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Miocene mounds on the Ross Sea paleo-continental shelf: evidence of the onset of Antarctic glaciations or mud volcanoes?

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ABSTRACT Buried mounds have been identified on seismic reflection profiles in the southern Roosevelt sub-basin of the eastern Ross Sea, Antarctica. Since they have never been sampled, the composition of these mounds can only be inferred from their acoustic character. Previous studies have hypothesised that they are buried glacial moraines deposited by ice grounding near the paleo-continental shelf edge, suggesting the beginning of the growth of the West Antarctic Ice Sheet (WAIS) as early as the late Oligocene. This hypothesis conflicts with earlier evidence of the WAIS advance over the central-eastern Ross Sea. An alternative explanation for the origin of the mounds, as mud volcanoes, is formulated here on the basis of seismic reflection profile reprocessing and comparison with other, better studied, mound provinces in the Ross Sea. Shallow drilling is required to verify, which hypothesis is correct, and this has implications for various WAIS scenarios, ice volumes, and thermal rheological modelling.

Key words: Ross Sea, Antarctica, seismic interpretation, mounds, mud volcanoes, moraines.

1. Introduction

The Ross Sea is a large embayment that has become an area of growing interest in recent decades, with numerous geological, geophysical, and oceanographic surveys conducted by many countries to reconstruct the Antarctic environments of the past. The Ross Sea embayment is bounded by Marie Byrd Land to the east, the Ross Ice Shelf to the south, Victoria Land to the west, and the continental slope to the north (Fig. 1). It has been characterised as a 1,000-km wide rift, whose formation is related to the break-up of east Gondwana and which, together with the western Marie Byrd Land (wMBL), is part of the West Antarctic Rift System (WARS) (Anderson, 1999; Talarico *et al*., 2022 and reference therein). The Ross Sea is formed of elongated, NNE-SSW trending tectonically controlled sedimentary basins, such as the Victoria Land basin, Central Trough, Northern basin, and Eastern basin (EB), which are bounded by basement highs (Fig. 1).

The EB encompasses most of the Ross Sea east of 180° and is bounded on the east by Marie Byrd Land and on the west by the Central High (Fig. 1). The morphology of the continental shelf and the sedimentary history of the basin have been influenced by the retreat and advance of the West Antarctic Ice Sheet (WAIS), making the EB one of the most important areas for the study of the WAIS itself (De Santis *et al*., 1999).

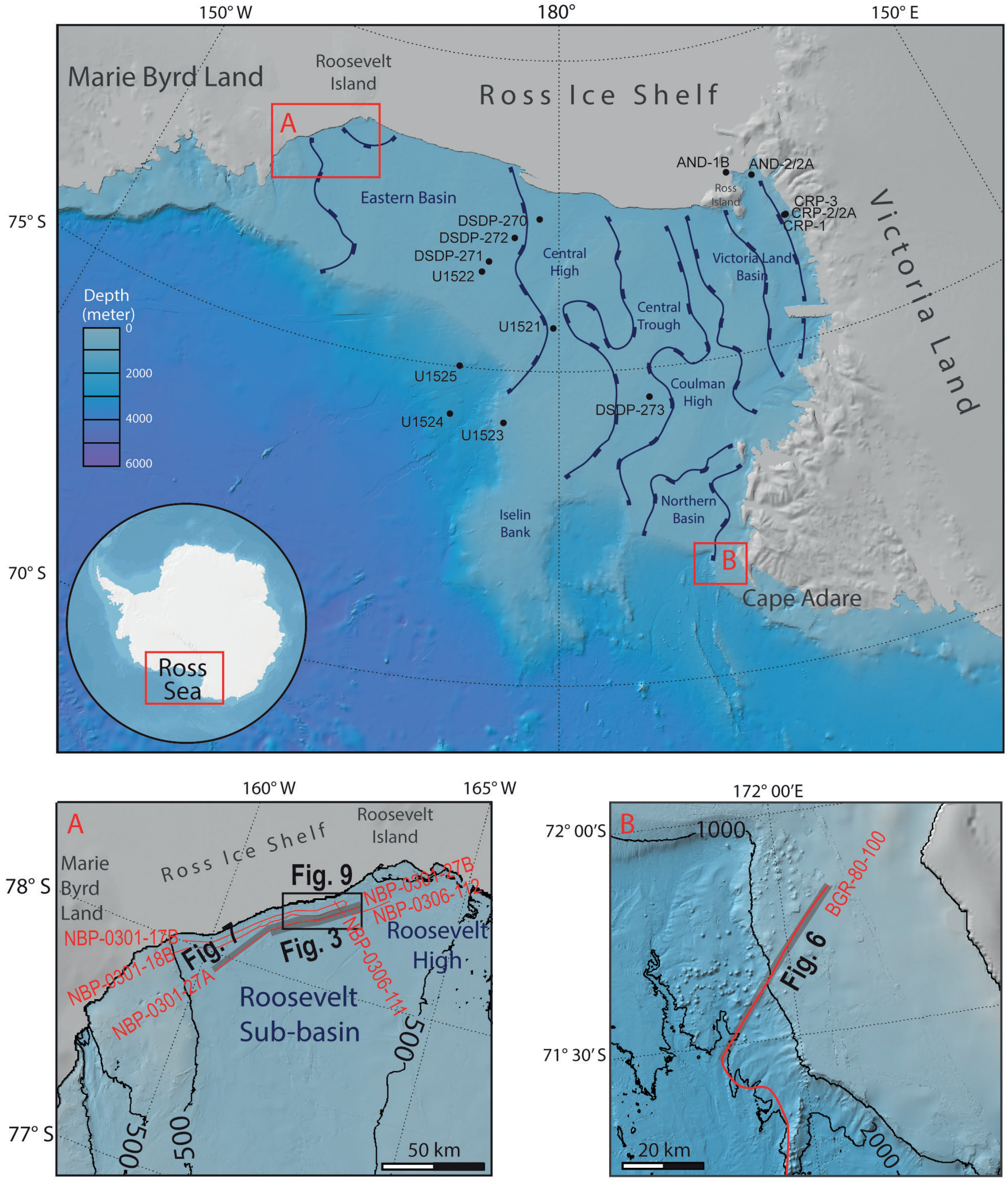

Fig. 1 - Ross Sea morpho-bathymetric and topographic map from IBCSO (Dorschel *et al*., 2022) and from GeoMapApp [www.geomapapp.org; CC by Ryan *et al*. (2009)], showing major structural basins and highs outlined in dark blue, Deep Sea Drilling Project sites (DSDP 270-273) (Hayes *et al*., 1975) and International Ocean Discovery Program Expedition 374 (IODP U1521-1525) marked with black dots (from Davey and De Santis, 2006; Pérez *et al*., 2022). Insert A: location map of the seismic profiles used in this study in the easternmost part of the EB. Insert B: location map of the seismic profile used in this study offshore Cape Adare. Insert B shows the circular mounded features characterising the present-day seabed, on the continental shelf and slope that are investigated in this paper.

The sedimentary sequence that fills the EB was studied using a large amount of seismic data that enabled identifying eight main Ross Sea sequences (RSS1 the oldest, RSS8 the youngest) separated by nine regional unconformities, the so-called Ross Sea unconformities (RSU1 the youngest, RSU7 the oldest), adopting the nomenclature proposed by Brancolini *et al*. (1995). Their formation has been attributed to several factors, including sea-level fluctuations, glacial erosion and tectonic events (Hinz and Block, 1984; Cooper *et al*., 1987; Brancolini *et al*., 1995; De Santis *et al*., 1995; Luyendyk *et al*., 2001) (Table 1). The age of the Ross Sea sequences and unconformities is constrained by the Deep Sea Drilling Project (DSDP) Leg 28 (Hayes *et al*., 1975), the International Ocean Discovery Program (IODP) Exp. 374 (McKay *et al*., 2019), the Cape Roberts Project (CPR) (Barrett *et al*., 1998, 2000, 2001), and the ANtarctic DRILLing Project (ANDRILL) (Naish *et al*., 2009) drill sites (Fig. 1).

In the south-eastern corner of the EB, between Roosevelt High and Marie Byrd Land, there is a ~3-km deep sedimentary basin, referred to as the Roosevelt sub-basin (Fig. 1A). This sedimentary basin contains thick Cenozoic strata that have recorded glacial erosion and deposition at least since the Oligocene (Sorlien *et al*., 2007b).

Table 1 - Ross Sea seismic sequences (RSS), boundaries (RSU), and age [data from Hinz and Block (1984), Cooper *et al.* (1987), Brancolini *et al.* (1995), De Santis *et al.* (1995), Luyendyk *et al.* (2001)].

SEISMIC SEQUENCES (RSS)	SEQUENCE BOUNDARIES (RSU)	AGE
	Seafloor	
RSS-8		Plio(?)-Pleistocene
	RSU1	
RSS-7		Plio(?)-Pleistocene
	RSU2	
RSS-6		Late Miocene and early Pliocene
	RSU3	
RSS-5		Middle to late Miocene
	RSU4	
RSS-4		Early to middle Miocene
	RSU4a	
RSS-3		Early Miocene
	RSU5	
RSS-2-upper		Late Oligocene and early Miocene
	Local unconformity	
RSS-2-lower		
	RSU6	
RSS-1-upper		Early Oligocene
	RSU7	
RSS-1-lower		Late Cretaceous
	Basement	

Buried features (whose tops are between a few metres and 150 m below the seafloor) were identified by Sorlien *et al*. (2007a, 2007b) from high-resolution seismic reflection data in an area of about 257.5 km^2 in the southern Roosevelt sub-basin along the front of the Ross Ice Shelf (Fig. 1A), where water depths range from about 700 to 900 m.

Sorlien *et al*. (2007b) interpreted these features as buried moraines deposited under marine conditions in water depths of several hundred metres and dated to 25 Myr. Accordingly, Sorlien *et al*. (2007b) suggested the presence of Oligocene grounded ice in this area, thus placing the onset of WAIS formation in the late Oligocene. Paleo-depth reconstruction (De Santis *et al*., 1995, 1999) indicates that the paleo-continental shelf edge of the eastern Ross Sea was located about 30 km south of its present position in the early Miocene, consistent with the location of buried mounds in the Roosevelt sub-basin. Therefore, these mounds could have formed as moraines deposited by grounded ice that expanded up to the paleo-continental shelf edge. However, alternative hypotheses are also possible, and imply different scenarios that reconstruct the volume, dynamics, and thermal regime of the WAIS.

Buried and recent mound-like structures of similar size and acoustic nature to those in the Roosevelt sub-basin have been identified in other sectors of the Ross Sea and interpreted as relict depositional/erosional structures formed by glacial advance and retreat (Pérez *et al*., 2022), but also as volcanic structures (Böhm *et al*., 1993; Lawer *et al*., 2012) or mud volcanoes associated with the presence of free gas and gas hydrates (Geletti and Busetti, 2011). Sedimentary mounds such as those observed in the Ross Sea may have an accretionary carbonate component, as is observed in mid- and low-latitude cold regions (Wheeler *et al*., 2005; Hovland, 2008; Somoza *et al*., 2014), but they are highly unlikely in an extreme polar environment that is thermodynamically unfavourable for calcifying organisms (Hovland, 2008).

Although mounds are quite common in the Ross Sea, their origin is unfortunately unknown at present as they have never been sampled and their composition and age can only be inferred from their acoustic signature.

This paper presents new analyses of seismic reflection profiles performed on the buried Roosevelt sub-basin mounds to validate previous hypotheses about their origin and to formulate new alternative possible explanations. The acoustic facies, velocity, size, and shape of the buried structures observed in the Roosevelt sub-basin sediments are compared with similar features observed on the present seafloor, along the continental slope and shelf near Cape Adare (Fig. 1B).

The velocity analysis performed in the Roosevelt sub-basin, by reprocessing seismic data, is used to estimate the depth of sedimentary sequences targeted in the IODP pre-998 proposal (McKay *et al*., 2020). Deep drilling in the Roosevelt sub-basin will provide direct evidence to confirm or refute the hypothesis of mound formation, but also to reconstruct paleo-water depth at the time of formation of the main unconformities. Paleo-water depth is needed as a boundary condition proxy for modelling ice sheet and sea level changes, in order to reconstruct the history of the WAIS.

2. Methods

2.1. Acquisition parameters of seismic and multibeam data

The Roosevelt sub-basin area (eastern Ross Sea) was surveyed by the R/V Nathaniel B. Palmer (USA) with high-resolution single- and multi-channel seismic reflections during two cruises, in 2003 and 2004 (NBP-0301 and NBP-0306), after the ice shelf calving made the area accessible to marine geophysics.

During cruise NBP-0301 (chief scientist: Lou Bartek; investigator: Bruce Luyendyk), a single airgun and streamer, with 45 working channels spaced 25 m apart and an average recording length of 5 s, were used. During cruise NBP-0306 (chief scientist: Bruce Luyendyk), 6 airguns were used, the streamer consisted of 48 working channels spaced 25 m apart, and the average recording length was 7 s (see acquisition parameters in Table 2). Most of the stacked seismic lines are available through the Antarctic Seismic Data Library System (https://sdls.ogs.trieste.it/cache/index.jsp). Field data are available through the Marine Geoscience Data System (https://www.marine-geo.org/).

The buried mounds can be seen on 6 seismic profiles (Fig. 1A; seismic profiles NBP-0301-17B, NBP-0301-18B, NBP-0301-27B, NBP-0301-27A, NBP-0306-111 and NBP-0306-112). These profiles are parallel to each other and to the Ross Ice Shelf front, except for one profile that intersects the others orthogonally (Fig. 1A).

The bathymetry data set was collected during the Nathaniel B. Palmer Expedition, NBP-0301, using a ship-based Kongsberg EM120 multibeam echo sounder system.

In the area offshore of Cape Adare, multibeam echo sounder surveys (NBP-0209 and NBP-0701, available through the Marine Geoscience Data System, www.marine-geo.org/) show the occurrence of circular and hummocky structures (Fig. 1B). Multichannel seismic data intersecting some of these hills were acquired in 1980 by the German Federal Institute for Geosciences and Natural Resources (*Bundesanstalt für Geowissenschaften und Rohstoffe,* BGR) using the R/V Explora and in 2007 by Scripps University (U.S.A.) using the N.B. Palmer (NBP-0701). The BGR-80 and NBP-0701 seismic stack lines are available through the SCAR Seismic Data Library System (https://sdls.ogs.trieste.it/cache/index.jsp).

For scientific purposes, the BGR-80 field data are available from OGS in cooperation with BGR. The BGR-80 data were acquired using a combination of 24 tuned ‘U’ airguns and a streamer consisting of 48 channels spaced 50 m apart. The average recording length was 9 s (see acquisition parameters in Table 2).

The seismic profile that we specifically considered and reprocessed for the analysis of these features is the BGR-80-100 (Fig. 1B).

Table 2 - Acquisition parameters of geophysical surveys collected during expeditions NBP-0301, NBP-0306, and BGR-80.

ACQUISITION PARAMETERS	**NBP-0301**	**NBP-0306**	**BGR-80**
Source information	Airgun (Sercel: GI 105/105)	Airgun (Sercel: GI 105/105)	Tuned ‘U’ Airgun
Number of guns	1	6	24
Source depth (m)	3	3	8
Volume (cu. in.)	105	630	1,431
Streamer length (m)	1,125	1,200	2,400
Streamer depth (m)	7.5	7.5	12
Number of channels	45	48	48
Group spacing (m)	25	25	50
Near offset (m)	25	100	250
Shot spacing (m)	25	27	50
Total record (s)	5	7	9

2.2. Seismic and multibeam data processing

Multi-channel seismic profiles were processed using Echos and Geodepth software packages by Aspen Technology Inc. The processing was mandatory to improve the primary reflection and increase the quality of the seismic data. In particular, the specific processing flow adopted (Fig. 2) enabled us to improve the signal-to-noise ratio, attenuate random noise and multiple reflections, improve temporal and spatial resolution, and define an accurate velocity field. For a complete and detailed explanation of all the processing steps, reference should be made to Brancatelli *et al*. (2022).

Two techniques were used to attenuate the multiple reflections that interfered with the primary reflections, namely: Surface Related Multiple Elimination [SRME: Verschuur *et al.* (1992)] and Wave Equation Multiple Attenuation [WEMA: Wiggins (1988)]. SRME results were improved by interpolating traces, halving shots, and spacing between receivers.

The BGR data set was strongly affected by high amplitude water bottom multiples. Therefore, after applying SRME and WEMA, attenuation of the multiples in the parabolic Radon domain was also performed.

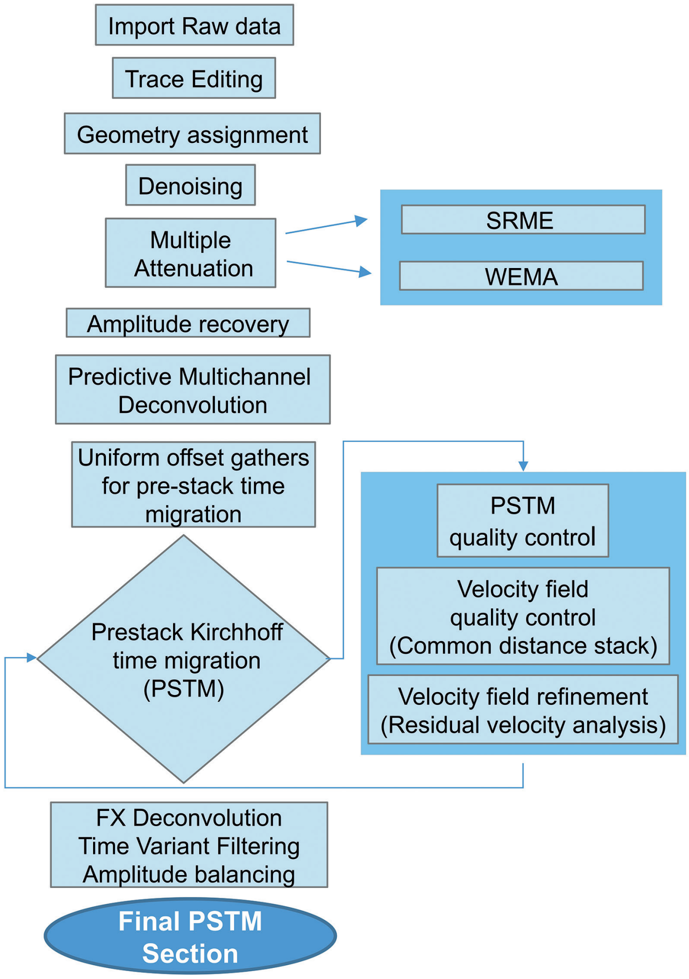

Fig. 2 - Processing flow steps adopted.

To compress the wavelet, attenuate the short-period reverberation, and increase the temporal resolution, a predictive multichannel deconvolution, preceded by a spherical divergence correction, was performed.

Pre-stack time migration (PSTM), using the Kirchhoff method, was applied to increase spatial resolution, attenuate diffractions, and shift horizons to their true positions (Yilmaz, 2001). Iterative velocity analysis and quality controls were performed on the migrated pre-stack gathers. The quality controls consisted of estimating the residual move-out errors on common image gathers. Finally, F-X deconvolution, time variant filtering and amplitude balance were applied to improve the migrated sections.

To assure the reliability of the root mean square (RMS) velocity field obtained, we carried out a sensitivity analysis, by applying a velocity perturbation below the seafloor (by step of ±1% of the RMS velocity). After a perturbation of 2%, it was possible to note that the reflections were no longer flat and that the residuals on the velocity semblance were not focused around zero. It can, therefore, be assumed that a 2% error can be appreciable in analysing velocity semblance. This result is in agreement with other studies (i.e. Vargas-Cordero *et al.*, 2010) that reported a velocity error lower than 5%. The RMS velocity field, obtained with the iterative velocity analysis on the time pre-stack migrated gathers, was converted to a time interval velocity field through the Dix equation.

To address pull-up issues related to strong vertical and lateral velocity variations and to better image the geometry of subsurface structures, an advance processing that included pre-stack depth migration (PSDM) and reflection grid tomography was performed on a portion of seismic profile NBP-0301-27B, where some mounded features lie. The building of the velocity model involved an iterative PSDM model update (i.e. Jones, 2018). Starting from an initial velocity model, the reflectors flatness within the common image gathers (CIGs) was evaluated at each iteration by means of the residual moveout (RMO) errors, which are the tomography inputs. The iterative process ended when RMOs were generally low enough to be acceptable. The RMS velocity model of seismic profile NBP-0301-27B, obtained by velocity analysis in time domain, was smoothed and converted to a depth interval velocity field (by the Dix equation) to be used as the starting velocity model. Moreover, the velocity model was discretised into a 50x50 m^2 regular grid and 7 tomographic iterations were performed.

Only one Digital Terrain Model (DTM) was created for the multibeam data acquired during expedition NBP-0301 because the other processing steps had already been applied and made available through the Marine Geoscience Data System (www.marine-geo.org/).

It is important to note that no tidal correction was applied to the multibeam echo sounder data because, due to the magnitude of the tides and accuracy of the data collected, it was assumed that the tides would not significantly affect the final DTM.

2.3. Seismic stratigraphic interpretation

Seismic stratigraphic interpretation of the seismic profiles was performed using the IHS-Kingdom software. The IHS-Kingdom software was also used to create a gridded surface of the horizon picked along the top of all observable buried structures in all six seismic profiles acquired in the Roosevelt sub-basin, and to evaluate their correlation, trend, and relief variation as a function of Two Way Travel Time (TWTT) in the area. The algorithm used by IHS-Kingdom for interpolation is ‘flex gridding’ with square cells of 80 m by 80 m.

3. Results

3.1. Seismic velocity models

The interval velocity field of seismic profile NBP-0301-27B shows velocity anomalies within the seven buried mounded features (M1-M7) (Fig. 3). The mounded features are characterised by velocity values between 2,400 and 3,000 m/s, whereas the adjacent sediments have velocities of about 2,200-2,300 m/s (Fig. 3).

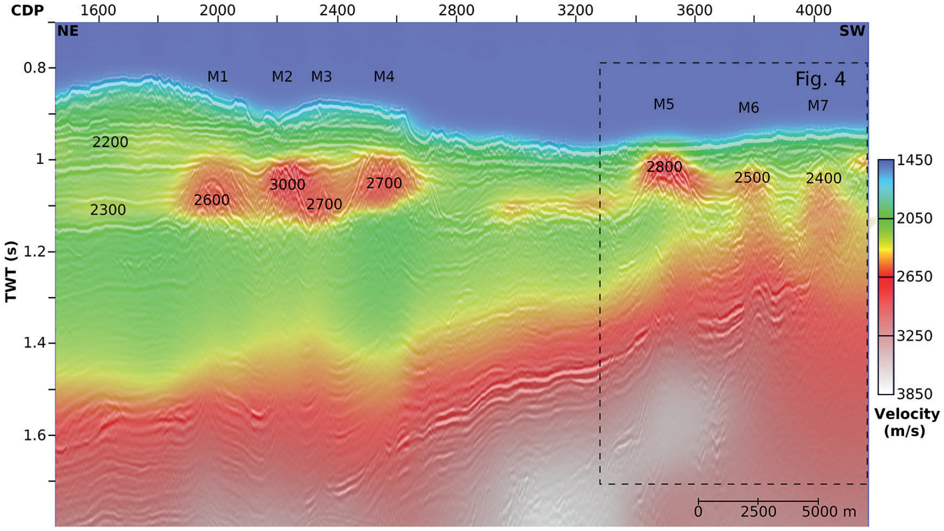

Fig. 3 - Interval velocity field superimposed on seismic profile NBP-0301-27B, showing high velocity anomalies (see Fig. 1 for location).

Depth migration (Fig. 4) revealed the true geometries and relocated the horizons beneath the mounded features back to their actual positions by removing the deformation caused by the higher local seismic velocity within the mounded features.

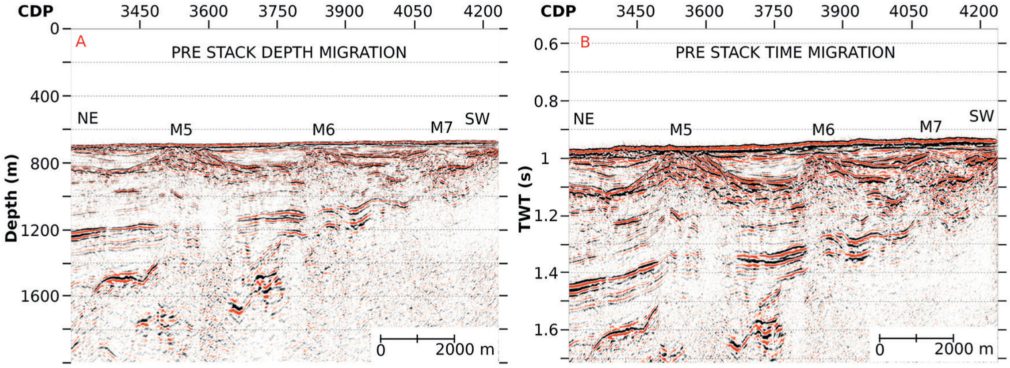

Fig. 4 - Comparison of a portion of the NBP-0301-27B depth migrated (A) and time migrated (B) seismic profiles (see Fig. 1 for location and Fig. 3 for the entire NBP-0301-27B seismic profile).

In a context of strong lateral variations, the depth interval velocity field, obtained with the reflection grid tomography, allowed the velocity anomalies related to the mound features to be investigated in more detail. In particular, the M5 and M6 features showed velocities of about 2,800 and 2,600 m/s, respectively, at a depth of about 800 m bsf (Fig. 5), in agreement with the values computed with the velocity analysis in time domain (see the M5 and M6 mounds in Fig. 3). These velocities are higher if compared with the velocity values of surrounding sediments. The sediments underlying the mounds show velocities greater than 3,100 m/s.

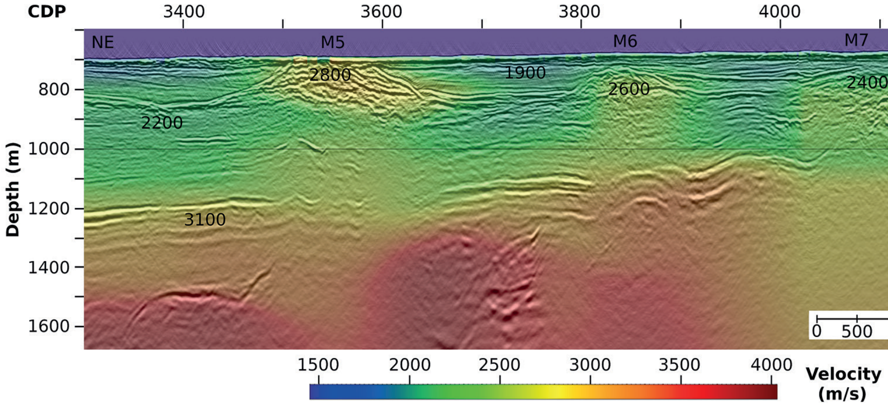

Fig. 5 - The depth interval velocity sections of NBP0301-27B, showing high velocity anomalies (see Fig. 1 for location).

The velocity field on a portion of seismic profile BGR-80-100 (Fig. 6), acquired near Cape Adare, has revealed that the core of the mounded feature has a velocity of 2,100 m/s, whilst its base is formed by high velocity layers of approximately 2,700 m/s.

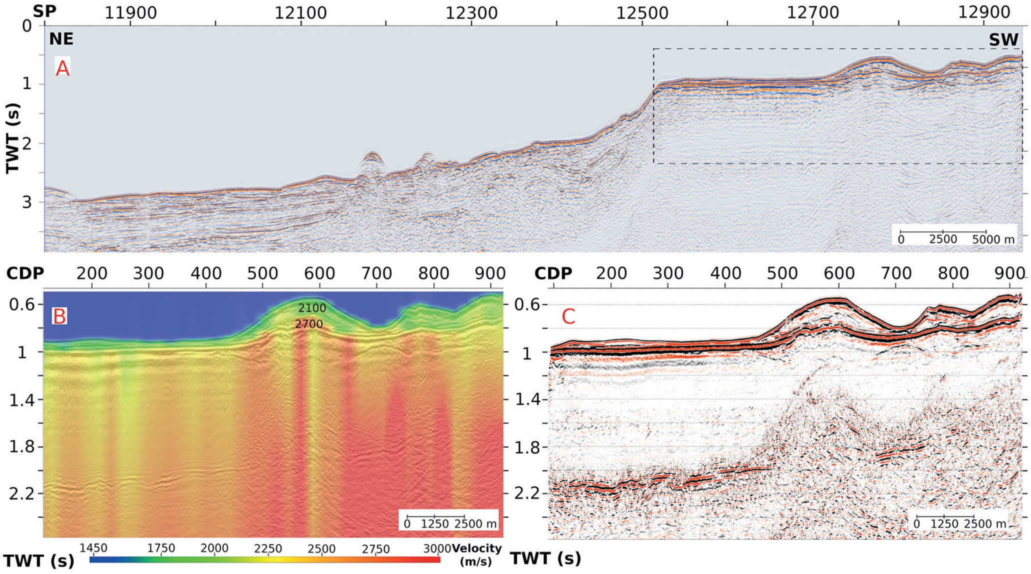

Fig. 6 - The BGR-80-100 profile from SP 11800 to SP 12950 (A). B and C: time interval velocity and seismic section of a portion of the BGR-80-100 profile (see Fig. 1 for location).

3.2. Seismic stratigraphic description of the Roosevelt sub-basin sequences

Within the Roosevelt sub-basin, 2 km of stratigraphic sequences (RSS-) separated by unconformities (RSU-) are preserved (Table 1). These sequences terminate in onlap or pinch-outs on the basin flanks that correspond to structural highs (Fig. 7).

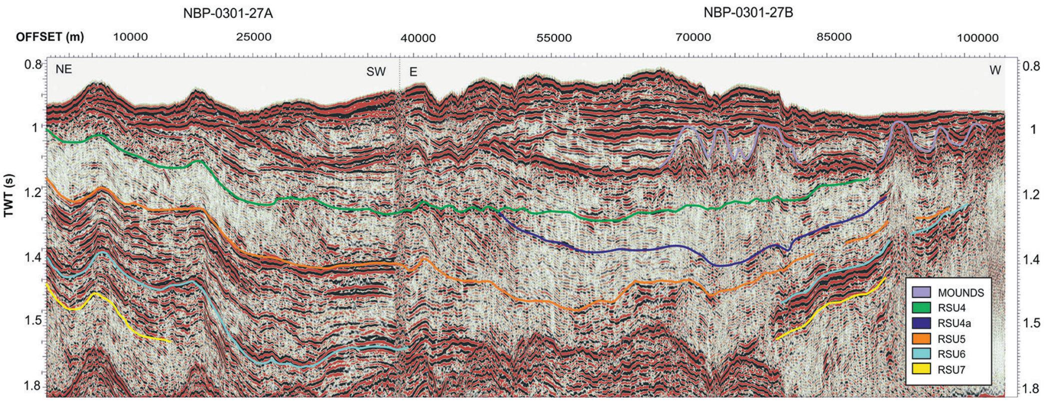

Fig. 7 - Profile composed by the NBP-0301-27A (left) and NBP-0301-27B (right) seismic lines with the interpretation of the Ross Sea unconformities (see Fig. 1 for location).

The mounds lie on a laterally discontinuous, high-amplitude irregular reflector (reflector B in Fig. 8A) and the top of some of the mounds is truncated by an erosional unconformity (reflector T in Fig. 8A). Reflector B at the base of the mounds is a truncation surface that, with a low angle, cuts a package of sub-horizontal reflectors lying below it. The mounds are located above and within an aggradational sequence and are onlapped and draped by sub-horizontal reflectors with low amplitude and medium lateral continuity (Fig. 8B). Locally, these reflectors are inclined and parallel to the flank of the mounds or pinching towards the mounds (Fig. 8A).

Typical current moat-sediment drifts are found on the side of the mound M4 (Fig. 8A) and aggradational strata infill the depressions among the mounds (Fig. 8B). The seven buried features, observed on the seismic profile of the Roosevelt sub-basin, are fairly similar in size and shape.

Depth-migrated, 2D seismic profiles (Fig. 4, left) show that the buried mounds are up to 150 m high and 5,000 m wide. The mounds have an internal chaotic or transparent seismic nature (Figs. 8A and 8C). Locally, a reduction of amplitude producing acoustic blanking is observed beneath the mounds (Fig. 8C), interrupting the continuity of the reflectors. In some of these cases, reflectors offset and upward bending are also observed, possibly caused by dragging along faults (Figs. 8B and 8C). As shown in Fig. 8C, at the top of the M2 the reflectors are interrupted, probably by the fault systems.

The multibeam bathymetry shows a semicircular depression (dashed circle in Fig. 9) on the present-day seafloor above M2. Due to poor coverage of the data, it is not possible to determine its full shape.

Fig. 10 shows the three-dimensional view of the mounds. They appear to be approximately circular isolated features. However, their shape may be an effect of the poor data coverage interpolation, with profiles that are widely spaced (~2.5 km) and mainly parallel to each other. Apparently, the mounds are not aligned, and it is difficult to discern a trend in their spatial arrangement.

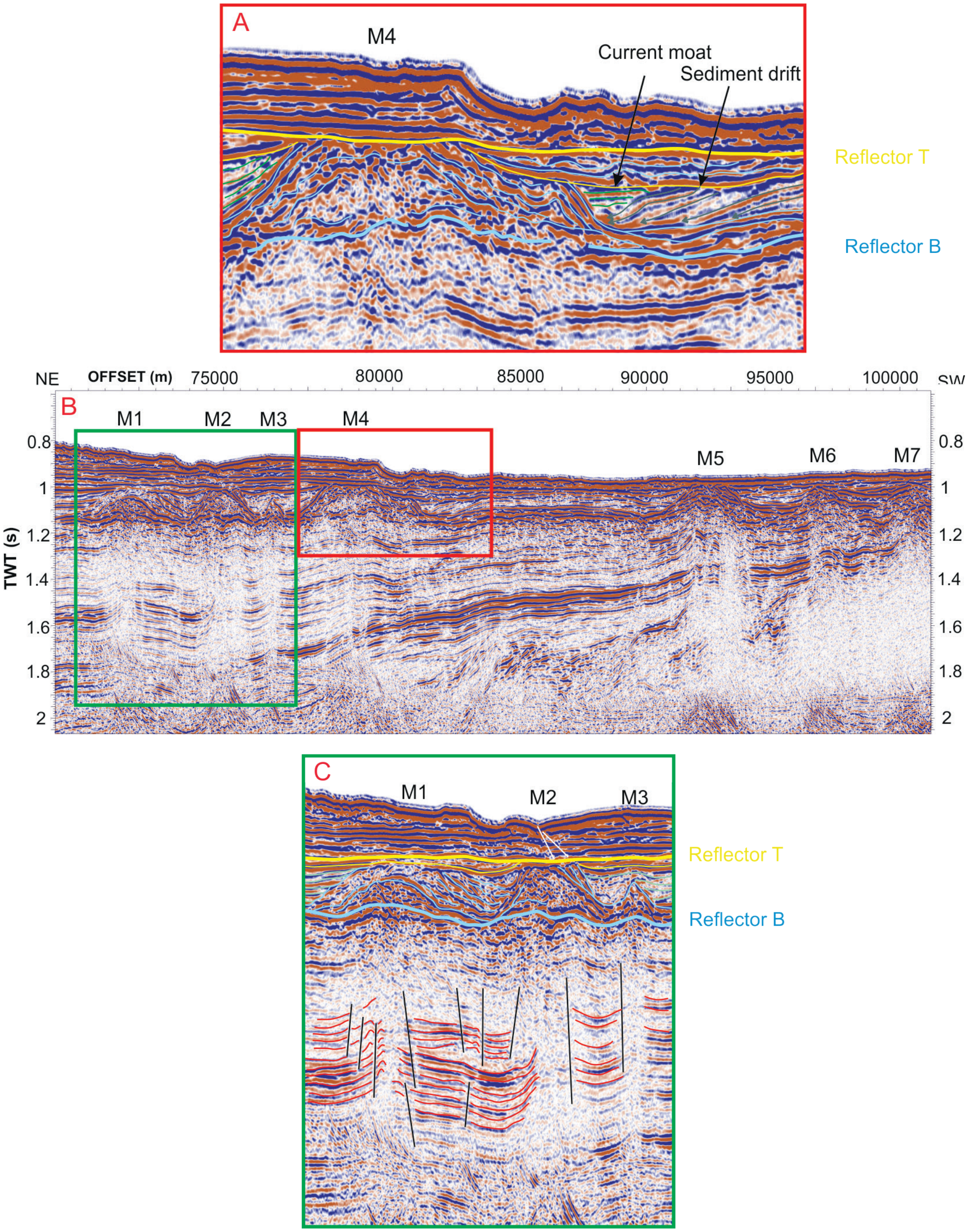

Fig. 8 - The NBP-0301-27B seismic profile (see Fig. 1 for location): A) showing sediment drift, B) showing the six analysed buried structures, C) showing faults beneath the mounds (black lines) and above M2 (white lines).

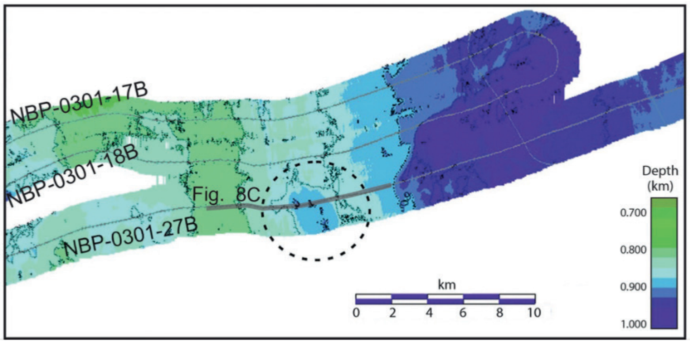

Fig. 9 - Multibeam bathymetry of the southern Roosevelt sub-basin showing seismic tracks (grey lines) and semicircular depression (dashed black circle, see Fig. 1 for location).

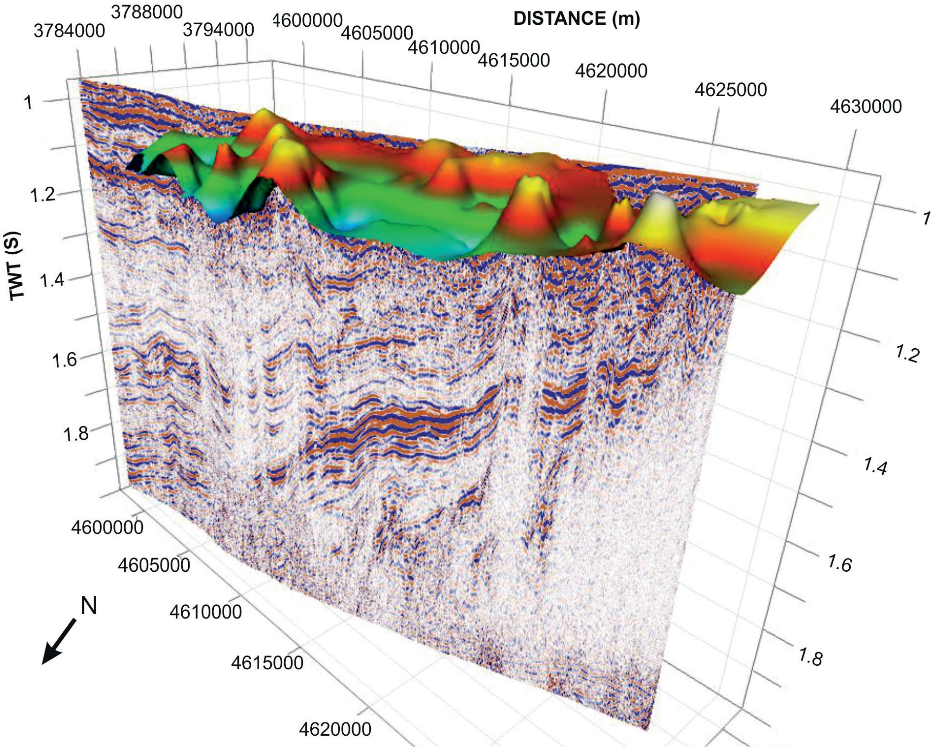

Fig. 10 - Three-dimensional view of the Roosevelt sub-basin buried mounds and seismic profile NBP-0301-27B (see Fig. 1 for location).

3.3. Seismic stratigraphic description of the mounds off Cape Adare

The mounds located near Cape Adare (Fig. 1B), along the continental slope and near the continental shelf edge at a depth of ~700 m, are characterised by a circular shape with a diameter of 5,000 m and a relief of 300 m (Fig. 6).

As shown in Fig. 6, the mound observed on the BGR-80-100 seismic profile has an internal chaotic signature and is located on a reflector with very strong amplitude that is deformed at its base. The low amplitude laterally discontinuous reflectors, below the base of the mound, also appear bent slightly upwards.

A strong amplitude reflector occurs at a depth of 1.75 s (cdp 645-736), laterally disappearing below the mound.

4. Discussion

The buried mounds located in the southern Roosevelt sub-basin were previously interpreted as glacial moraine ridges, elongated in the E-W direction [Fig. 1A in Sorlien *et al*. (2007b)]. However, the data set, consisting mainly of parallel profiles, is not suitable to reconstruct the actual shape of the mounds (Fig. 10): the mounds imaged by each seismic section may, or may not, be the same features along the six profiles, so their spatial extension and orientation is not clear. They could be circular instead of SE-NW elongated ridges, although new seismic profiles are needed to verify such hypothesis.

The seismic velocity of the mounds (~2,800 m/s, Fig. 5), the chaotic internal facies and the strong amplitude reflector at their base are consistent with compacted material, which would support the hypothesis of Sorlien *et al*. (2007b), who interpreted them as formed of sediments eroded by the glaciers, transported subglacially and released at the ice grounding zone. These kinds of sediments can be highly compacted under ice and lithostatic pressure, during and after burial (Bennett, 2001).

However, the possibility that the structures might have a circular shape, leads us to consider possible alternatives for their origin. The hypothesis that they could be partly composed of lithified mud and carbonate material is consistent with their high seismic velocity. The high amplitude B reflector, lying at the base of the mounds, can represent a hard and coarse residual seabed, swept by a bottom current, which is coherent with the location near the paleo-continental margin, where bottom currents are generally strong even at the present time (Anderson, 1999).

Circular mound-shaped carbonate mounds form at high latitudes, continental shelves, and slope areas under particular environmental conditions (Bosence and Bridges, 1995; Hebbeln and Samankassou, 2015). This occurs through the active role of calcifier organisms, such as cold-water corals (Roberts *et al*., 2009; Taviani *et al*., 2011), siliciclastic-dominated sponge reefs (Howell *et al*., 2016), and microbial species (Riding and Awramik, 2000).

The occurrence of bottom currents ventilating the seabed and delivering nutrients would stimulate the growth of biogenic cold carbonates. At present, this type of condition is typically observed along the Ross Sea continental slope and outer continental shelf (Taviani *et al*., 1993). Therefore, we may assume that similar conditions may also have occurred at the time of the growth of the mounds.

The occurrence of fluids and gas seeps at the seabed would also favour the formation of methanogenic bacteria colonies, whose acoustic facies and conical shape (Mazzini and Etiope, 2017; Ceramicola *et al*., 2018) are similar to what we observe in the seismic profiles of the Roosevelt sub-basin. The acoustic blanking observed beneath some mounds (Fig. 8C), interrupting the continuity of the reflectors, may, indeed, be indicative of chimneys beneath the buried mounds, where upward migration of gas and fluids occurs along fractured and faulted sediments (e.g. Løseth *et al*., 2009) (Fig. 8C). This would explain the reflectors offset and upward bending (in-depth migrated seismic profiles). Therefore, an explanation for the Roosevelt sub-basin mounds is that they originated as mud volcanoes and/or as cold carbonate-methanogenic encrusted colonies, instead of glacial moraines, as previously inferred.

The draping and onlapping on the mound flanks, by the reflectors, may have been deposited by hemipelagic settling and bottom currents, as indicated by moat-sediment drift features (Fig. 8A).

The acoustic blanking and faults do not seem to characterise the sediments above reflector T, representing an erosion at the top of the mounds. This observation may suggest that the gas and fluid release was particularly intense during the formation of the mounds but ended after their burial. On the other hand, the multibeam data show the presence of a semicircular feature that could, possibly, have originated from gas seeps, in the form of pockmarks, rising to the surface from fractures just above mound M2 (Figs. 8C and 9). However, this feature can also be interpreted as a depression excavated by ice flowing and grounding on the continental shelf. More data are needed to determine the shape and origin of this depression on the seafloor and of the fluids in the underlying sediments. Hovland and Thomsen (1997), studying cold-water coral reefs (CWC) in Norway, suggest a link between CWC and hydrocarbon intrusions determined by a direct or indirect role of chemo-autotrophic bacteria in coral feeding. However, no direct evidence of the presence of these fluids in the Roosevelt sub-basin has been provided to date.

In the case of carbonate mounds, consideration must also be given to the potential water circulation necessary to nourish CWC mounds, which tend to settle on topographic highs influenced by currents and turbulences (Genin *et al.*, 1986; Masson *et al.*, 2003; Thiem *et al.*, 2006). Therefore, further studies are needed to determine the paleo-hydrographic conditions and whether the area may be suitable for the formation of such structures. The IODP pre-998 proposal will shed light into the paleoceanographic and paleoclimatic setting at the time of the formation of the Roosevelt sub-basin mounds and this work is preparatory to guiding the drill site location and depth of targeted features.

Buried mounds identified in the western Ross Sea by Böhm *et al.* (1993) and Geletti *et al.* (1993) are similar in size and acoustic character to those identified in the Roosevelt sub-basin. In all cases, we do not have a closely spaced 3D seismic survey over the mounds and, therefore, we must consider that the estimate of their size and shape depends on the orientation of the seismic 2D profiles.

Böhm *et al.* (1993) suggest a volcanic origin for the mounds located in the western Ross Sea, based on the high values of seismic velocity and on the strong magnetic susceptibility contrast. An analysis of magnetic anomalies of data collected in the Roosevelt sub-basin area is needed to better compare the mounds forming in the two Ross Sea provinces. However, considering that there is documented volcanic activity in Marie Byrd Land, as well as in Victoria Land, and considering that the acoustic facies of the Roosevelt sub-basin mounds can also be explained as magmatic manifestation, we suggest that an origin as a magmatic volcano cannot be discounted.

Volcanism generating fluids and gas may also be coupled with mud and possible carbonate mounds south of the Drygalski Ice tongue, where Geletti and Busetti (2011) identified seafloor conic and flat-topped mounds, each up to 5,000 m wide and 100 m high, characterised by seismic velocity of ~1,800 m/s. In this case, as the mounds lie over a fault system connected to Bottom Simulating Reflectors (BSRs) believed to be caused by gas hydrate, they suggest that the observed conic shaped mounds originated as mud volcanoes formed by the uprising of free gas along the fault zone from the BSRs. Lawver *et al.* (2007, 2012) interpreted the same flat-topped seafloor mounds as magmatic volcanoes, considering also the occurrence of short-wavelength magnetic anomalies.

The mounds identified on the present seafloor, near Cape Adare, fringing the continental margin at a depth of ~700 m, are characterised by a circular shape, 5,000 m in diameter, and 295 m in relief (Figs. 1B and 6). The mounds generally have an acoustic facies, similar to the mounds buried in the Roosevelt sub-basin (Figs. 6 and 8), although the seismic velocity is much lower. As a matter of fact, the Cape Adare mounds show low-velocity (2,100 m/s) and are located on a very high amplitude, high-velocity horizon (2,700 m/s) (Fig. 6). The circular shapes and their spatial arrangement exclude the possibility that they are morainal structures. The low velocity would also discount their origin as lava-volcano, although extensive volcanism is still occurring in the western Ross Sea along the axes of the Victoria Land basin, from Ross Island to Mount Melbourne (Armstrong, 1978; Rilling *et al*., 2009). The low velocity is rather similar to the one estimated by Geletti and Busetti (2011) for the mounds located south of the Drygalski Ice tongue. According to Giustiniani *et al*. (2018), conditions for the presence of stable gas hydrates at shallow depths (<300 m bsf) are present offshore of Cape Adare. The origin of the mounds forming here could, then, be related to the presence of gas upward migration within the sediments.

Given the proximity of the mounds in the shelf edge area off Cape Adare, where the water is enriched with nutrients carried from ocean currents (Genin *et al*., 1986; Masson *et al*., 2003; Thiem *et al*., 2006), we can suggest that it is possible that the mounds formed as mud-volcanoes, encrusted carbonate and methanogenic formations. However, for carbonate sediments, the internal seismic velocity of 2,100 m/s is lower than would be expected for such kind of features. We also cannot rule out the possibility that carbonate, mud, and volcanic mounds coexisted. Therefore, further geophysical and lithological investigations are necessary to determine the actual nature of these structures.

4.1. The formation environment of the Roosevelt sub-basin mounds

Fig. 11 illustrates a schematic reconstruction of the evolution of the continental margin in the eastern Ross Sea. Fig. 11A shows a period during which the WAIS expanded over the continental shelf up to its edge and deposited glacial moraine. This period corresponds to the formation of the erosional regional unconformity RSU4, at ca. 14 Myr (Pérez *et al*., 2022). Fig. 11B shows the features forming during a period of ice sheet retreat, when mud volcanoes formed above a basin filled by sediments. The reflector at the base of the mounds can be interpreted as a regional erosional surface. It does not show typical glacial valley incisions or other peculiar erosional features that may suggest an origin from grounded ice, during ice sheet advance. Therefore, we suggest that the base of the mounds is possibly a transgressive marine surface, a residual, coarse sedimentary lag, swept by bottom currents, similar to the present-day seabed in the mid to outer continental shelf. This would justify the strong amplitude of the reflector lying at the base of the mounds.

The occurrence of typical current moat-sediment drifts within the mounds and the aggradational geometry of the strata below, onlapping the mounds and infilling the depressions (Fig. 7), would indicate marine sediment deposition during a period of ice retreat and relative high sea level, which occurred during and after mound formation. During this time, the combination of local subsidence, global sea level rise and morphology provided sufficient accommodation space for the deposition and preservation of the mounds and surrounding sediments.

If the mounds were mud volcanoes, their preservation and burial below 200 m of thick sedimentary cover would suggest that this sector of the paleo-continental shelf was free from grounded ice for quite a long time. Otherwise, ice grounding up to the continental shelf edge would have likely plastered and deeply eroded mud volcanoes and would have left a clear imprint of glacial erosion in the seismic sequence. The truncation of the top of the mounds suggests a later re-advance of the ice sheet over the continental shelf, up to the shelf edge, that only partially eroded the previous sedimentary deposits (Fig. 11C).

If, instead, as suggested by Sorlien *et al*. (2007b), the mounds are glacial moraines, they would be proof of a period of limited ice sheet advance, up to the mid continental shelf edge, much prior to the more expanded phase.

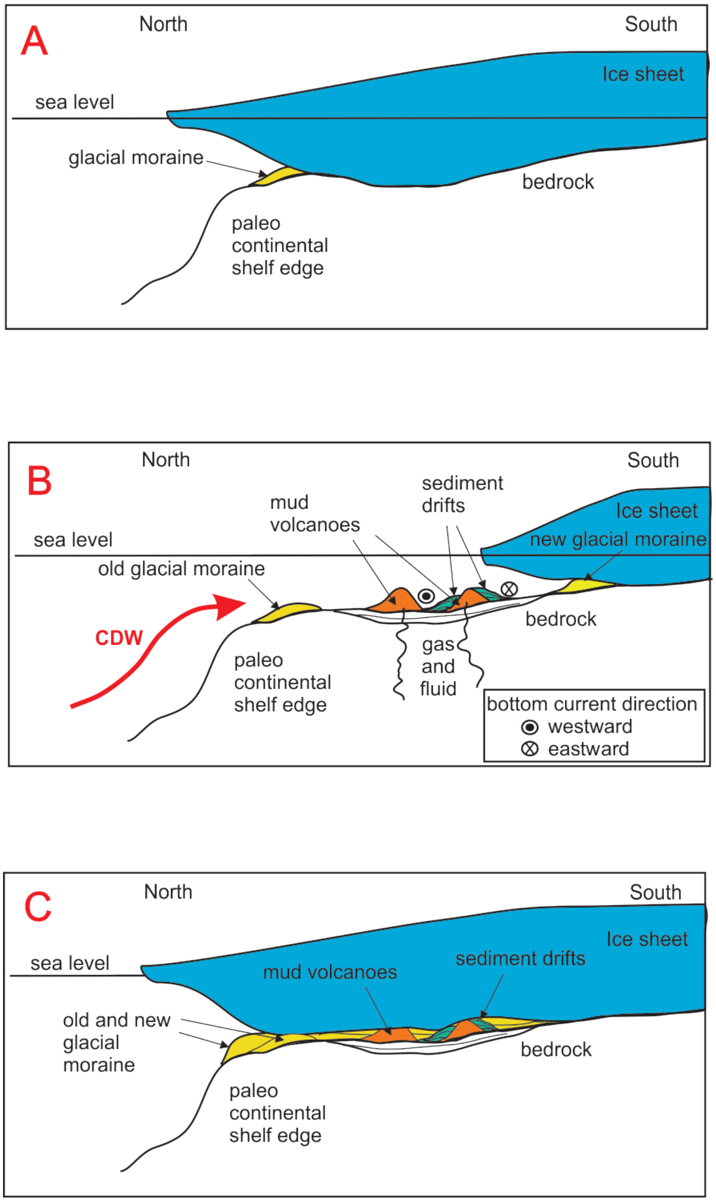

Fig. 11 - Schematic reconstruction (not to scale) of three different evolutionary hypotheses of the eastern Ross Sea continental margin during the formation of the mud volcanoes. Panel A: maximum expansion of the ice sheet up to the paleo-continental shelf edge, where a glacial moraine forms. This period corresponds to the time of formation of the erosional unconformity RSU4 at ca. 14 Myr. Panel B: retreat of the ice sheet and formation of mud volcanoes on the paleo-continental shelf. Moat and sediment drifts form under the action of bottom currents (inferred current direction is indicated with symbols, over the moats) among the mud volcanoes. CDW: Circumpolar Deep Water is the warm water mass that today rises up the continental slope, delivers nutrients and impinges the continental shelf. Panel C: re-advance of the ice sheet up to the paleo-continental shelf edge where a new glacial moraine forms seawards of the older moraine. The base of the ice sheet erodes the top of the mud volcanoes.

5. Conclusions

The analysis and comparison of the mounds observed on the modern seafloor, along the continental slope and shelf near Cape Adare, has enabled us to hypothesise that the Roosevelt sub-basin mounds might have formed as mud volcanoes and/or as cold carbonate-methanogenic encrusted colonies, instead of glacial moraines, as previously inferred. The main geophysical evidence acquired from reflection seismic data is:

- the possible circular shape;
- the high amplitude reflector at the base of the mounds can represent a residual seabed, swept by bottom currents which deliver nutrients helping the growth of biogenic, cold carbonate mats;
- the acoustic blanking observed beneath the mounds, which may be indicative of the upward migration of fluids along fractured and faulted sediments;
- the presence of a possible pockmark above mound M2;
- the similarity with the acoustic facies, seismic velocity, and size of the buried mounds identified in the western Ross Sea by Böhm *et al*. (1993) and Geletti *et al*. (1993) along seismic line IT88A-06, which are assumed to have a magmatic volcanic origin.

The two alternative hypotheses proposed by Sorlien *et al*. (2007b) and by this work, related to the origin of the Roosevelt sub-basin mounds, have important implications for determining different WAIS scenarios, ice sheet volumes, and thermal rheological modelling.

However, the lack of direct lithological and age constraint prevents understanding their growth ruling mechanism.

Mounds identified on the present seafloor, near Cape Adare, likely have mud and magmatic volcanic origin. However, considering the proximity of the mounds in the shelf edge area, where the water is enriched with nutrients, we cannot exclude that some of them form as cold carbonate features.

This work demonstrates that understanding the origin of the mounds, formed in the different Ross Sea provinces, potentially provides direct paleoclimate and paleoceanographic proxies.

In the case of the Roosevelt sub-basin, the mounds would constrain a more or less conservative WAIS reconstruction. Future work should focus on collecting closely spaced geophysical surveys and sediment samples to validate the hypotheses about the origin of the mounds.

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