntheses capture major reorganizations across the Late Pliocene–Pleistocene and the MPT (e.g., Clark et al., 2025; Elderfield et al., 2012; Yi et al., 2023), but they do not resolve the timing or pathways of DSW formation and export. In the Ross Sea, Bollen et al. (2022) inferred stronger interglacial DSW export and weaker glacial export between ~ 1.2 and 0.3 Ma, with a reduction of channelized dense water export when the grounding-ice margins were closer to the shelf break, consistent with evidence for large marine-based WAIS variability and strong ocean sensitivity from geological records and modeling (R. M. McKay, Naish, Powell, et al., 2012; Patterson et al., 2026; Pollard & DeConto, 2009). However, continuous, high-resolution physical shelf–slope records spanning the last ~ 3.3 Myr that can be directly aligned with Ross Sea WAIS oscillations remain scarce, limiting the understanding of the mechanisms linking how grounding-line position and shelf–slope exchange modulated DSW export and downstream AABW formation, particularly through intervals where interpretations of Southern Ocean overturning remain debated (Hines et al., 2024).

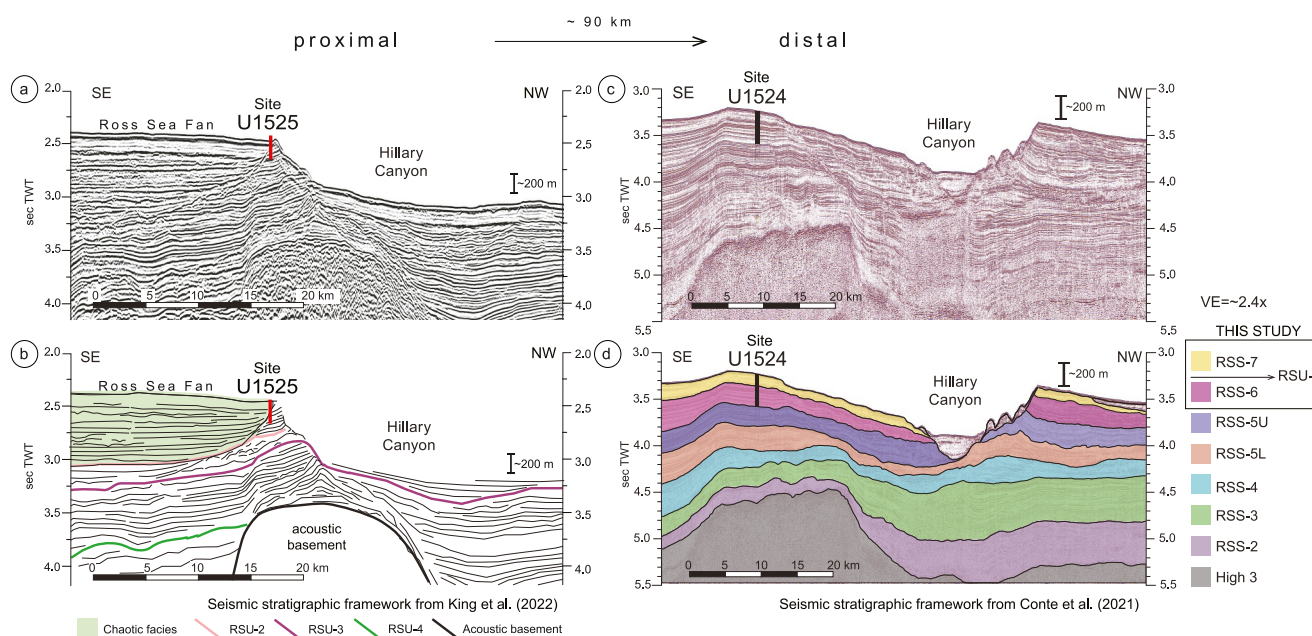


Figure 2. Seismic lines and their interpretation for Sites U1525 and U1524 (proximal to distal to the shelf edge). (a) Seismic profile for U1525 using seismic line IT94AR-127 (Profile collected by Istituto Nazionale di Oceanografia e Geofisica Sperimentale (IOGS, Italy). Data available from the Antarctic Seismic Data Library System). Modified from R. M. McKay et al. (2019). (b) Interpretation adapted from R. M. McKay et al. (2019). The highlighted green unit shows trough-mouth fan facies above RSU2 (King et al., 2022; R. M. McKay et al., 2019). (c) Seismic profile line IT17RS-303B with the location of Site U1524 (modified from R. M. McKay et al., 2019). (d) Interpretation of Ross Sea Seismic Sequences by Conte et al. (2021). Site U1524 includes RSSs 6 and 7, separated by the Ross Sea Unconformity 2.

1.3. Hillary Canyon Channel-Levee System

Hillary Canyon is a 180 km long submarine conduit on the eastern Ross Sea continental margin with erosional morphology at the shelf edge and continental slope (Gales et al., 2021) (Figures 2a and 2b) that transitions to depositional channel-levee morphology on the continental rise (Figures 2c and 2d; Conte et al., 2021). Because the head of Hillary Canyon occurs at the shelf edge (Gales et al., 2021), it serves as a pathway for glacial sediments eroded from the continental shelf via ice streams (De Santis et al., 1999; Gales et al., 2021) and pelagic detritus from highly productive Ross Sea surface waters. Sediments mixed with DSW are delivered downslope via gravity flows (Baines & Condie, 1998; Gales et al., 2021, 2023; Gordon et al., 2009; Ivanov et al., 2004; Shapiro, 2003), which overspill and contribute to the formation of the distal levees.

Regional seismic-stratigraphic mapping in combination with sedimentary and geophysical logs data from Sites U1523 and U1524 provide important context for our study (Conte et al., 2021). Eight seismic sequences (Ross Sea Sequences; RSSs) bounded by regional Ross Sea unconformities (RSUs; Figure 2d) (Brancolini et al., 1995; De Santis et al., 1999; Conte et al., 2021; Figure 1a), and their associated sedimentary records reveal the climate-driven evolution of the Ross Sea continental shelf, Hillary Canyon, and DSW production between the late Oligocene and Pleistocene.

Previous studies (Conte et al., 2021; De Santis et al., 1999) hypothesize that DSW production and Hillary Canyon levee development began in the early Miocene. In the Late Miocene, ice expansion produced a regional hiatus between ~8 and 5 Ma (RSU-3). During the early to mid-Pliocene, possibly in association with the mPWP (3.264–3.025 Ma), the Antarctic Slope Front weakened (Conte et al., 2021). After ~2.5 Ma (RSU-2), glacial erosion of cross-shelf troughs (De Santis et al., 1995, 1999) resulted in the deposition of a shelf-margin prograding fan southeast of Hillary Canyon (Gales et al., 2021). Pleistocene cooling resulted in an invigorated ASC, polynya development, and sea-ice production, all primary drivers for AABW formation (Conte et al., 2021; R. M. McKay, Naish, Powell, et al., 2012).

1.4. IODP Site U1524

Our study uses two temporally overlapping IODP Expedition 374 sites within the Hillary Canyon depositional system. The more distal site, IODP Site U1524 (74°13.05'S, 173°37.98'W; water depth: 2,934 m), is located 120 km north of the continental shelf edge on the southeastern levee crest of Hillary Canyon (Figure 2c) (R. M. McKay et al., 2019). Vertical relief from the channel thalweg to the levee crest is ~500 m, the width of the thalweg is 5 km, and the width of the entire channel system, from levee crest to crest, is ~45 km (Figure 2c). Hole U1524A was drilled to 282.35 mbsf using Advanced Piston Coring and Extended Core Barrel systems (See R. M. McKay et al., 2019 for further detail on the methods used during Expedition 374.) This study focuses on the continuous, nearly complete sedimentary record from Hole U1524A (94% recovery), which spans the Late Pliocene (~3.3 Ma) through the Pleistocene. The portion of the U1524A record younger than 2.1 Ma is compared with sediments from the more proximal Site U1525.

Site U1524 (Figures 3 and 4a) consists of unconsolidated interbedded diatom-bearing/rich muds/sandy muds, muddy diatom oozes, and muddy diamictites. Most contacts between units and subunits are gradational, with a progressive downhole increase in diatom abundance (R. M. McKay et al., 2019). Unit I consists of ~200 m of Upper Pliocene to Pleistocene sediments and is subdivided into three subunits (IA, IB, and IC) based on relative biogenic content, which decreases upsection (R. M. McKay et al., 2019). A sharp contact separates Unit I and Unit II. Unit II consists of interbedded diatom-rich muds and diatom oozes.

Both IODP sites studied contain distinctive light yellow-gray layers, which contrast with the gray-to-brown background lithology. The layers have sharp basal contacts, and visibly coarser grain size relative to the encasing muds (Figure 3). The basal contacts do not indicate significant erosion of underlying deposits (e.g., inclined surfaces). The upper contacts are often irregular and resemble flame structures. The sedimentary structures within the morphological context of the levee depositional system (Figure 2) lead us to interpret these layers as turbidites.

1.5. IODP Site U1525

IODP Site U1525, drilled to a depth of 213 mbsf (recovery: 73.6%) in the southeastern Hillary Canyon levee near the base of the continental slope (75°0.06'S, 173°55.20'W; water depth: 1,776 m) This site is part of the same depositional system as that at Site U1524 (Figures 2a–2c) (R. M. McKay et al., 2019). Because Site U1525 is closer to the continental shelf edge, the levee geometry is highly asymmetric, including a 500-m-high northwest erosional flank and a less steep 30-m-relief flank to the southeast (R. M. McKay et al., 2019). This site is situated beneath the modern westward-flowing ASC (R. M. McKay et al., 2019; Orsi & Wiederwohl, 2009; Whitworth et al., 1998).

Site U1525 is divided into three lithostratigraphic units. Unit I (0–51.11 mbsf) consists of unconsolidated, bioturbated gray diatom-rich sandy mud with dispersed clasts, interbedded with clast-poor/rich muddy diamict, and is interpreted as a mass transport deposit (King et al., 2022; R. M. McKay et al., 2019). Unit II (51.1–118.58 mbsf), the primary focus of this study, is greenish-gray massive to laminated diatom-rich mud with higher and more variable clay content than Unit I. It features cm-scale micro-faulting, diamicts, and gravels, and is subdivided into Subunits IIA and IIB based on laminations, grain size, and diatom abundance (R. M. McKay et al., 2019). Subunits IIA and IIB include turbidite layers, referred to as “Type A” laminations by King et al. (2022), defined as mm-scale yellowish fine sand to silt laminae with sharp lower contacts. Subunit IIA (51.11–98.20 mbsf) includes massive-to-laminated greenish gray diatom-bearing mud interbedded with sandy mud with dispersed clasts and fine sand to silt layers (Figure 3a) (King et al., 2022). Subunit IIB (98.2–118.58 mbsf) features laminated greenish-gray diatom-rich mud interbedded with bioturbated diatom-rich sandy mud with dispersed clasts and diamict beds. The turbidite layers (e.g., “Type A” laminae) are less abundant than in Subunit IIA. Gray silty laminae with sharp upper and lower contacts and no grading, defined in King et al. (2022) as the “Type B” laminae, are not a focus of this study (King et al., 2022).

Unit III (118.58–208.7 mbsf) consists of laminated greenish-gray diatom-rich muds to muddy diatom oozes, interbedded with bioturbated light greenish-gray diatom-rich sandy muds to muddy diatom oozes with dispersed clasts and diamicts, with no identifiable turbidites (R. M. McKay et al., 2019).

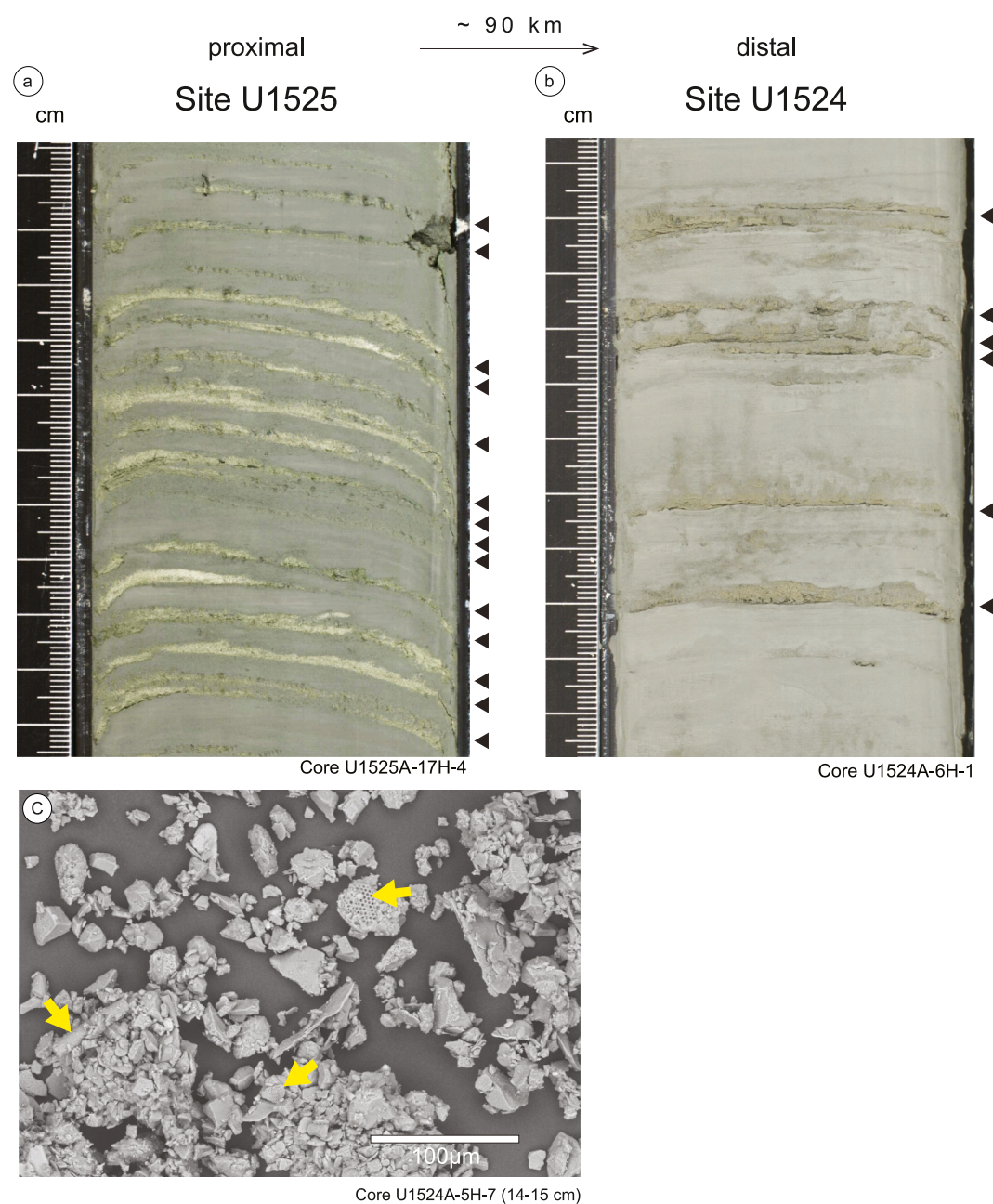


Figure 3. Core photographs from Sites U1525 (a) and U1524 (b) (proximal to distal to the shelf edge, respectively), highlighting the millimeter-thick (<2 mm) turbidite layers (black arrows). The sharp basal contact, along with the light yellowish color, are common features between the sites. (c) Scanning electron microscopy image showing the content of one of the turbidite samples, composed of a mix of terrigenous and fragmented biogenic material (yellow arrows).

2. Data and Methods

2.1. Core Characterization

The sedimentological characterization of turbidite layers in Sites U1524 and U1525 focuses on three parameters: stratigraphic position and total number of turbidites, thickness of individual turbidites, and grain size of a representative sampling of the turbidites.

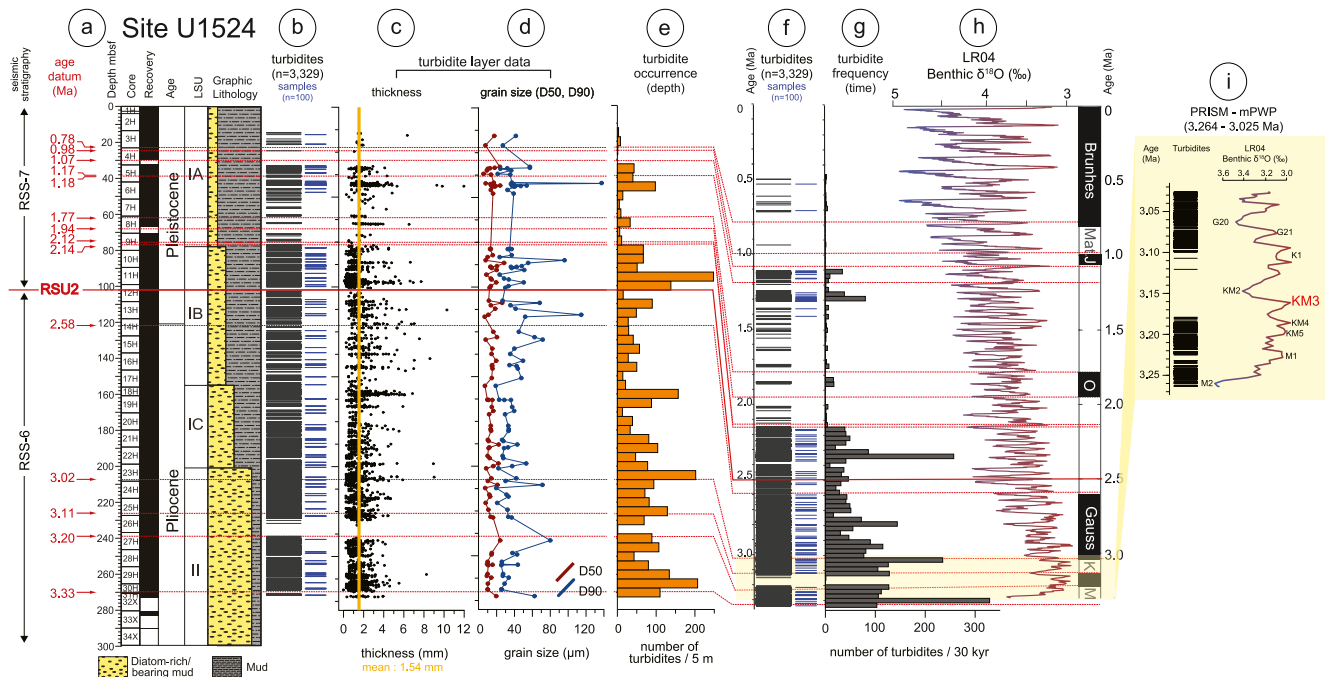


Figure 4. (a) Stratigraphic context for International Ocean Discovery Program Site U1524. Seismic stratigraphic framework from Conte et al. (2021). Age datums are denoted by the red lines (modified from R. M. McKay et al., 2019). (b) Stratigraphic position of all ($n = 3,329$) turbidites with sampled layers ($n = 100$) shown in blue. (c) Thickness of each turbidite layer with the orange line showing the mean (1.54 mm). (d) Grain size data of 100 turbidite samples showing the D50 (red) and D90 (blue) values (in μm). (e) Turbidite layer occurrence by depth (number of layers per 5 m). (f) Turbidite layers (black) and sampled layers (blue) in time. (g) Turbidite layer frequency (number of layers per 30 kyr). (h) Benthic $\delta^{18}\text{O}$ LR04 stack (Lisiecki & Raymo, 2005) with magnetochrons. (i) Inset showing the turbidite record in context of the mPWP and the KM3 interglacial in red.

2.1.1. Occurrence and Thickness of the Turbidite Layers

We visually identified the coarse bases of turbidite layers in high-resolution core photographs (Figure 3) and recorded the position of the base and top using a custom MATLAB script, which determines the thickness of the coarse division. Accurately determining the position of the finer-grained upper division of a turbidite requires distinguishing it from overlying sediment of similar grain size that is hemipelagic or bottom-current in origin, which is challenging to do systematically (Stow & Smillie, 2020). Thus, the phrase “turbidite layer(s)” hereafter refers to the coarse division that is readily visible. We also evaluated the lateral continuity and other characteristics from core images. The midpoint depth of each layer was assigned an age as explained in Section 2.2. To aid visualization of longer-term patterns of turbidite layer frequency, we computed and plotted the number of layers per time increments of 30 kyr and computed a kernel density estimate curve that is overlain on plots showing the interpolated age position of each turbidite layer.

2.1.2. Grain-Size Analysis of the Turbidite Layers

For the Upper Pliocene to lowermost Pleistocene interval (3.3–2.1 Ma), we took 78 samples of the turbidite layers in Hole U1524A to evaluate the sedimentological variations, including thickness and lateral continuity of the layers (visible in core images; Figure 3), throughout the succession (Figure 4b). For the Pleistocene interval recovered in Sites U1524 and U1525 (2.1–0.7 Ma), we identified and selected 21 and 50 samples, respectively (Figure 5b). For the <0.7 Ma interval, we took two samples from Site U1524, as turbidites are not preserved after 0.7 Ma in Site U1525 due to the deposition of mass transport deposits since that time. We subsampled material from the mm-scale turbidite layers within bulk samples for grain-size analyses.

To characterize the grain-size distribution within the turbidite layers, we used a laser particle analyzer (Malvern MasterSizer 3000). The average amount of sediment obtained from each layer was ≤ 1 g. No chemical treatment was necessary. We manually poured the sediment into the wet dispersion unit until it reached a stable obscuration range of 8%–10%. Each sample was measured three times. If the sample showed irregular distribution during the

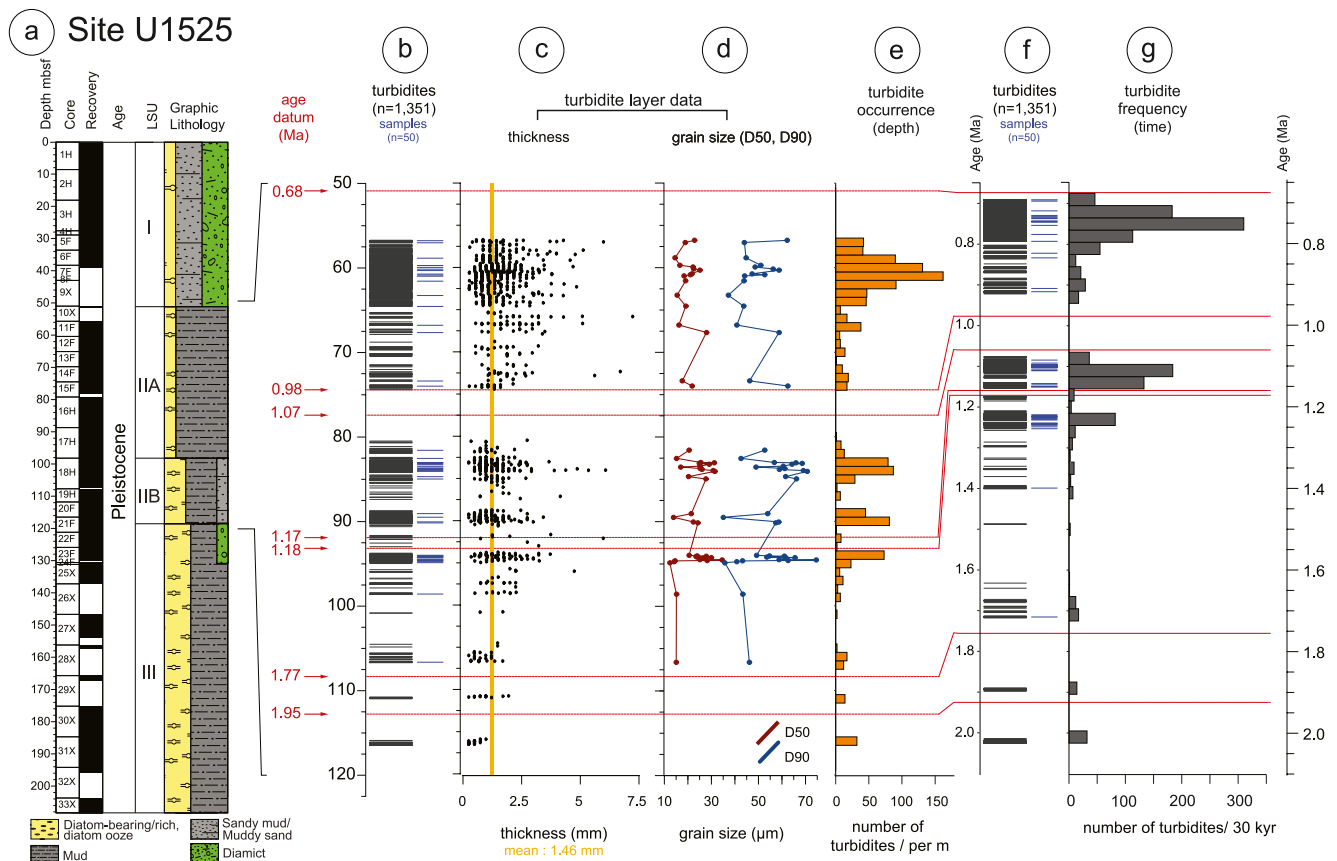


Figure 5. (a) Stratigraphic context for International Ocean Discovery Program Site U1525. Age datums are denoted by the red lines (modified from R. M. McKay et al. (2019)). (b) Stratigraphic position of all ($n = 1,351$) turbidites with sampled layers ($n = 50$) shown in blue. (c) Thickness of each turbidite layer, with the orange line showing the mean (1.46 mm). (d) Grain size data of 50 turbidite samples showing the D50 (red) and D90 (blue) values (in μm). (e) Turbidite layer occurrence by depth (number of layers per m). (f) Turbidite layers (black) and sampled layers (blue) in time. (g) Turbidite layer frequency (number of layers per 30 kyr).

analyses (e.g., large variations between analyses), additional analyses were conducted to ensure data quality. Data were processed using Gradistat version 9.1 (Blott & Pye, 2001), and the results are reported in volume percentage. We summarized the grain-size data by calculating the median (50th percentile; D50) and the 90th percentile (D90) from the distributions.

2.2. Chronology of the Turbidite Layers

To define the ages of the turbidite layers, we employed the shipboard age models, which combined biostratigraphy and magnetic polarity reversals placed on the 2020 Geomagnetic Polarity Timescale (Gradstein & Ogg, 2020; R. M. McKay et al., 2019). An ash layer at Site U1524 (Section U1524A-6H-2; 43.99–44.19 mbsf), interpreted as in situ was dated, and the resulting age (1.282 ± 0.012 Ma) is consistent with paleomagnetic age constraints (Di Roberto et al., 2021).

To determine the age of each turbidite event, we used linear interpolation between datums and assigned ages to the midpoint depth (average between base and top) of each turbidite layer. Because this approach carries inherent uncertainty, our interpretations emphasize longer-term trends and intervals constrained by multiple closely spaced age datums.

2.3. Modeling of Turbidity Current Properties

To explore the relationship between DSW processes and the hypothesized turbidity current deposition, we used a Rouse modeling approach (Rouse, 1938) to integrate the seismic-reflection-derived morphology of Hillary Canyon with sedimentological data (e.g., thickness and grain size of the turbidite layers) from Site U1524. This

approach emphasizes the vertical profile of suspended sediment concentration, allowing us to investigate sediment transport processes, particularly how DSW cascading off the shelf may drive down-slope sediment transport via gravity flows. We used the distributions of measured grain size, thickness of the turbidite layers, and the morphology and dimensions of the channel-levee conduit at Site U1524 as constraints for 100,000 model simulations, which incorporated a wide range of parameters using Latin hypercube sampling (LHS; M. D. McKay et al., 1979). Details of the methods and data used to constrain the calculated results are reported in the Supporting Information S1.

3. Results

3.1. Turbidite Layer Occurrence, Frequency, and Thickness

In Hole U1524A, we identified 3,329 individual turbidite layers between 272.5 and 14.5 mbsf (Figures 4–6), spanning the upper part of Unit II through Subunit IA. Turbidite-layer abundance is higher in Unit II, and Subunits IC and IB, between ~272.5 and ~78 mbsf (~3.3 and ~2.1 Ma; Pliocene; ~50–300 turbidites/30 kyr), and declines in Subunit IA (~10–50 turbidites/30 kyr). Within the lower part of the hole, an interval lacking turbidite layers occurs between ~239.6 and ~232.5 mbsf (~3.17–3.12 Ma). In the upper section (<~78 mbsf; Subunit IA) a high-frequency peak at ~45 mbsf (~1.3 Ma; >200 turbidites/30 kyr) is followed by a decline over the last ~1 Myr, culminating in the absence of turbidites above 14.5 mbsf (after ~0.5 Ma) (Figure 4g). Turbidite-layer thickness in Hole U1524A ranges from 0.4 to 6 mm, with rare exceptions >6 mm (Figure 4c). The average and median thicknesses are 1.54 and 1.29 mm, respectively.

At Site U1525, turbidite layers are less frequent from the base of the record to ~98.6 mbsf (~1.41 Ma), then increase upsection between ~98.6 and ~80.4 mbsf (~1.41–1.07 Ma) before a distinct gap in turbidite deposition from ~80.4 to ~74.3 mbsf (~1.07–0.92 Ma) (Figure 5b). Turbidites resume above this gap and are more common between ~74.3 and ~57.3 mbsf (~0.92–0.7 Ma), near the top of Subunit IIA. When binned in 30 kyr increments, two high-frequency intervals stand out (Figure 5g): a lower-frequency interval at 98.6 to ~80.4 mbsf (~1.41–1.07 Ma; 43 turbidite layers/30 kyr), and a higher frequency interval at ~74.3–57.3 mbsf (~0.92–0.7 Ma; up to ~188 turbidite layers/30 kyr). In both clusters, turbidite frequency increases upsection, with the upper bins exceeding 100 turbidite layers/30 kyr. Despite these differences in frequency, mean layer thickness is similar between clusters (1.40 vs. 1.50 mm).

The ~2.1 to ~0.7 Ma interval was recovered in both sites. At Site U1524, this interval (~75.3–21 mbsf) contains 254 turbidite layers out of 3,329 total, a relatively low concentration of layers (~8% of the total) for the site. In contrast, Site U1525 contains 1,351 layers over the same time interval (~116.4–56.7 mbsf) (Figure 6). The average thickness of the turbidite layers for the ~2.1 to ~0.7 Ma interval in Site U1524 is larger: ~1.9 versus 1.2 mm for Site U1525. However, it is worth noting that Site U1524 has significantly fewer turbidite layers ($n = 254$) compared to Site U1525 ($n = 1,351$) for this interval.

3.2. Grain Size

The grain size of the turbidite layers in Site U1524 ranges from very fine silt to very fine sand (5 to >100 μm) (Figure 4d). The median particle size (D50) ranges from very fine to medium silt (5–29 μm), whereas the D90 (90th percentile) extends from medium silt to very fine sand (9 to >115 μm) for the analyzed samples. There is no systematic trend in grain size as a function of depth. Figure 6 shows the distributions of D50 and D90 grain-size results from Sites U1524 and U1525 for turbidite layers that were deposited during the same time interval (2.1–0.7 Ma). The D50 values for Sites U1525 turbidites range from 13 to 35 μm (fine to medium silt) and from 5 to 24 μm (very fine to medium silt) for Site U1524 with no overlap in their interquartile ranges (Figure 6a). The difference in D90 grain-size values (Figure 6b) further indicates that the turbidite layers at Site U1525 are generally coarser-grained than Site U1524.

3.3. Rouse Concentration Profile Modeling Results

The constraints from our sedimentological measurements (Figure S1 in Supporting Information S1) and the channel-levee conduit morphology (Figure S2a in Supporting Information S1) reduced the total number of simulations from 100,000 to 1,759 (<2%) that matched the observed data (Figure S3 in Supporting

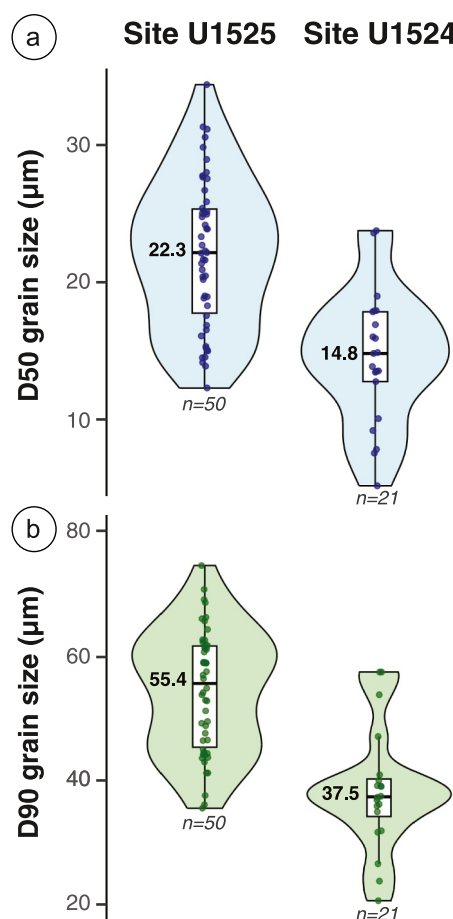


Figure 6. Violin plots with boxplot overlay of (a) D50 (median) grain size and (b) D90 (90th percentile) grain size for interpreted turbidites in proximal site U1525 (left) and distal Site U1524 (right) for the 2.1–0.7 Ma time interval. The number inside the violin plots corresponds to the median value (horizontal line with the boxplot) of the distribution.

Information S1). Our results indicate that the density currents responsible for these deposits were generally low velocity (<0.7 m/s) with a very low concentration of suspended sediment in the basal part of the flow ($<1\%$) (Figure S4 in Supporting Information S1). The scarcity of coarser grains in the levee deposits may reflect their unavailability, suggesting that Hillary Canyon's thalweg also lacks the thick, coarse-grained turbidite deposits typically found in canyon-channel systems linked to terrestrial sediment sources. Instead, these results suggest that the flows were likely driven by water-mass characteristics, with fine sediment suspensions producing a wider range of concentrations and flow durations.

4. Discussion

DSW–AABW formation in the modern Ross Sea is controlled by physical factors, including: continental shelf area (Amblas & Dowdeswell, 2018), seasonal polynya dynamics, and sea ice formation (Amblas & Dowdeswell, 2018; Baines & Condie, 1998; Zhang et al., 2024), interactions with CDW/LCDW (Amblas & Dowdeswell, 2018; Budillon et al., 2011; Morrison et al., 2020), ASC strength (Thompson et al., 2018, 2020), sub-ice shelf circulation (Gordon et al., 2009; Jacobs et al., 1979, 2002), and bathymetry (Amblas & Dowdeswell, 2018; Gales et al., 2021). We posit that focused density currents of sufficient velocity entrain and resuspend sediment from the shelf edge and/or upper slope, resulting in a low-concentration turbidity current in Hillary Canyon. Rouse modeling (see Supporting Information S1) indicates an estimated flow velocity of <0.7 m/s that is broadly consistent with limited direct observations of DSW transport off the shelf (~ 0.25 m/s (Budillon et al., 2002); 0.4 – 0.8 m/s (Gales et al., 2021)) and a low suspended sediment concentration ($<1\%$) is consistent with water-mass-driven density flows. These sediment-laden density currents, in turn, contribute to the construction of levee deposits adjacent to and defining the channel.

Here, we investigate the relationship between levee turbidite records from Sites U1524 and U1525 and climatic conditions over the past ~ 3.3 Myr, with an emphasis on the DSW–AABW outflow history. Our interpretations of outflow history (Figure 7) focus on well-dated intervals.

4.1. Late Pliocene Through Pliocene–Pleistocene Transition (~ 3.3 – 2.1 Ma) AABW Production

Site U1524 records its highest turbidite frequencies (~ 50 to >300 layers/30 kyr) between ~ 3.3 and ~ 2.1 Ma (Figure 4g), spanning the Late Pliocene into the Early Pleistocene. We interpret this clustering as reflecting repeated episodes of enhanced shelf-to-slope export linked to DSW–AABW formation under increasingly cooler surface conditions, when sea-ice production and polynya-style wind mixing could promote brine rejection and dense-water formation, yet grounded-ice occupation of the Ross Sea shelf remained dynamic rather than persistently shelf-wide (Figure 8a). This idea is consistent with AND-1B evidence that (i) Late Pliocene cooling included increased sea ice alongside ice-sheet expansion, and (ii) after ~ 2.6 Ma, interglacial conditions included polynya-like deep mixing comparable to the modern central Ross Sea polynya, a key region for sea-ice production and deep-water formation (R. M. McKay, Naish, Carter, et al., 2012). Finally, the same time window is compatible with repeated switches between grounded/ice-shelf states and open-water conditions in the Ross embayment, as documented for Pliocene WAIS oscillations (Hodell & Venz-Curtiz, 2006; Naish et al., 2009; Patterson et al., 2018).

During the Pliocene, and particularly during the mPWP (3.264–3.025 Ma), Antarctic ice volume was reduced during interglacials, relative to modern (Austermann et al., 2015; Cook et al., 2013; Dowsett et al., 2013; Naish et al., 2009). Earlier coupled climate simulations for the mPWP predicted globally warmer ocean temperatures, a weaker large-scale overturning circulation, and reduced AABW export, particularly into the Pacific sector, among

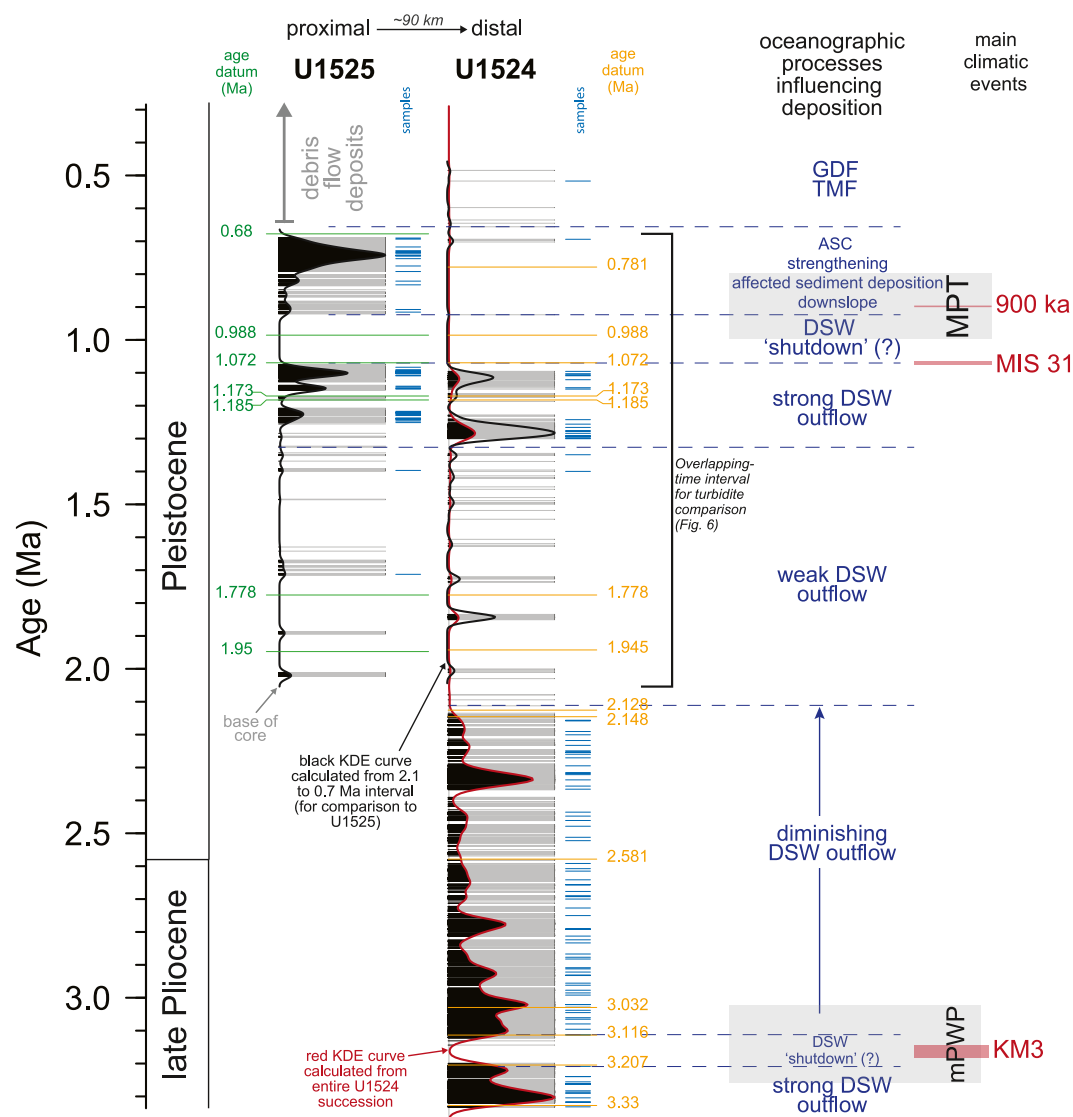
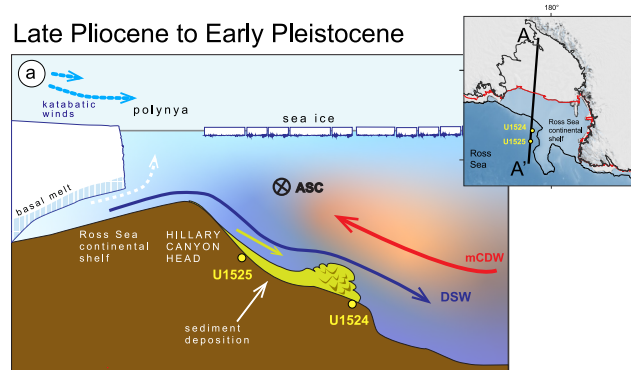


Figure 7. Comparative plots of turbidite frequency for Sites U1524 (right) and U1525 (left). Black horizontal bars on each plot indicate the positions of turbidite layers, while blue bars represent grain size sample points. Age datums are marked in orange for Site U1524 and in green for Site U1525. To visualize trends in intervals with abundant turbidite layers, kernel density estimate (KDE) curves were computed: the red KDE curve represents the entire Site U1524 succession (3.3 Ma to present), and the black KDE curve represents the shared interval between both sites (2.1–0.7 Ma). The “oceanographic processes” column highlights major trends in dense shelf water outflow and the influence of the Antarctic Slope Current (separated by blue dashed lines). In the upper part of the column, glacial debris flow-dominated trough mouth fan deposits are shown, which impact turbidite records in this region. The “main climatic events” column serves as a reference for broader contextual events: MPT = Mid-Pleistocene Transition; Marine Isotope Stage (MIS) 31 = MIS 31; KM3 = Marine Isotope Stage KM3.

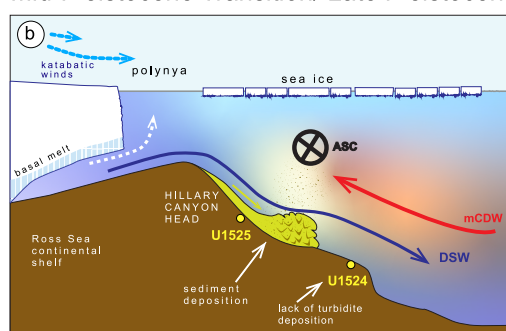
others (Dowsett et al., 2009; Haywood et al., 2016; Haywood & Valdes, 2004). More recent ice-sheet modeling incorporates ice-shelf dynamics and grounding-line migration, highlighting the sensitivity of Antarctic ice extent to ocean forcing while still lacking dynamic feedbacks between sub-ice-shelf processes and large-scale ocean circulation (Dolan et al., 2018; Halberstadt et al., 2024). Therefore, the implications of Pliocene ice-shelf behavior for Southern Ocean overturning and bottom water formation remain uncertain.

Between 239.6 and 232.5 mbsf (~3.17–3.12 Ma), there is a noticeable gap in the occurrence of turbidite layers at Site U1524 (Figures 4b–4f). Marine isotopic stage KM3 (3.17–3.15 Ma), recorded in Integrated Ocean Drilling Program Site U1361 from Wilkes Land (Patterson et al., 2014), has been described as an anomalously warm

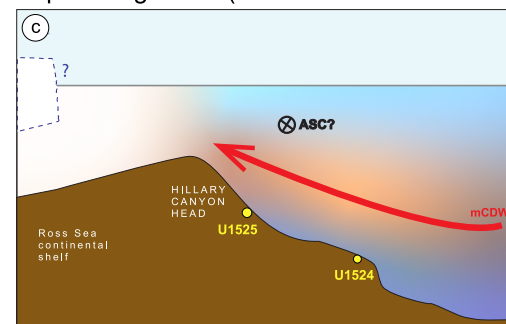
Late Pliocene to Early Pleistocene



Mid-Pleistocene Transition/ Late Pleistocene



Superinterglacials (Late Pliocene and mid-Pleistocene)



Pleistocene after 0.75 Ma

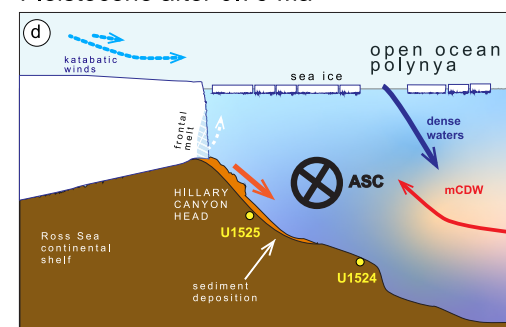


Figure 8.

interglacial based on diatom assemblages (Taylor-Silva & Riesselman, 2018). This short (~20 kyr) event has been linked to the southward migration of the Antarctic Polar Front (Barron, 1996; Dowsett et al., 1996; Taylor-Silva & Riesselman, 2018) and a significant reduction in sea ice (Dowsett et al., 1996; Haywood et al., 2016). We hypothesize that the observed gap in turbidite layers is the expression of the KM3 “superinterglacial” (or similar intervals within this period), which may have temporarily halted DSW-driven AABW export through Hillary Canyon (Figures 4i and 8c). Support for Ross Sea warming at this time comes from Site U1523 on the Iselin Bank of the Ross Sea, where Seidenstein et al. (2024) observed subtropical and temperate planktic foraminifera species indicative of warm open marine conditions. Gales et al. (2023) identified a coincident diatom-rich interval and minimal winnowing supporting regional warmth and reduced ASC strength at this time. Following KM3, cooler conditions returned, leading to increased sea ice presence, which was required to resume production of DSW and AABW (Taylor-Silva & Riesselman, 2018). This abrupt reduction (and resumption) of DSW-driven turbidity currents highlights the system's climate sensitivity during the mPWP, where partial deglaciation may have initially enhanced DSW formation, but more expansive deglaciation and decreased sea ice formation eventually reduced formation.

Full glacial conditions and the grounding of the WAIS at the continental shelf edge in the Eastern Ross Sea are interpreted to have occurred at ~2.5 Ma, as indicated by the regional unconformity RSU-2 (Figure 2) (Brancolini et al., 1995; Conte et al., 2021). Cooler conditions would have increased regional wind strength, polynya formation, sea ice production, and reinvigorated the ASC (Conte et al., 2021; R. M. McKay et al., 2019). The Site U1524 record indicates there was DSW-AABW production during the Pliocene-Pleistocene transition, with a potential increase in turbidite layer occurrence in the interval above RSU-2 (~102 mbsf) (Figure 4b). The diminished frequency of outflow events in the earliest Pleistocene might be associated with a reduction of continental shelf area as the AIS increased in size and extent.

Figure 8. Synoptic transect views of the Ross Sea area showing dense shelf water-Antarctic Bottom Water production history since 3.3 Ma. Conditions depicted do not specify glacial versus interglacial endmembers but generalized conditions. (a) Late Pliocene to Early Pleistocene, (b) Mid-Pleistocene Transition (MPT) and late Pleistocene, (c) “superinterglacials” during both Late Pliocene and Pleistocene, and (d) Pleistocene after 0.7 Ma. Inset map in (a) showing the modern Ross Sea and major features, along with the locations of Expedition 374 Sites U1524 and U1525. Approximated location of the transect shown as a black line (A-A'). Arrows depict the flow direction of the main currents and water masses, with arrow size representing their relative flow strength during each time interval: DSW = dense shelf water (blue arrows); mCDW = modified Circumpolar Deep Water (red arrows). The dark circle with an “X” indicates the Antarctic Slope Current (ASC) flow perpendicular to the profile (directed away from the reader). The turbidite plume (a and b; in yellow) highlights the variability of sediment deposition for Sites U1524 and U1525 during the (a) Late Pliocene to Early Pleistocene, and the (b) MPT and late Pleistocene, due to the influence of the ASC. (c) During the superinterglacials (KM3 and Marine Isotope Stage 31), sea ice was greatly reduced or even absent, while larger incursions of mCDW amplified the West Antarctic Ice Sheet (WAIS) retreat. (d) During the Pleistocene, after 0.7 Ma, the extension of the WAIS up to the shelf edge prevented DSW formation in Hillary Canyon, pushing its formation further offshore in an “open ocean polynya” style.

4.2. Variability in DSW Outflow During Marine Isotopic Stage 31 and the Mid-Pleistocene Transition (2.1–1 Ma)

Analysis of layer frequency, thickness, and grain size within the turbidite record at IODP Sites U1524 and U1525, allows for assessment of DSW–AABW production and transport via Hillary Canyon between 2.1 and 0.7 Ma. Comparison of grain-size data from the two sites for this time interval (Figure 6) indicates that the more proximal Site U1525 is systematically coarser, which we interpret to reflect its position closer to the shelf edge sediment source. Turbidite frequency at both sites shows broadly similar long-term variability during this interval (Figure 7). A hiatus in turbidite deposition at ~1.07 Ma in both sites aligns with peak MIS 31 warmth, when Ross Sea sea surface temperatures would have been between 3 and 5°C warmer than the present, leading to a strong reduction or collapse of the WAIS (R. M. McKay, Naish, Powell, et al., 2012; Pollard & DeConto, 2009; Scherer et al., 2008). We infer that warm conditions increased meltwater input and Southern Ocean stratification, which suppressed DSW–AABW production (Beltran et al., 2020; Golledge et al., 2014). A contemporaneous slowdown of the ASC may have reinforced this shutdown (Figure 8c). Turbidites remain absent until ~1.0 Ma at Site U1525 and until ~0.7 Ma at Site U1524, implying that the outflow remained quiescent for ≥ 0.07 Myr after MIS 31. These observations further link extreme interglacial warmth with sediment-routing inactivity in the Hillary Canyon system.

MIS 31 is followed by the latter part of the Mid-Pleistocene Transition (MPT), a period characterized by progressively colder conditions and changes in the mean state and variability of global ice volume (Clark et al., 2006, 2025). These conditions coincide with renewed evidence for DSW export to the deep ocean, which we interpret to have intensified around ~900 ka based on increased turbidite frequency at Site U1525 (Figure 7). Elderfield et al. (2012) linked an abrupt increase in seawater $\delta^{18}\text{O}$ at ~900 ka to suppressed melting during MIS 23 followed by renewed Antarctic Ice Sheet growth into MIS 22, pointing to a dominant Antarctic control on this climate transition. Recent work suggests that large-scale changes in deep-ocean circulation across the MPT may have been more modest than previously proposed, with gradual adjustments in ocean stratification rather than abrupt reorganizations of overturning circulation, as inferred from coupled neodymium and benthic carbon isotope records (Hines et al., 2024). In this context, while direct evidence for stepwise strengthening of AABW formation remains limited, our site-specific turbidite record indicates a clear intensification of DSW-linked sediment export, consistent with changing Southern Ocean influences on deep-ocean ventilation during the transition toward 100-kyr glacial cycles.

4.3. Pleistocene Cooling and the Strengthening of the Antarctic Slope Current After 1 Ma

Following the cessation of turbidite deposition at Sites U1525 and U1524 at ~1.0 Ma, their records diverge. Turbidite deposition resumed, reaching peak frequency, at proximal Site U1525, between ~0.92 and ~0.7 Ma (Figures 5–7). The peak in turbidite frequency suggests a resurgence in AABW production during the MPT. After ~0.7 Ma, there is a cessation of fine-grained turbidite deposition at Site U1525 and a shift to diamict-dominated lithofacies (lithostratigraphic Unit I; Figure 5a) indicating the onset of trough-mouth fan deposition (King et al., 2022).

At distal Site U1524, turbidite deposition did not resume after ~1.07 Ma; only a few layers are observed upsection. We interpret the intersite difference to reflect variable influences of the ASC. Seismic-stratigraphic evidence suggests that the ASC strengthened during cooler Pleistocene climate conditions, as indicated by sediment drifts west of Hillary Canyon (Conte et al., 2021). We propose that an intensified ASC laterally redistributed sediments carried by sediment-laden plumes cascading down Hillary Canyon (Figure 8b). Consequently, the Site U1524 turbidite record became decoupled from DSW–AABW processes over the past ~1 Myr.

As a result of trough-mouth fan deposition and bottom current intensification, we avoid interpreting the turbidite layer records after ~0.7 Ma. However, the overall depositional history of the Hillary Canyon offers insight into Pleistocene ice-ocean interactions. Gales et al. (2021) posit that gully incision of the Ross Sea slope occurred during glacials and early deglacials (when ice was grounded near the shelf edge) and that DSW production during interglacials was strong enough to prevent the infilling of gullies. This suggests that DSW cascades occurred over a broader region and were not confined to Hillary Canyon. This interpretation aligns with previous research suggesting that during partial ice advances across the continental shelf, denser waters were produced in coastal and ice front polynyas (Figure 8d) (Amblas & Dowdeswell, 2018; Bollen et al., 2022; Hillenbrand et al., 2017). Thus, records from Sites U1524 and U1525 capture longer-term climate trends of the Late Pliocene to early

Pleistocene and the system's response to warm climate intervals (e.g., KM3 and MIS 31) but suggest a more nuanced DSW-AABW production history during the late Pleistocene.

5. Conclusions

We present physical sedimentological data spanning the past ~3.3 Myr from IODP Expedition 374 Sites U1524 and U1525, both located on the depositional levee of Hillary Canyon on the Ross Sea continental rise and slope, respectively. Our data set and analysis focus on the stratigraphic position, thickness, and grain size of mm-scale sedimentary layers interpreted as the deposits of turbidity currents that flowed down-slope through Hillary Canyon. Sedimentologic data and associated turbidity current modeling support the hypothesis that these sediment-laden currents were driven primarily by dense bottom water and can be linked to DSW cascading into Hillary Canyon. Between ~3.3 and ~2.1 Ma, active DSW-AABW production indicated by the Site U1524 record was likely driven by enhanced polynya activity associated with Late Pliocene cooling. A notable gap in the turbidite record between ~3.17 and 3.12 Ma coincides with interglacial KM3, which was an anomalously warm interglacial (Seidenstein et al., 2024; Taylor-Silva & Riesselman, 2018). Turbidite frequency was low and generally similar at both sites between ~2.1 and ~1.0 Ma. Around ~1.07 Ma, there was a cessation of turbidite deposition at both sites during MIS 31 that may reflect reduced DSW-AABW formation. After this interglacial, the records at the two sites diverge, with turbidite deposition resuming at the proximal Site U1525 at ~0.92 Ma but not at distal Site U1524. We interpret these differences to reflect ASC strengthening. The system's response suggests that variability in bottom current strength or polynya activity can lead to nonlinear responses in sediment delivery, triggering significant shifts in both the initiation and spatial distribution of density-driven flows along Antarctica's continental margins. Our novel physical proxy for DSW-AABW production in the Ross Sea highlights interactions between ice sheet dynamics, continental shelf area, and climate conditions since the Late Pliocene.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

IODP Expedition 374 datasets are publicly available in the TAMU repository (<http://web.iodp.tamu.edu/OVERVIEW/>). The grain size data and turbidite layer occurrence from Sites U1524 and U1525 generated for this study are available at the U.S. Antarctic Program Data Center (USAP-DC) repository (Romans & Varela, 2024) <https://doi.org/10.15784/601807> with Creative Commons Attribution Only v4.0 Generic [CC BY 4.0].

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