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ANTARCTIC ICE SHEET RE-ADVANCE DURING THE ANTARCTIC COLD REVERSAL IDENTIFIED IN THE WESTERN ROSS SEA

Abstract: Baroni C., Tenti M., Bart P.J., Salvatore M.C., Gasperini L., Busetti M., Sauli C., Stucchi E.M. & Tognarelli A., *Antarctic Ice Sheet re-advance during the Antarctic Cold Reversal identified in the Western Ross Sea.* (IT ISSN 0391-9838, 2022).

Marine geophysical data collected from the Ross Sea continental shelf during several oceanographic expeditions enabled evaluation of the Last Glacial Maximum (LGM) extent of the Antarctic Ice Sheet (AIS) through the presence of large Grounding Zone Wedges (GZWs), particularly evident in the outer reaches of the Drygalski and Joides basins to the north of Coulman Island. Seismo-stratigraphic observations confirmed by geomorphological and stratigraphic data show a deep grounding line embayment dating back to the early deglacial transition, which preceded the last rapid sea-level and atmospheric CO_2 rise. In this work, a new reconstruction based on the analysis of morpho-bathymetric and seismic reflection data from the middle reaches of the Drygalski Basin shows that the post-LGM retreat was followed by a short-lived re-advance of the grounding line during the Antarctic Cold Reversal (ACR). Evidences include GZWs that partly overprint mega-scale glacial lineations associated with the Coulman Island grounding line, followed by a Holocene retreat phase, which caused the final southward withdrawal of the grounded and floating ice. This late re-advance suggests a significant impact on the extent and thickness of the grounded ice from relatively small amplitude climate oscillations, able to exert a significant control on the AIS during the latest Pleistocene (i.e. the Last Glacial Termination). Given that the marine-based portion of the AIS in the Ross Sea was sensitive to millennial-scale climate oscillations, this evidence will contribute to clarify how the ice sheet may respond to ongoing and future climate change.

Key Words: Drygalski Basin, Seafloor geomorphology, Geophysical data, Deglaciation, Antarctic Cold Reversal, AIS Re-advance, Antarctica.

Riassunto: Baroni C., Tenti M., Bart P.J., Salvatore M.C., Gasperini L., Busetti M., Sauli C., Stucchi E.M. & Tognarelli A., *Evidenze dell'avanzata della calotta glaciale antartica durante l'Antarctic Cold Reversal (ACR) individuate nel settore occidentale del Mare di Ross.* (IT ISSN 0391-9838, 2022).

I dati geofisici raccolti sulla piattaforma continentale del Mare di Ross nel corso di numerose spedizioni oceanografiche hanno permesso di valutare l'estensione della calotta glaciale antartica (AIS) nell'Ultimo Massimo Glaciale (LGM) tramite l'individuazione di corpi sedimentari associati alla linea di ancoraggio (*Grounding Zone Wedges*, GZW), particolarmente evidenti nel settore più esterno dei bacini Drygalski e Joides, a nord di Coulman Island. I dati sismo-stratigrafici, confermati da nuovi dati geomorfologici e stratigrafici, mostrano la presenza di profonde indentature delle linee di ancoraggio (*grounding zone*) attribuibili alle prime fasi della deglaciazione, che ha preceduto il rapido innalzamento del livello del mare e della CO_2 atmosferica nell'Olocene. In questo lavoro, una nuova ricostruzione basata sull'analisi dei dati morfo-batimetrici e sismici del settore centrale del bacino del Drygalski mostra che l'arretramento post-LGM è stato seguito da una breve ma significativa fase di ri-

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Authorship Statement - Project design by CB with contribute from MT, PB, MCS, and LG. MT processed geophysical data under the supervision of EMS and AT with contributes from LG, and collected US multibeam data under the supervision of PB. CB and MCS conducted seafloor geomorphological analysis and interpretation. MT and MCS organized the database and processed the GIS data. CB, MCS and MT organized the database of existent radiocarbon dates and ice core stratigraphy. CS and MB provided Italian morphobathimetric data and assisted MT during her traineeship at OGS. CB, MT, PB and MCS prepared the first draft of the manuscript, while the final version was accomplished with contribute from all authors.

Declaration of Competing Interest - The authors declare that they have no conflict of interest.

avanzata della linea di ancoraggio durante l'*Antarctic Cold Reversal*. Evidenze morfologiche mostrano che i depositi associati alle GZWs coprono forme di erosione glaciale (*mega scale glacial lineation*) associate alla fase di massima espansione della calotta che si estendeva fino a Coulman Island nel LGM. Questa fase di avanzata è stata seguita, nell'Olocene, dal definitivo arretramento verso sud dei ghiacci continentali e marini. L'avanzata tardoglaciale individuata nel Drygalski Basin suggerisce che anche le oscillazioni climatiche di minore ampiezza esercitano un impatto significativo sull'estensione e sullo spessore dei ghiacciai continentali, in grado di controllare il comportamento delle calotte antartiche durante la Terminazione I. Se la porzione di calotta antartica che poggia sui fondali marini nel Mare di Ross è veramente sensibile alle oscillazioni climatiche su scala millenaria, allora questa scoperta contribuirà a meglio comprendere come la calotta glaciale possa rispondere ai cambiamenti climatici in corso e a quelli attesi per il futuro.

Termini Chiave: Bacino del Drygalski, Geomorfologia sottomarina, Dati geofisici, Deglaciazione, *Antarctic Cold Reversal*, Riavanzata della calotta antartica, Antartide.

INTRODUCTION

During the past several decades, the Ross Sea has been intensively investigated to reconstruct the Antarctic Ice Sheet (AIS) dynamics from geological and geophysical data, in both its eastern (De Santis & *alii*, 1999; Mosola & Anderson, 2006; Bart & Cone, 2012; Bart & *alii*, 2017; Bart & Tulaczyk, 2020) and western sectors (Bart & *alii*, 2000; Fielding & *alii*, 2008; Levy & *alii*, 2012; Sauli & *alii*, 2014; Halberstadt & *alii*, 2016; Spector & *alii*, 2017; Lee & *alii*, 2017; Greenwood & *alii*, 2018; Prothro & *alii*, 2020). These data provide strong evidence that during the Last Glacial Maximum (LGM, from ~26 to 19 ka BP) the marine-based terminus was fed by several outlet glaciers and ice streams that drained the East Antarctic Ice Sheet (EAIS) and the West Antarctic Ice Sheet (WAIS). In several coastal areas, grounded ice markedly expanded as the grounding line advanced towards the continental shelf edge. The ice surface was thickened by more than 700 m at Ross Island and by 400 m at Terra Nova Bay (Denton & *alii*, 1989; Orombelli & *alii*, 1990; Denton & Hughes, 2000; Sugden & *alii*, 1999; Hall & Denton, 2000; Di Nicola & *alii*, 2009; Anderson & *alii*, 2014). In the offshore areas, fast-flowing ice streams scoured six deep trough basins across the Ross Sea embayment, leaving well-preserved Mega-Scale Glacial Lineations (MSGLs) that marked the former maximum extents. From the peak of the glaciation the grounding-line had advanced to within 200 km of the continental shelf edge in the western Ross Sea. Large Grounding Zone Wedges (GZWs) were deposited north of Coulman Island in the Drygalski and Joides basins (fig. 1; e.g. Licht & *alii*, 1996, 1999; Domack & *alii*, 1999; Shipp & *alii*, 1999; Anderson & *alii*, 2014). In contrast to the presumably slow advance of grounded ice leading up to the LGM, the subsequent deglaciation occurred rapidly, with the grounding line retreating by more than 1000 km with respect to its current location on the inner continental shelf. Indeed, during the deglaciation period (Last Glacial Termination, LGT, from 18 ka to 11.7 ka; e.g. Denton & *alii*, 2010; Fogwill & *alii*, 2017), Antarctica experienced a sea-level rise and a warming climate that triggered ice-sheet retreat. As a consequence of a positive feedback, an increase in carbon dioxide in the atmosphere (Toggweiler & *alii*, 2006) contributed also to produce a temperature rise and acceleration in the sea-ice retreat (Bianchi & Gersonde, 2004; Mandal & *alii*, 2022). Previous studies have demonstrated that this warming period was interrupted by abrupt cooling, the Antarctic Cold Reversal (ACR), chronologically constrained to 14.7-13 ka interval from the ice cores (Jouzel & *alii*, 1987; Ciais & *alii*, 1992; Blunier & *alii*, 1997; Pedro & *alii*, 2011; Stenni & *alii, 2011*), whose impact on the extent of floating and grounded ice in Antarctica has not yet been clearly defined. ACR is correlated to the warming Bølling-Allerød event in the Northern Hemisphere and this global pattern is an expression of the bipolar seesaw (McManus & *alii*, 2004; WAIS Divide Project Member, 2015; Pedro & *alii*, 2015, 2018). According to Pedro & *alii* (2015), a significant correlation exists between Antarctic ice core data and South Atlantic and Southern Ocean temperature records. This means that Antarctica experienced a strong ACR, especially around the Ross Sea area.

Being a key observation point, the Ross Sea has been investigated since the 1970s to constrain the timing and pattern of AIS retreat (Denton & *alii*, 1975, 1989; Kellogg & Kellogg, 1981, 1988; Stuiver & *alii*, 1981; Anderson & Bartek, 1992; Licht & *alii*, 1996; Conway & *alii*, 1999). Although not fully resolved, the western sector of the Ross Sea represents a key area for reconstructing the AIS retreat phases, from the ice-shelf maximum extent during the LGM to the evidence of inland deglaciation, and of the local onset of open marine conditions (Orombelli & *alii*, 1990; Baroni & Orombelli, 1989, 1991; Baroni & Hall, 2004; Gao & *alii*, 2022). In particular, the David Glacier, whose drainage basin extends over 213,500 km^2 (Rignot & *alii,* 2019), represents the most important outlet glacier entering the Victoria Land Basin (VLB), flowing from Talos Dome to the Ross Sea (Frezzotti & *alii*, 1998; Strasky & *alii*, 2009; Stutz & *alii*, 2021). The David drainage basin during the LGM and Termination I might have been significantly different from the present one (represented in fig. 1 after Zwally & *alii*, 2015). The present-day David Glacier advances on the Drygalski trough basin with a floating ice tongue 20 km wide and 100 km long, namely the Drygalski Ice Tongue (fig. 1).

The general paucity of multibeam data and of sediment cores in the southern Drygalski Basin (DB) relative to the large extent of deglaciated areas does not allow a detailed reconstruction of the ice-sheet retreat phase identified in the neighbouring areas, such as the major GZW north of Coulman Island testifying the peak LGM extent (Licht & *alii*, 1999; Shipp & *alii*, 1999), and the subglacial lineation and glacial landform assemblages around southern Crary Bank (Yokoyama & *alii*, 2016; Greenwood & *alii*, 2018), which suggest a complex retreat history for the AIS since the LGM.

A review of these and of other attempts to reconstruct the EAIS retreat scenario in the western Ross Sea (Conway & *alii*, 1999; Ackert, 2008; Anderson & *alii*, 2014; Halberstadt & *alii*, 2016; Prothro & *alii*, 2020) reveals some chronological inconsistencies. Early studies (e.g. Domack & *alii*, 1999) have shown that an abrupt backstep of the grounding line retreat had created a deep embayment prior to ~11 ka BP in the DB. Based on acid insoluble organic dating, Anderson & *alii* (2014) suggested an even earlier (~13 cal ka BP) EAIS post-LGM retreat in the Joides Basin. Prothro & *alii* (2020) shifted the retreat of grounded-ice from Coulman Island to ~16.5 cal ka BP, followed by the apparently rapid development of a deep grounding line embayment, with the Drygalski Ice Tongue reaching its present-day position by 12 cal ka BP. This reconstruction spans a phase range during which the atmosphere experienced a significant post-LGM warming trend, but an analysis of ice-core data also suggests that there was a noticeable return to cold conditions in the Southern Hemisphere during the ACR (Stenni & *alii*, 2011).

In this work, we examine seismo-stratigraphic and geomorphological evidences for understanding whether or not the shift to colder conditions caused either a cessation of the retreat and/or even a re-advance of the grounding zone in the western Ross Sea during the ACR.

DATA AND METHODS

We used marine geophysical data collected from 1988 to 2017 during several geophysical expeditions in the Ross Sea, including re-processed multichannel seismic reflection (MCS) profiles and multibeam morpho-bathymetric maps. Seafloor geomorphological analyses were combined with seismo-stratigraphic analyses, using the free software packages SeisPrho (Gasperini & Stanghellini, 2009), ArcGIS, and QGIS (https://www.qgis.org/it/site/), which allowed a pseudo-3D analysis of diagnostic glaciomarine features for the reconstruction of different phases of glacial dynamics.

Multichannel seismic (MCS) profiles

The MCS profiles IT90AR-60 (114 km long) and IT90AR-61 (125 km long) were collected by the Italian National Antarctic Programme (PNRA) onboard the R/V OGS-Explora in the austral summer 1989-90 (fig. 2). These profiles were selected on the basis of their position and orientation relative to the David-Drygalski paleo-ice stream, i.e., where the highest sediment flux is expected to have occurred during the AIS retreat. The two profiles are parallel and cross the Drygalski basin in E-W direction. The seismic acquisition parameters are listed in Table S1 in Supplementary Material.

The 1992 processing included a standard sequence consisting in resampling (from 2 ms to 4 ms), Common Mid Point (CMP) sorting, velocity analysis, amplitude recovery, deconvolution, normal moveout (NMO) correction, and stacking. For this work, we performed a different processing sequence (fig. 3) with the aim of improving the resolution of the uppermost part of the profile with respect to previous elaborations (Tenti, 2019), leaving out the deeper

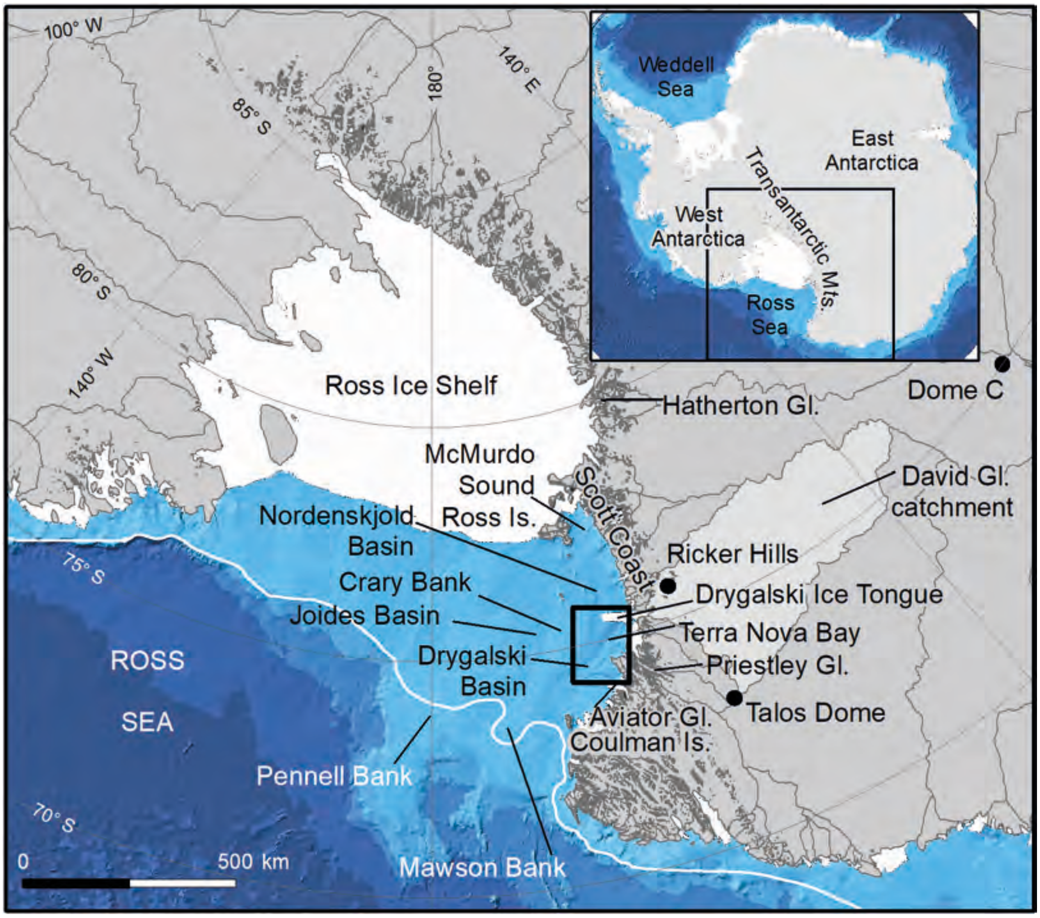

FIG. 1 - The Ross Sea bathymetry (Arndt & *alii*, 2013) with the study area evidenced in the black rectangle and the David Glacier catchment size highlighted in different grey tone. The white line indicates the LGM grounding line of the AIS at 20 ka (from Bentley & *alii*, 2014).

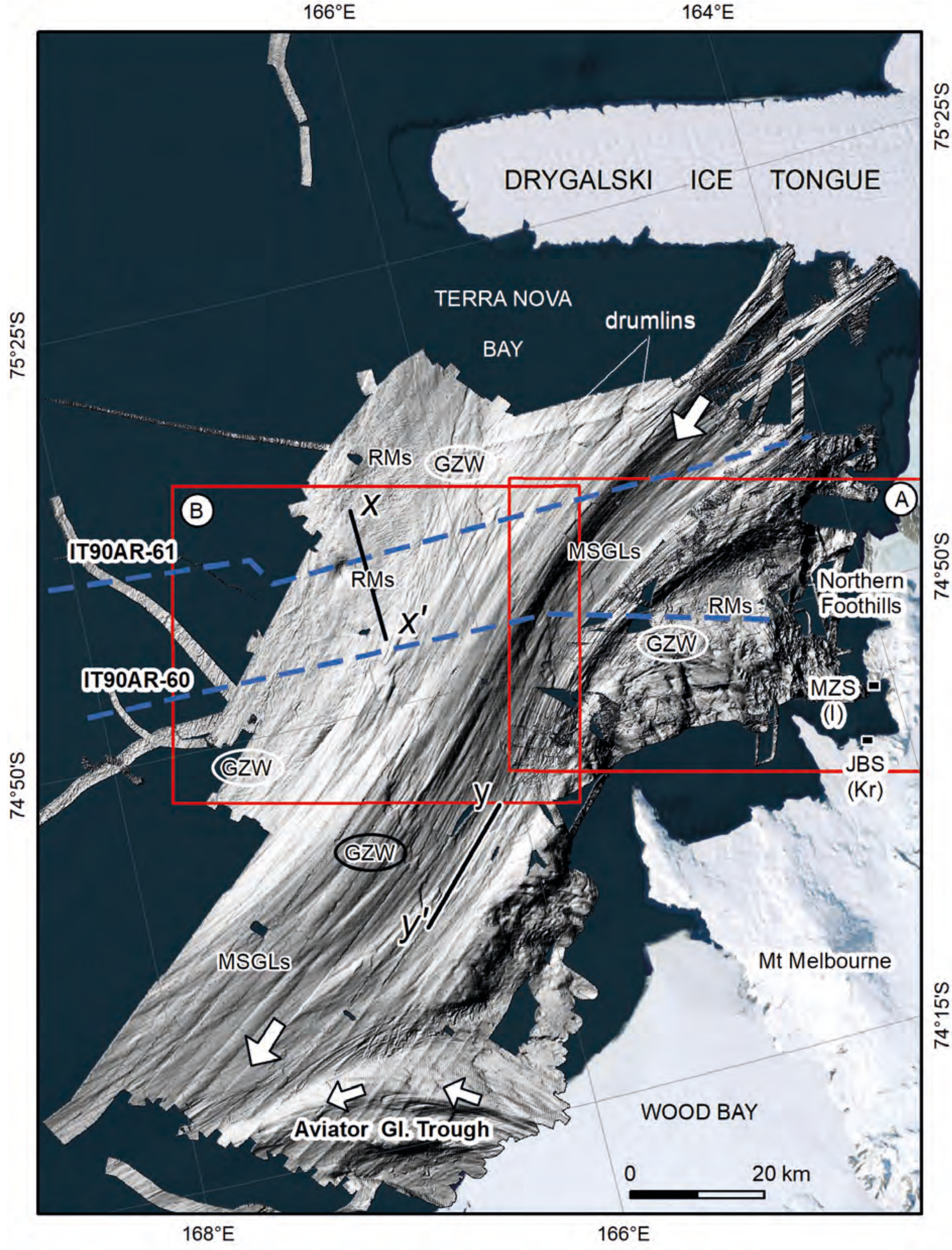

Fig. 2 - The Drygalski Trough Basin. Tracklines from cruise IT90AR (blue dashed lines); multibeam data compiled from US cruises NBP0801, NBP1801, NBP1704 and the Italian cruise compiled in the austral summer 2005-06; white arrows indicate the ice-flow direction during LGM; MSGLs: mega-scale glacial lineations; GZW: grounding-zone wedge (letters within the black oval indicate recessional stationary phases, while those within the white oval evidence the advance phase); RMs: recessional moraines. X-X' and Y-Y' indicate sections in fig. 5. Enlargements of red rectangles are reported in figs. 6 and 7 (A and B, respectively). Satellite image Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

part of the profile (including seafloor multiple), and investigating pre-Pleistocene deposits and the seafloor multiple). The initial steps were characterized by geometry loading, trace editing, and filtering, by applying a bandpass filter (the low cut and high cut frequencies are 0 and 110 Hz, respectively. 8 and 85 Hz are the high pass and low pass corner frequencies, respectively). Subsequently, we conducted a preliminary velocity analysis, by picking the first reflection related to the seafloor to create a first velocity model. We then applied a predictive deconvolution by using information derived from trace autocorrelation. After performing several tests (Table S2 in Supplementary Material), the best parameters showing improvements in resolution and enabling to attenuate reverberations were a prediction lag of 20 ms and a filter length of 130 ms for line IT90AR-60, and 20 ms and 180 ms respectively for line IT90AR-61. The pre-stack Kirchhoff migration both in time and in depth was applied to the deconvolved data. Because of the complex geology of the area, the root mean square (RMS) velocity field was smoothed to avoid abrupt lateral velocity changes and therefore a better handling of the Kirchhoff time migration algorithm, in which an aperture of 3125 m was used. However, owing to the theoretical limitations of the Kirchhoff pre-stack time migration in handling lateral velocity variations, we decided to perform a Kirchhoff pre-stack depth migration. To achieve this objective, we performed an in-depth migration velocity analysis and, to obtain a reliable estimate of the interval depth velocity field, we applied a layer stripping method (fig. S1 in Supplementary Material). This is an iterative method, which consists in determining layer velocity, starting from the top part of the section and observing the flatness of the reflection in common image gathers (CIGs) after migration. If the analysed reflection is horizontal, a correct velocity is used for migrating the data and the procedure is then repeated moving downwards to the following layer; otherwise, the velocity field must be modified, and the data need to be migrated again with the updated velocity field. This iterative procedure is largely time-consuming, but it provides the correct velocity field for migrating the data. Theoretical and practical analysis of the different processing steps applied can be found in Yilmaz (2001).

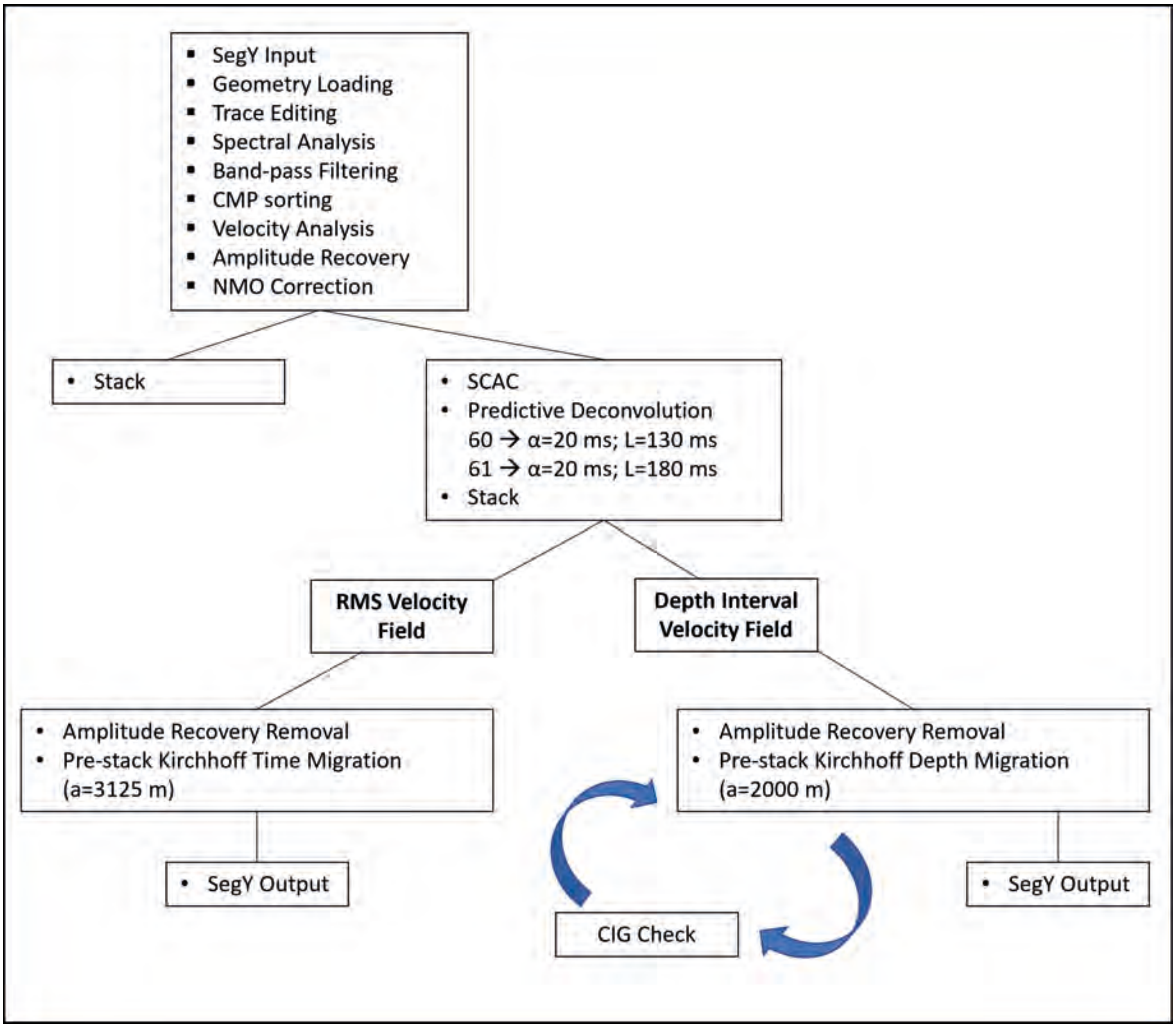

FIG. 3 - Processing sequence applied to multichannel seismic profiles. NMO = normal moveout; SCAC = surface consistent amplitude correction; ID = interval in depth; CMP = (common mid- point).

Multibeam data and seafloor morphological analysis

The multibeam echo-sounder (MBES) data presented in this study were collected during three different cruises onboard the R/V Nathaniel B. Palmer expeditions NBP0801, NBP1801 and NBP1704. Expedition NBP0801 conducted in 2008 acquired a data set by using a ship-based Kongsberg EM120 Multibeam Sonar system, while expeditions NBP1704 and NBP1801 conducted in 2017 acquired data sets with a Kongsberg Maritime EM122 Multibeam Sonar. Raw data taken from the Marine Geoscience Data System at www.marine-geo.org were processed with the Caris version 11.3 software, and gridded using the CUBE algorithm to reach a resolution of 5×5 m.

US multibeam data were merged with those of the Italian dataset, which were acquired by OGS as part of PNRA in 2006 with the R/V OGS Explora using a Reason 8111 MBES (depth range 600-800 m) and an 8150 MBSE (depth range of 400-1300 m). Most of the Italian data were processed using the Reson PDS 2000 software to produce a digital terrain model for morpho-bathymetric images. These data cover an area of 4500 km^2 between the Drygalski Ice Tongue and Coulman Island. Once processed, multibeam data were exported as geotiff files, and analysed using ArcGIS to interpret and map subglacial and seafloor landforms and deposits (figs. 2, 6, 7). US multibeam data were then imported in Blender 3.0, firstly as generic geotiff files to build the model, and then as raster images to build the texture. Subdivision surface, triangulate and decimate tools were applied to increase the resolution of the digital elevation model, capable of showing and measuring the real size of the detected geomorphological features (fig. S2 in Supplementary Material).

A geomorphological seafloor analysis was conducted to identify and to map relevant morphological features preserved at the sea bottom, represented within a GIS environment. An integrative way to visualise multibeam data consisted in importing the built model into the 3D Gaia software, which is a SaaS virtual reality platform (Supplementary Material).

Radiocarbon dates correction and calibration

Calcareous macrofossils provide the most reliable AMS radiocarbon ages for dating Antarctic marine sediments. On the other hand, many radiocarbon dates in the Ross Sea were obtained from acid insoluble organic matter (AIOM) extracted from bulk sediment samples, which can be contaminated by older carbonates, thus supplying both "old" surface age of marine sediment cores and biased ages within the cores. It is widely accepted to subtract the top age of the cores (if the top layer is preserved) so as to obtain "corrected" ages to be calibrated. For those cores that lost the top layer or did not supply any radiocarbon age of the organic matter at the sediment-water interface (according to Andrews & *alii*, 1999), we applied a correction of 3000 yrs before calibrating the dates.

We used previously published radiocarbon dates from sediment cores collected in the western Ross Sea to chronologically constrain the age of glacial features and marine deposits in the study area. All the collected dates (n= 147) are listed and described in the Supplementary Material (Table S3), while selected cores supplying relevant ages are reported in fig. 8. Apart from a few dates related to foraminifers, bivalves, and other biogenic carbonates, most dates were obtained from acid insoluble organic matter (AIOM). Table S3 in Supplementary Material presents: i) a brief core description; ii) uncorrected ^{14}C ages; iii) corrected ages as reported in original papers (obtained by authors applying different correction methods); iv) new corrected ages that we obtained by subtracting the age of the organic matter at the sediment-water interface (applied to dates from AIOM, not to carbonate ages); v) corrected ages we obtained by applying a correction of 3000 years (according to Andrews & *alii*, 1999) for those cores for which no radiocarbon age was available for the organic matter at the sediment-water interface.

All the new corrected dates (and dates from carbonates) were then calibrated using CALIB v 8.10, with the Marine20 curve (Heaton & *alii*, 2020), by applying a DR of 609 +/- 137 following the most recent values calculated for the Ross Sea region (Gao & *alii*, 2022).

RESULTS

The re-processing of MCS lines improved the imaging of seismo-stratigraphic features diagnostic for ice dynamics in the study area (figs. S3, S4 and S5 in Supplementary Material). The combined interpretation of MCS lines IT90AR-60 and IT90AR-61 (figs. 4 and 5), and multibeam-derived slope maps (fig. 2) offered a pseudo-3D view of the DB from the western flank of Crary Bank, showing both erosional and depositional features.

At a depth of about 1100 m, profile IT90AR-60 (fig. 4) shows a sharp unconformity (Unc-10) with high amplitude and continuity along almost the entire section. On the western side, it drops to ~1400 m within the trough and reaches down to ~900 m on the eastern side, suggesting a larger subglacial erosional event across the entire DB. This unconformity can be correlated to unconformity 10 detected in the Northern Basin described in Bart & *alii* (2000, fig. 4). The evidence for that is that both unconformities are located between 1.2 and 1.5 s two-way travel time. The stratigraphic level of unconformity 10 relative to DSDP Site 273 was carefully described by Bart & *alii* (2000); in the Northern Basin it is assumed to be equivalent to RSU2 by Brancolini & *alii* (1995a, b, c). Towards the seafloor, along the western flank, we observed a series of subparallel reflectors interrupted by a shallower unconformity that we correlated with the LGM (LGM unconformity in fig. 4), and this could be correlated to the Coulman Island GZWs on the outer reaches of the DB. The corrispondence of previously interpreted unconformities in the western Ross Sea is shown in Table S4 in Supplementary Material.

Paleo ice-flow features related to the flow of the AIS during the LGM are documented by the presence of MSGLs on morphobathymetric maps along the entire length of the DB (fig. 2). MSGLs show SW-NE orientations, and lengths between 8 km and 13 km, consistent with similar features identified in the Ross Sea by Anderson & *alii* (2014). In the northern sector of the DB (fig. 2), the MSGLs change direction from SW-NE to N-NE, at the confluence of the paleo Aviator Glacier trough into the LGM marine-based ice sheet. Drumlins (fig. 2) observed in the southernmost sector of the study area represent other clear markers of the ice-flow direction. Drumlins with maximum lengths of 5.5 km, widths of 1.7 km and heights of 50 m are very similar to the landforms documented at many locations on the Antarctic continental shelf and beneath the modern ice sheet (Shipp & *alii*, 1999; King & *alii*, 2007; Smith & *alii*, 2007; Clark & *alii*, 2009). Within the DB, line IT90AR-60 crosses a symmetric seabed structure that shows a maximum height of 30 m, representing a drumlin with layered and semi-transparent acoustic facies (fig. 4). All detected drumlin sizes agree with the morphometric data supplied by Clark & *alii* (2009).

Multibeam bathymetry shows two lobate GZWs within the deep narrow axis of the DB (fig. 2). These features are post-LGM in age, since they overprint the LGM unconformity. The relatively small GZWs are clearly evident on the shaded relief map of the DB (figs. 6, 7), and mark the former locations of the retreating grounding line, when the deep embayment evolved towards the present-day location of the Drygalski Ice Tongue. The outermost GZW in the middle of the valley has a maximum height of ca 40 meters, while the other GZW, 10 m high, is located ca 10 km behind the first one (figs. 2, 5). The offlap break of the wedge identifies the grounding line position during a still-stand phase of the post-LGM retreat.

Above the LGM unconformity, at a higher stratigraphic level, we observe prograding wedges perched at shallower depths on the flanks of the DB (figs. 4, 5). These remarkable structures represent GZWs perched above eroded flanks and adjacent deeper axes of the basin. Well-defined offlap breaks record the former extent of the grounded ice for an interval of time after the DB has been vacated. The wedges downlap over the underlying eroded strata and highlight the re-organization of the ice-flow between these two episodes.

On the western flank of the DB, the perched GZW foresets downlap the erosional base (fig. 4); the prograding wedge is ~150 m thick, with an observed horizontal extent > 10 km. On the eastern flank of the basin, the perched wedge has a thickness of 220 m and an extent of over 12 km. The upper surface of the eastern GZW is mantled by several small-scale ridges, with heights ranging from 3 to 8 m (figs. 4-5). These features cover ca 45 km with variable spacing between 400 and 500 m. Ridges on top of the perched GZWs show the same orientation, suggesting that they represent recessional moraines (figs. 2, 4, 5, 6, 7).

DISCUSSION

LGM and initial retreat from the Coulman Island extent

Onshore and offshore data show that the AIS greatly expanded across the Ross Sea continental shelf during the Last Glacial Maximum (Anderson & *alii*, 2014, 2018; Halberstadt & *alii*, 2016, 2018; Prothro & *alii*, 2020). As the climate cooled down and the sea-level dropped globally, grounded ice reached Ross Island and advanced towards the north. Radiocarbon ages of bulk carbon from biosiliceous mud in the Nordenskjold Basin, i.e., south of the Drygalski Ice Tongue, show that this area was covered by grounded ice after 25.1 ka BP (Finocchiaro & *alii*, 2007). Similar ages for the LGM glacial deposits are documented on land, in the Northern Foothills, where pelecypods and other reworked marine shells collected in glacial deposits and identified as "Terra Nova I drift" (corresponding to the "younger drift" in southern Victoria Land; Denton & *alii*, 1975) gave ages ranging from >33 to 23.5 ^{14}C ka BP (Baroni & Orombelli, 1989; Orombelli & *alii*, 1990; Di Nicola & *alii*, 2009). Maximum limiting ages for the AIS advance are also furnished by pre-Holocene marine deposits and penguin remains discovered in relict ornithogenic soils on the Scott Coast and dated to 24-45 ka ^{14}C ka BP (Gardner & *alii*, 2006; Emslie & *alii*, 2007; Lambert & *alii*, 2010; Parks & *alii*, 2015).

The marine-based AIS advance scoured the Drygalski Basin and remained grounded up to the latitude of Coulman Island, where the most advanced GZW was recognized (fig. 1; Bentley & *alii*, 2014; Halberstadt & *alii*, 2016).

In the offshore areas, evidence of the peak expansion includes MSGLs leading to extremely large, seismically resolvable GZWs in the outer reaches of the Drygalski and Joides basins (Shipp & *alii*, 1999). The underlying base of the LGM-GZW forms a downlap surface correlated towards the north with the outermost reaches of the DB and also with the Mawson Bank (fig. 1), where the GZW is observed close to the seafloor above a thin section of glacial marine sediments (Domack & *alii*, 1999; Bart & *alii*, 2011). The base of the glacial marine section is coeval with the Coulman GZW deposited during the LGM (Licht & *alii*, 1999). The large volume of the GZWs indicates a long-lived grounding line stillstand during the LGM.

In the western Ross Sea, the ice flow converged from several Victoria Land glacier outlets and other tributary valleys. The fast streaming of marine-based ice deeply scoured the DB, although the grounding-line remained far south to the continental shelf edge (figs. 1, 8; Bentley & *alii*, 2014; Halberstadt & *alii*, 2016). The ice advance direction is recorded by SW-NE oriented MSGLs (figs. 2, 6, and 7), which drape the topset of the large GZW on the outer continental shelf (Shipp & *alii*, 1999). Also clearly evident is the glacial trough scoured by the Aviator Glacier, the flow direction of the paleo-ice stream being marked by MSGLs oriented WNW-ESE through Wood Bay (fig. 2), turning towards WSW-ENE after its confluence into the DB, where the LGM unconformity delimits major subglacial erosion in the inner reaches.

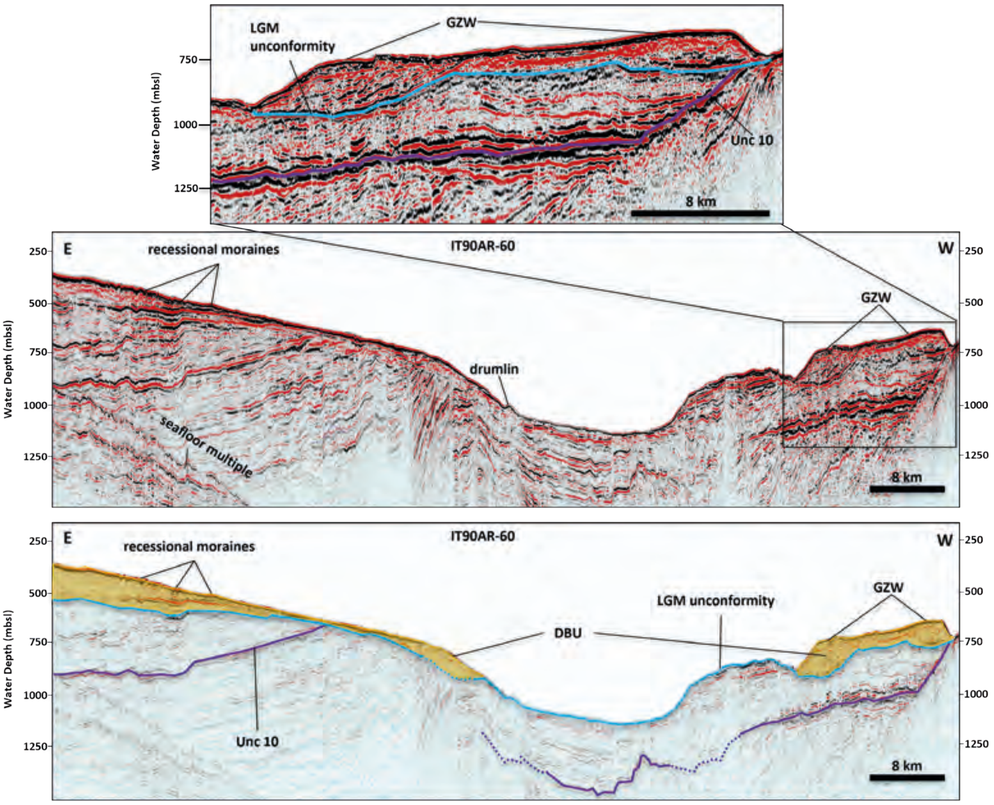

FIG. 4 - Processed and interpreted seismic line IT90AR-60 with detected geomorphological structures. The vertical scale is reported in meters below sea level. Unc 10 = unconformity 10 by Bart & *alii*, 2000 (purple horizon); LGM unconformity = unconformity related to the LGM event (blue horizon). Inferred horizons are drawn with dashed lined. GZW = Grounding Zone Wedge; DBU = Drygalski Basin Unit. Prograding wedges deposited during the re-advance are marked in orange.

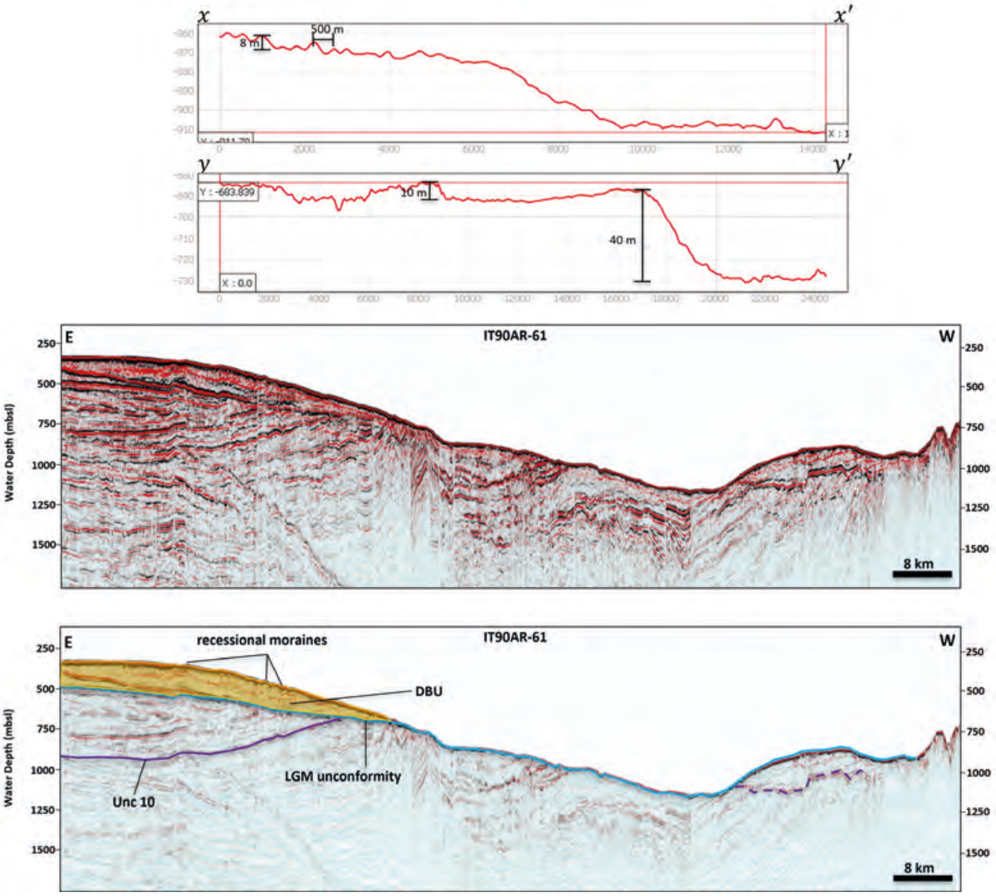

FIG. 5 - Processed and interpreted seismic line IT90AR-61 with detected geomorphological structures. The vertical scale is reported in meters below sea level. Unc 10 = unconformity 10 by Bart & *alii*, 2000 (purple horizon); LGM unconformity = unconformity related to the LGM event (blue horizon). Inferred horizons are drawn with dashed lined. DBU = Drygalski Basin Unit. Prograding wedges deposited during the re-advance are marked in orange. Top: x-x' profile traced in fig. 2 showing the size of the post-ACR recessional moraines and the y-y' profile representing the outermost GZW formed during the post-LGM retreat and visible in the middle of the trough basin (vertical scale reported in m below sea level).

The post-LGM retreat history of the AIS in the western Ross Sea is still debated, although geomorphological data, upcore sediment transitions, and chronological constraints show that deep grounding line embayment formed abruptly early in the deglacial transition, prior to either rapid sea level and/or atmospheric CO_2 rise (e.g., Licht & *alii*, 1996; Domack & *alii*, 1999; Shipp & *alii*, 1999). Domack & *alii* (1999) proposed that an abrupt backstep of the LGM grounding line retreat might have created a deep embayment prior to ~11 ka BP. Anderson & *alii* (2014) suggested an even earlier EAIS post-LGM retreat ~13 cal ka BP, based on acid insoluble organic dating in the Joides Basin. Prothro & *alii* (2020) proposed that the retreat was even earlier, i.e., prior to ~16.5 cal ka BP (according to core KC-37, fig. 8). Based on both radiocarbon dates and tephra layers, Di Roberto & *alii* (2020) provided strong evidence that grounded ice had retreated from Coulman Island GZW early in the deglaciation, i.e., by before ~15.1 ka BP (fig. 8, core 05PC) and that the Aviator Glacier trough had been completely deglaciated since at least 11 ka.

Within the axis of DB, a slightly diachronous succession of large scale MSGLs can be traced south of the LGM-GZW and of the Drygalski Ice Tongue. The occurrence of small-scale backstepped GZWs with sinuous grounding lines in the deep axis of the DB shows that the GWZs are younger to the south. In the area of our study, these relatively small lobate GZWs record the grounding line retreat after ~17.0 ka BP. Such wedges are significantly smaller than the GZWs north of Coulman Island in terms of dip and strike dimensions. The small volume and the sinuous grounding line orientation suggest that the unit represents deposition at a rapidly retreating grounding line (Simkins & *alii*, 2018). Had retreating ice paused significantly, there would have been a greater aggradation of subglacial sediment along a greater length of DB that more fully-filled the entire width (given the enormous drainage area and sediment yield potential of the David Glacier and adjacent tributaries converging to the basin). On this basis, we may hypothesize that the grounding line embayed deeply to the south, up to the current location of the Drygalski Ice Tongue. A minimum age of 12.8 ka BP from core ANTA91-30 further sustains this interpretation (fig. 8 and Supplementary Material, Table S3; Brambati & *alii*, 1997; Frignani & *alii*, 1998). Despite the grounding line retreat, the calving front of the ice shelf was located near the modern Drygalski Ice Tongue until at least 12 cal ka BP, and open marine conditions were not established until 9.5 ka, based on a chronological control in core TH95-1604 (Prothro & *alii*, 2020; fig. 8, point GC1604). Slightly older ages for the onset of open marine sedimentation, 10.4 and 9.6 ka, were obtained from cores ANTA91-29 and DF80-PC102 respectively (Prothro & *alii*, 2020; fig. 8: points 29 and PC102).

ACR re-advance

The geomorphological and geophysical data presented in this paper provide evidence of a cessation in retreat and of an AIS grounding zone re-advance after the grounding line retreated through the deep axis of the DB after 16.6 cal ka BP (Prothro & *alii*, 2020). Evidence of this re-advance includes the partial burial of LGM unconformity in the coastal zone where it fronts the Transantarctic Mountains and from the western flank of Crary Bank (figs. 6 and 7). The perched GZWs identified in figure 4 represent the Drygalski Basin Unit (DBU), an unconformity bounded depositional sequence. We propose that the DBU was deposited during the re-advance phase by a grounded marine portion of the AIS coming from the interior, most probably fed by the Reeves and Priestley glaciers and directed from WSW towards the ENE. The internal structure of this GZW is clearly highlighted by the geophysical analysis of seismic line IT90AR-60, which shows a well-expressed foreset structure aggrading and downlapping older recessional seafloor features (fig. 4). These foresets fit very well with the GZW evident on multibeam data (fig. 7).

Chronological evidence supports our hypothesis of the ACR re-advance. As a matter of fact, the DBU is bracketed, above and below, by radiocarbon ages and by a stratigraphic framework; relevant maximum ages are furnished by dates from LGM glacial tills and/or glacial marine sediments drilled in the study area: 26.6 ka BP (ANTA99-cD38), 26.8 (NBP95-01-KC37), and 27.3 ka BP (NBP95-01-KC44). On the other hand, although the upper limit of the DBU is diachronic, the ACR overlies an unconformity that spans at least 10 ka (from 26.6-26.8 ka BP to 17-16.6 ka BP; Finocchiaro & *alii*, 2007; Prothro & *alii*, 2020; Brambati & *alii*, 2002). Ar/Ar dates from tephra layers collected in marine sediment cores are constrained to have been deposited prior to the major last onset of deglacial warming and sea-level rise (Licht & *alii*, 1996, 1999; Cunningham & *alii*, 1999; Domack & *alii*, 1999; Licht & Andrews, 2002; Mosola & Anderson, 2006; Finocchiaro & *alii*, 2007; Melis & Salvi, 2009; Bart & *alii*, 2011; Anderson & *alii*, 2014; Yokoyama & *alii*, 2016; Mezgec & *alii*, 2017; Di Roberto & *alii*, 2020; Prothro & *alii*, 2020).

The minimum ages for the GZWs re-advance are provided by dates from the base of marine sediments (fig. 8) covering glacial deposits and/or recessional moraines at cores ANTA91-29 (10.4 cal ka BP), DF-80-PC102 (9.6 cal ka BP), NBP95-01-KC31(9.8 cal ka BP) and ANTA99-cD38 (9.1 cal ka BP).

GZW detected in the eastern flank of the DB, descending from Crary Bank, is SW-NE oriented (fig. 7), and represents a re-advance phase that we correlate to the one identified in the western sector of the same trough. This GZW buries the MSGLs throughout the basin and is overlapped by recessional moraines recording a subsequent grounding zone retreat, deposited above the wedge. This feature witnesses the resumption of a south-eastward retreat, first directed towards Crary Bank and then continuing beyond the Drygalski Ice Tongue (Halberstadt & *alii* 2016; Greenwood & *alii*, 2018). We speculate that the latest southward retreat of grounded and floating ice might have been rapid, as suggested by the presence of small-scale recessional moraine fields and might have been triggered by the onset of warmer conditions.

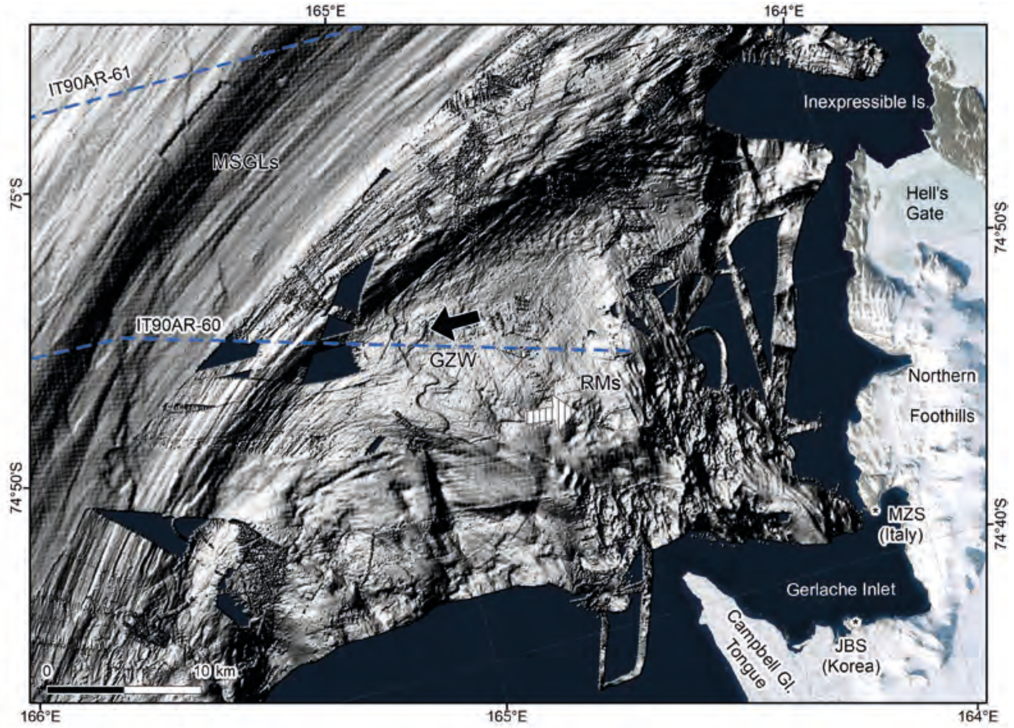

FIG. 6 - Detail of the Drygalski Basin Trough and of the Terra Nova Bay area (see fig. 2 for location). Morphobathimetric data compiled during the US cruises NBP0801, NBP1801, NBP1704 and the Italian OGS-PNRA cruise in the austral summer of 2005-06. Blue dashed lines indicate the seismic lines IT90AR_60 and IT90AR_61 (see fig. 2). MSGLs: mega-scale glacial lineations (LGM); GZW: grounding-zone wedge (ACR); the black arrow indicates ice-flow direction during ACR; RMs: recessional moraines; the white dashed arrow indicates mean receding ice flow direction. Satellite image Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

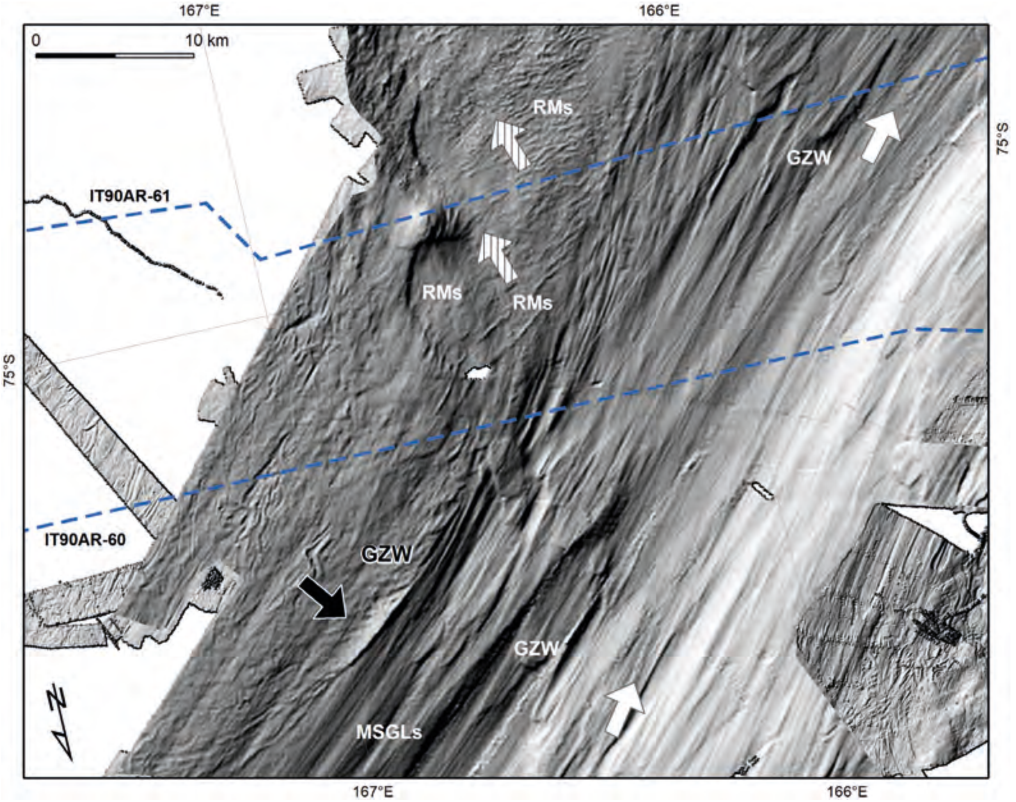

FIG. 7 - Detail of the Drygalski Basin Trough (see 2 for location). Morphobathimetric data compiled during the US cruises NBP0801, NBP1801, NBP1704 and the Italian OGS-PNRA cruise in the austral summer of 2005-06. Blue dashed lines indicate the seismic lines IT90AR_60 and IT90AR_61. The white arrow refers to the NNE-SSW oriented retreat of the marine-based Ross Ice Shelf (after the LGM); GZWs in white indicate stationary positions of the retreating ice sheet onlapping the previously scoured seafloor with mega-scale glacial lineations (MSGs, LGM). GZW in black and the black arrow show the ice-flow direction of an advanced phase of the ice sheet (ACR). White dashed arrows indicate the glacial retreat direction after the ACR, as underlined by recessional moraines (RMs) covering older seafloor features.

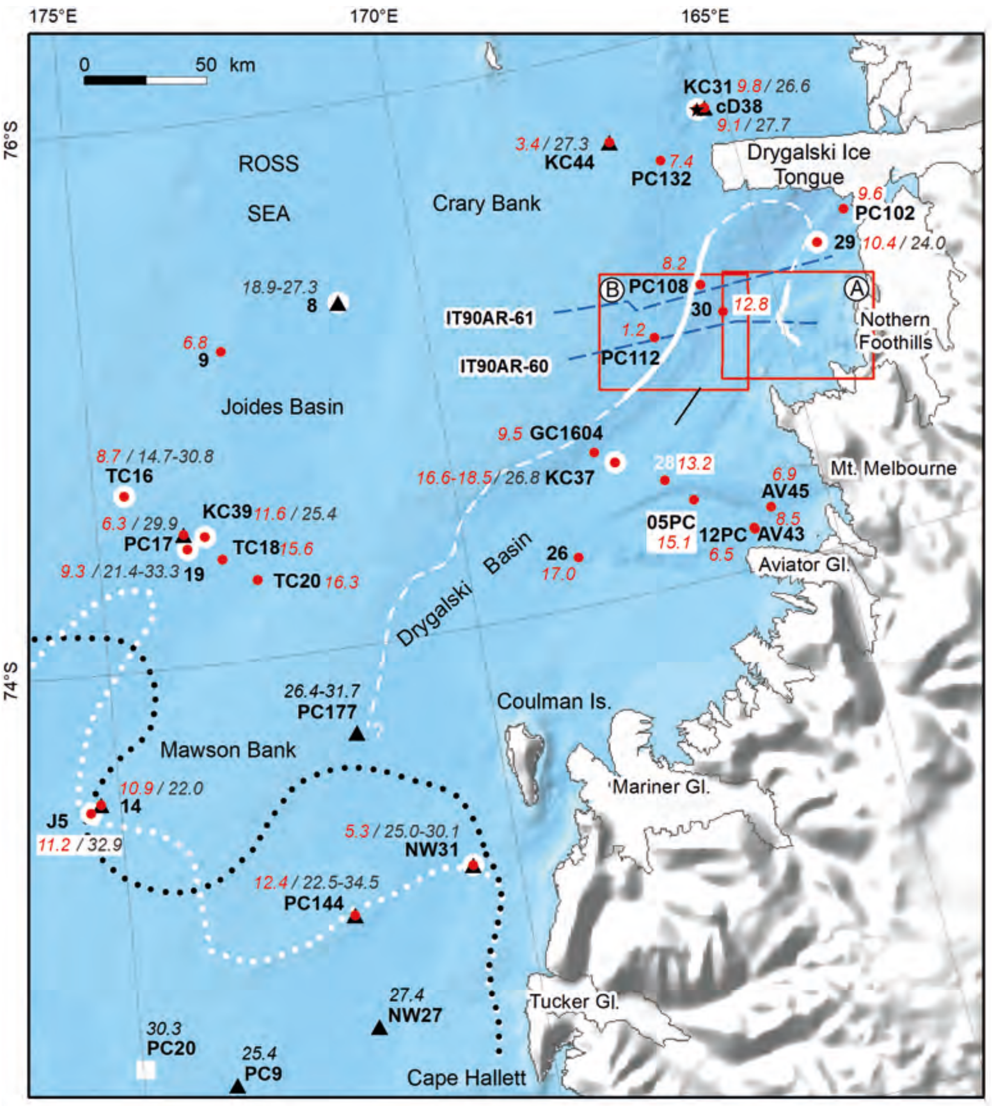

FIG. 8 - Selected sea-bottom cores in the western Ross Sea (facing the northern Victoria Land) used to constrain AIS retreat phases (core id in bold). Red numbers in italics indicate minimum cal age for deglaciation (^{14}C cal age BP); black numbers in italics refer to radiocarbon dates predating the LGM glacial deposits (^{14}C cal age BP). Table S3 in Supplementary Material provides the complete list of cruises, cores, lithology, radiocarbon dates from selected cores, and reference. White square: pre-LGM marine deposits; white circles: glacial diamicton (subglacial till, LGM); black triangles: late Pleistocene glacial-marine deposits; black star: LG glacial marine diamicton; red dots: marine deposits providing minimum ages for deglaciation. LGM grounding line position according to Bentley & *alii* (2014; black dots) and Halberstadt & *alii* (2016; white dots). Reconstructed ACR advance is marked with white lines (dashed: inferred). Blue dashed lines indicate the seismic lines IT90AR_60 and IT90AR_61. Enlargement of red rectangles is reported in figs. 6 and 7 (A and B respectively). Bathymetry from Arndt & *alii* (2013).

Reconstruction

The DBU boundaries are clearly diachronous, as evidenced by the distribution of ages bracketing this unit (fig. 8). As a matter of fact, several papers reconstruct different phases of grounding line retreat for the marine-based AIS after the LGM and recognize stationary positions of the grounding zone in a general trend of glacial recession, starting from at least ca 16.6 ka or even 17.0 ka (Prothro & *alii*, 2020; Brambati & *alii*, 2002). Various attempts have been made to reconstruct the retreat phases, including the swinging gate model by Conway & *alii* (1999), which suggests a general retreat in all troughs, and the "saloon door" model by Ackert (2008), with different troughs characterized by different retreat phases. Finally, supported by geomorphological evidence, the marine-based model by Halberstadt & *alii* (2016) showed nine steps of the AIS retreat, constrained with dating later resumed by Prothro & *alii* (2020).

Our reconstruction involves four main stages (fig. 9):

- an initial LGM configuration (Stage-1), well-known and widely-accepted;
- an early post-LGM retreat (Stage-2) started around 18.6-17.0 ka BP, according to Prothro & *alii* (2020) and Brambati & *alii* (2002), endured since at least 16.6 ka BP (grounding line position at NBP95-01-KC37, fig. 8), but presumably since 15-14.7 ka BP;
- an ACR re-advance (Stage-3) bracketed by the maximum limiting ages of 16.6 ka BP from the recessional position at KC37 and 15.1 ka BP at core 05PC (fig. 8); minimum limiting ages of 10.4-9.8 and 9.6 are furnished by cores 29, cD38, and PC102 respectively; these minimum ages were obtained from AIOM at the base of marine sediments onlapping the GZW of the DBU and/or the recessional moraines in Terra Nova Bay (figs. 6, 8);
- a post-ACR retreat (Stage-4) since at least 10.4-9.8 ka BP.

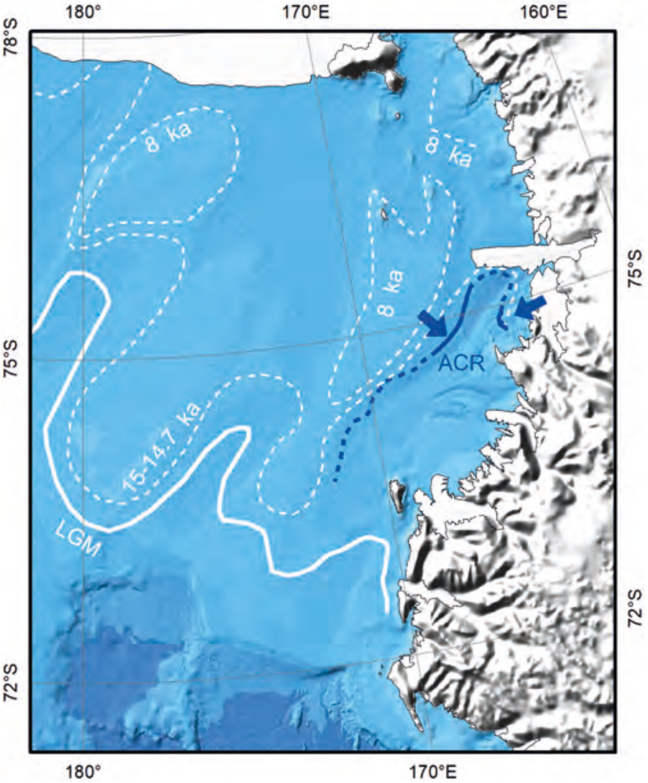

FIG. 9 - ACR re-advance model (blue lines; dashed: inferred) proposed in this study, based on glacial geomorphological evidence identified in the Drygalski Basin and legacy sediment core dating analyses (blue arrows indicate direction of re-advance). White continuous line marks LGM grounding line position, while white dashed lines indicate recessional phases (age ka BP). LGM and 8 ka GZWs positions after Halberstadt & *alii* (2016). Bathymetry from Arndt & *alii* (2013).

Stage-1 is marked by the position of the grounding line during the LGM north of Coulman Island in the western Ross Sea, as testified by well-known evidence (Licht & *alii*, 1996, 1999; Domack & *alii*, 1999; Shipp & *alii*, 1999; Anderson & *alii*, 2014). Stage-2 marks our hypothesized deeply embayed post-LGM retreat of the AIS. The main difference we demonstrate in our model is the introduction of a re-advance phase occurred during the ACR (Stage-3). Since there are not enough sediment and ice cores in this area, it is impossible to date the deposits more accurately. Nevertheless, knowing the location of the grounding line at 16.6 ka (core ANTA95-KC37, Prothro & *alii*, 2020; point KC37 in fig. 8), the coastward retreat and the subsequent re-advance would have been possible only if internal and external forcings had triggered a fast response of the AIS. Finally, Stage-4 represents the post-ACR retreat, reaching the coast of Terra Nova Bay at 8.2 ka BP (Baroni & Hall, 2004; Gao & *alii*, 2022), and pinning on the Crary and Mawson Banks on the opposite side.

CONCLUSION

The regional stratigraphic framework in the Drygalski Basin indicates that the post-LGM retreat was already underway at 17.0-16.6 ka BP, and had created a deep embayment migrating south of 75° S. Several GZWs, perched on the shallow east and west flanks of the basin, south of 74° 30'S, partially buried the backstepped GZWs along the deep axis of the basin. The seafloor geomorphological analysis and the re-processed marine geophysical data presented in this work, well-correlated within the stratigraphic frameworks available, enabled us to suggest that the perched GZWs mark the cessation of a retreat phase, followed by the onset of a subsequent re-advance during the ACR, in a time span between ca 15 and 13 ka. The re-advance of the AIS in this sector might have been mainly related to a rapid response of the Reeves and Priestey glaciers, smaller and thinner than the David Glacier, and more sensitive respect to ice-sheet/ocean interaction. In fact, Crotti & *alii* (2022) pointed out that the sector of the ice sheet culminating at Talos Dome and drained by the Reeves and Priestley glaciers is more sensitive to the intrusion of "warm water" as Circumpolar Deep Water (CDW) with respect to the sector drained by the David Glacier. Therefore, the re-advance of the AIS fed by the Reeves and Priestley glaciers could be attributed to a reduction of the intrusion of CDW during ACR in this sector of the Ross Sea as a response related to the bipolar seasaw.

Geomorphological features identified on the sea floor show that the post-ACR retreat is marked by small-scale recessional moraines recorded on both sides of the DB. They document the local retreat direction towards the SE on the Crary Bank and towards the WSW in Terra Nova Bay.

The results of this study offer new evidence on a regional scale effect, i.e., that the ACR had a significant impact on the extent of grounded ice and indicates how relatively small-amplitude climate oscillations might have exerted an important control on the Antarctic Ice Sheets during the Late Pleistocene. Our results offer new fundamental insights into the sensitivity of the AIS to ongoing climate change that emerges from recognizing its response to past climate change at millennial scale, i.e. the Antarctic Cold Reversal, which is of paramount importance to understand the future behaviour of the AIS.

SUPPLEMENTARY MATERIAL

Supplementary material associated with this article can be found in the online version, at http://gfdq.glaciologia.it/045_1_01_2022/

DATA AVAILABILITY

This project employed the data provided by the National Science Foundation (NSF) and by the National Programme of Researches in Antarctica (PNRA) within the framework of the Martina Tenti PhD project on Polar Sciences of the University of Venice "Ca Foscari" (supervisor C. Baroni). The US multibeam data used in this study are available online at www.marine-geo.org, Marine Geoscience Data System. The Italian multibeam data are available at the IBCSO Antarctic bathymetry (Dorschel & *alii*, 2022).

The two multichannel seismic profiles processed in this work were acquired by OGS as part of the PNRA, and they are available at the Antarctic Seismic Data Library System under the auspices of the Scientific Committee on Antarctic Research (SCAR) policy (https://sdls.ogs.trieste.it). Seismic processing was carried out with the academic license from Landmark for Promax software released at the University of Pisa (Italy). Seismic profiles have been interpreted both with SeisPhro software developed by Luca Gasperini (CNR Bologna, Italy) and with the IHS Markit Kingdom, whose academic license was released at Louisiana State University.

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