Chapter 3

Cenozoic history of Antarctic glaciation and climate from onshore and offshore studies

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3.1 Introduction

The influence of Antarctica's ice sheets and fringing sea ice belt on global climate is profound, and processes relating to changes in Antarctica's cryosphere are central to many of the largest feedbacks in the Earth System. Variations in polar ice cover and ice sheet volume directly affect Earth's absorption of solar energy through changes in planetary albedo, while shifts in atmospheric and oceanic currents associated with high latitude processes influence the way heat and marine nutrients are redistributed around the

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planet, and in turn form a significant control on global carbon cycling through time. Indeed, ice core records provide unequivocal evidence of a strong linear relationship between global temperatures, ice volume and atmospheric CO_2 concentrations through the glacial-interglacial cycles of the past 800,000 years (EPICA community Members, 2004; Lüthi et al., 2008).

For records older than 800 ka, the relationship between these three variables remains less certain. In part, this is due to significant uncertainties in measuring atmospheric CO_2 from geological proxies, such as boron isotopes from marine foraminifera, the carbon isotopic composition of marine algal biomarkers and stomata on terrestrial leaf fossils (Foster et al., 2017). Adding further uncertainty to understanding the relationship between CO_2, global temperature and ice sheet volumes is the history of the Antarctic ice sheets from geological data, which is limited by the lack of rock exposures and the small number of drill cores from the Antarctic region. In this context, understanding of long-term geological processes are essential to constrain, as factors such as the tectonic subsidence of the parts of the Antarctic continent through time invalidate the assumption of a uniform relationship between global temperature change, global ice volume and atmospheric CO_2 (Gasson et al., 2016b; Naish et al., 2021 (from this volume); Wilson et al., 2013).

Numerous long-term Cenozoic global climate and polar ice volume records have been inferred from far-field datasets, either from deep sea oxygen isotope records or sea level estimates derived from the continental margins in low- to mid-latitudes (Holbourn et al., 2013; Liebrand et al., 2016; Miller et al., 2020; Vleeschouwer et al., 2017; Zachos et al., 2001). While these records are fundamental to our understanding of Earth's climate and ice sheet history, they remain complicated by a range of uncertainties and assumptions. For example, deep sea foraminiferal oxygen isotopes record a signal of both temperature and global ice volume, which may not covary in a linear manner (Cramer et al., 2011; Elderfield et al., 2012; Miller et al., 2020), and cannot identify the hemisphere in which polar ice sheet volume change was occurring.

Identifying locations of ice volume change is also a significant issue for sea level reconstructions derived from low- to mid-latitude continental margins, but to obtain a true eustatic signal these records also require significant corrections for sediment supply and compaction, tectonic subsidence, and an understanding of the influence of glacio-hydrostatic adjustment and mantle dynamics (Grant et al., 2019; Kominz et al., 2008; Miller et al., 2020; Moucha et al., 2008). Consequently, these far-field proxy records remain subject to uncertainties and assumptions when assessing high-latitude climatic change. Examples include determining the magnitude of polar amplification of temperatures in past high CO_2 worlds and identifying the synchronicity of ice sheet behaviour in either hemisphere. Direct records from the Antarctic margin are needed to best understand the direct response of the Antarctic ice sheets to global climate and oceanographic shifts, as well as the influence of high latitude processes on global climate feedbacks and sea level change. Only these can provide the critical and unique datasets to refine interpretations derived from far-field records.

Direct records of Antarctic Cenozoic glacial history come from rare, disparate rock outcrops, and from more than 60 drill holes (of variable recovery and quality) that are mostly located around the periphery of the East Antarctic Ice Sheet (EAIS) or the deeper offshore waters of the Southern Ocean (see recent reviews by Barrett, 2008; Escutia et al., 2019; McKay et al., 2016) (Fig. 3.1). Here, we outline the current state of knowledge of Cenozoic climate history in Antarctica from near- and far-field records,

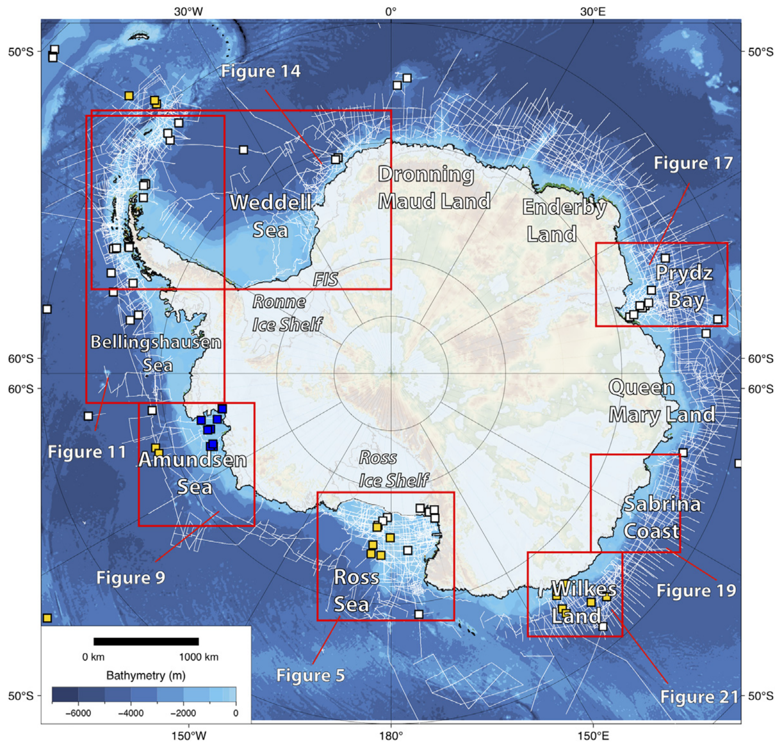

FIGURE 3.1 Location map showing sites, glaciological and topographic features discussed in text. Present-day ice sheet cover is slightly transparent to highlight the location of subglacial basins. Seismic tracks are from the SCAR Antarctic Seismic Data Library System (SDLS). Bathymetry is from Bathymetric Chart of the Southern Ocean (Arndt et al., 2013) and subglacial topography from BedMachine Antarctica dataset (Morlighem et al., 2020). Boxes show location of detailed map figures in the chapter. Small white filled squares represent deep drill sites collected prior to 2008, and yellow squares represent sites drilled since 2008 by the IODP program (see detailed map figures). Blue squares are sites collected by the PS104/MeBo expedition in the inner Amundsen Sea. *EAIS*, East Antarctic Ice Sheet; *FIS*, Filchner Ice Shelf; *WAIS*, West Antarctic Ice Sheet.

followed by a discussion of the seismic stratigraphy and drill core constraints and paleoclimatic records preserved within this stratigraphy from around the margin. In this sector-by-sector summary of the stratigraphy, we also provide a direction for future drilling projects in the Antarctic region that will address the outstanding challenge that extracting this history presents.

3.2 Long-term tectonic drivers and ice sheet evolution

Tectonic events are one of two fundamental controls on the long-term Antarctic climate trend over geological timescales, the other being atmospheric CO_2 levels. The most significant of these events was the break-up of the Gondwana supercontinent, which resulted in the formation of the Southern Ocean and allowed the modern global overturning circulation system to develop (Talarico et al., 2021, this volume). The opening of ocean gateways led to cooling and ultimately to the development of the Antarctic Circumpolar Current (ACC). This contributed to the Cenozoic cooling and expansion of Antarctica's continental ice sheets (Bijl et al., 2013; DeConto and Pollard, 2003; Hochmuth et al., 2020a,b; Kennett, 1977; Kennett et al., 1974), alongside concomitant shifts in global carbon cycling. Feedbacks associated with ice sheet initiation in Antarctica in turn acted to amplify the Earth system response to orbital forcing, creating large shifts in Antarctic ice volumes and eustatic sea level, atmospheric and oceanic circulation further altering global carbon cycling processes and heat transport around the planet.

Associated with post-Gondwana break-up is the evolution of the West Antarctic Rift System (WARS) (Figs. 3.1 and 3.2), a major control on ice sheet evolution through the Cenozoic, particularly for the West Antarctic Ice Sheet (WAIS). This rift system has influenced the timing and amount of West Antarctic subsidence, Transantarctic Mountain (TAM) uplift, sediment redistribution, mantle viscosity and crustal heat flux – all of which would have influenced the distribution of land and ocean areas, and in turn EAIS and WAIS evolution (Colleoni et al., 2018; Gasson et al., 2016b; Hochmuth and Gohl, 2019; LeMasurier et al., 1982; Levy et al., 2019; Paxman et al., 2019; Wilson et al., 2013). Rifting in West Antarctica likely initiated in Marie Byrd Land (between the Amundsen and Ross Sea sectors) at ~104 Ma.

Rifting continued through the Cenozoic, moving into the central then western Ross Sea Embayment, where it still persists today in the Terror Rift and is associated with the McMurdo Volcanic Group (Decesari et al., 2007; Eagles et al., 2004; Fielding et al., 2008; Wenman et al., 2020; Wilson and Luyendyk, 2009; Wobbe et al., 2012). Neogene to Quaternary rifting and active volcanism is also thought to have been widespread across much of Marie Byrd Land and the Ross Sea (Jordan and Siddoway, 2020; Kalberg and Gohl, 2014; Sauli et al., 2021; Wobbe et al., 2012).

Critically, the WARS has created large sedimentary basins in the Ross and Amundsen Sea region. These contain accessible archives of Antarctic

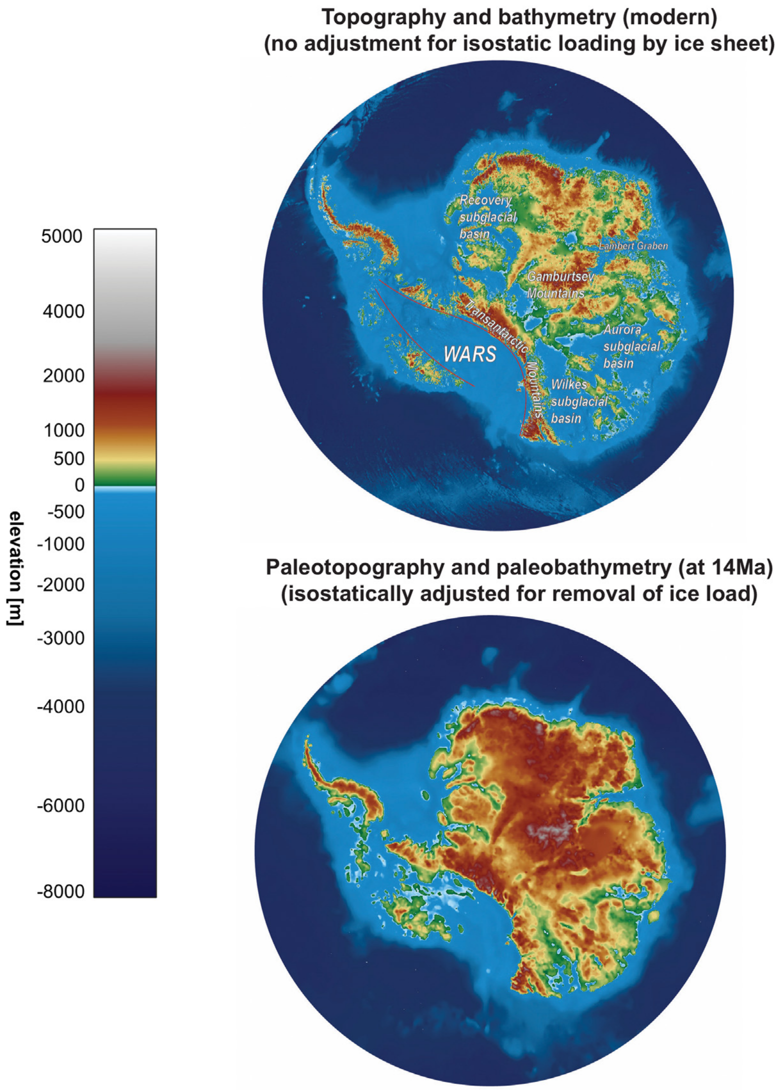

FIGURE 3.2 (Top) Map showing modern subglacial topography and bathymetry, and major geological and topographic features discussed in text. Base map above is plotted from MEaSUREs BedMachine Antarctica, version 2 (Morlighem, 2020). The approximate boundary of the West Antarctic Rift System (WARS) is shown as red lines. No isostatic adjustments have been made for removal of ice load. (Bottom) Middle Miocene (14 Ma) merged palaeotopographic and paleobathymetric models of the Southern Ocean and the Antarctic continent reconstructed based on all available geophysical and geological data after Paxman et al. (2019) and Hochmuth et al. (2020a,b). This map has been fully isostatically relaxed under ice-free conditions. The contrast in topography between the upper and lower panels highlights the importance of tectonic subsidence, erosion and isostatic responses to ice loading in influencing the sensitivity of the ice sheet to marine vs terrestrial mass balance controls.

environmental change since the Late Cretaceous, shedding light on the early history of the Cenozoic Antarctic ice sheets (Bart and De Santis, 2012; Brancolini et al., 1995; Decesari et al., 2007; Fielding et al., 2008; Gohl et al., 2013; Sorlien et al., 2007). In contrast, the rift basins in the Weddell Sea are much older, associated with back-arc rifting relating to subduction along the Pacific margin of the Gondwanan continent in the Jurassic (Huang et al., 2014; Jordan and Siddoway, 2020; Jordan et al., 2017; Riley et al., 2020). Drivers of topographic change and sedimentation in this region are directly related to erosion associated with the Cenozoic evolution of the EAIS and WAIS rather than active rifting processes (Hochmuth and Gohl, 2019; Paxman et al., 2019; Thomson et al., 2013).

Compared to the thinner crust of West Antarctica, the thicker, more tectonically stable cratonic crust of East Antarctica led to fundamentally different ice sheet dynamics and history there. Ancient high elevation orogenic belts in Dronning Maud Land and the Gamburtsev Mountains region were the most likely sites for the continent's first glaciers in the distant past, growing from alpine to ice caps with timing unknown but predating the first continental ice sheets 34 Ma ago (Bo et al., 2009; Ferraccioli et al., 2011; Rose et al., 2013). They also provided nuclei of the early glacial systems in East Antarctica (DeConto and Pollard, 2003; Galeotti et al., 2016; Stocchi et al., 2013). The Transantarctic Mountains, which began rising as a flank of the WARS from around 55 Ma ago (Gleadow and Fitzgerald, 1987), provided a growing buttress for East Antarctic ice flowing towards West Antarctica from the time of the first continental ice sheets. (DeConto and Pollard, 2003).

Today, approximately one-third of the EAIS is grounded below sea level. If this marine-based ice sheet were to melt it would contribute ~19.2 m to global sea level (Fretwell et al., 2013). The largest EAIS basins with marine-based ice are the Recovery Subglacial Basin (Weddell Sea sector) and the Wilkes and Aurora Subglacial Basins, with a smaller basin existing in the Prydz Bay region (Lambert Trough). These basins resulted from a range of predominately Mesozoic tectonic rifting processes, but have evolved through a range of subsequent erosion and sedimentary processes through the Cenozoic (Aitken et al., 2014, 2016; Ferraccioli et al., 2009, 2001; Harrowfield et al., 2005).

3.3 Global climate variability and direct evidence for Antarctic ice sheet variability in the Cenozoic

Several reviews on the long-term history of Antarctica's ice sheets have recently been compiled (Escutia et al., 2019; McKay et al., 2016; Noble et al., 2020; Shevenell and Bohaty, 2012). Chapters 3 (Barrett, 2008) and 5 (Cooper et al., 2008) of the first edition of this book (Florindo and Siegert, 2008) recorded discoveries made and strategies adopted to reveal Antarctic ice sheet age and evolution since the first International Geophysical Year (1957–1958).

These were largely achieved by over-snow traverses, the employment of post-World War II geophysical techniques in offshore surveying, and by ship-based and land-based deep drilling. Much progress has been made since that first edition. Areas like the Ross Sea and Prydz Bay, already relatively known, and less known areas (like the Amundsen Sea and most of the East Antarctic margin), have been revisited with new geophysical techniques, deep drilling and other multidisciplinary approaches. In this review, we provide an update of the current knowledge with a focus on regions seismically surveyed and sampled over the past two decades by geological drilling on the Antarctic margin, e.g., the ANDRILL and SHALDRIL projects, Ocean Drilling Program (ODP) and the Integrated Ocean Drilling Program/International Ocean Discovery Program (IODP). For detailed assessments of Antarctic ice sheet histories of specific time periods, or from more distal paleoceanographic records in the Southern Ocean and beyond, the reader is referred to Colleoni et al. (2021), Galeotti et al. (2021), Levy et al. (2021), Naish et al. (2021), Siegert et al. (2021) and Wilson et al. (2021).

3.3.1 Late Cretaceous to early Oligocene evidence of Antarctic ice sheets and climate variability

Low- and mid-latitude passive margins record moderate- to high-amplitude sea level variations (40–100 m) since Cretaceous times (Fig. 3.3), implying substantial ice sheets on Antarctica long before the assumed first glaciation in the earliest Oligocene (Hollis et al., 2014; Kominz et al., 2008; Miller et al., 2020, 2008). However, mantle dynamics may exert a significant influence that overwhelms a eustatic signal in the far-field sequence stratigraphic record (Moucha et al., 2008; Raymo et al., 2011), providing an alternative to ice sheets as the cause of pre-Oligocene sea level variations.

The only in situ Antarctic continuous continental shelf records obtained for the Late Cretaceous to earliest Paleogene are exposed on Seymour Island in the Antarctic Peninsula (Ivany et al., 2008; Mohr et al., 2020; Scasso et al., 2020), which at the time of deposition was an emergent volcanic arc at a paleolatitude of ~65°S, rather than part of continental Antarctica (Elliot, 1988; Lawver et al., 1992). Pollen assemblages indicate a cool to warm temperate coastal vegetation in the Late Cretaceous, with Mean Annual Temperatures (MAT) of ~10°C–15°C and dinoflagellate assemblages suggesting the possibility of winter sea ice (Bowman et al., 2014, 2013). ODP Leg 113 also recovered late Cretaceous (Maastrichtian) on the Maud Rise, with calcareous chalks and oozes that were interpreted to record warm temperate to cool subtropical climates with high seasonality in the Weddell Sea, with no clear evidence of cryospheric development (Kennett and Barker, 1990). This cooling trend in surface and intermediate Weddell Sea waters during the Maastrichtian is similar to that reported from Seymour Island.

Drilling in Prydz Bay recovered a short interval of terrestrial mid-Cretaceous sediment, with conifer-dominated woodland pollen suggesting a cool, humid climate (Macphail and Truswell, 2004a,b). As rifting in the eastern Ross Sea and Amundsen Sea sectors initiated during the Late Cretaceous, it is likely there are significant thicknesses of contemporaneous strata in these basins (Luyendyk et al., 2001; Wilson and Luyendyk, 2009). Indeed, reworked terrestrial Cretaceous palynomorphs are observed in surface sediments from the eastern Ross Sea, suggesting Cretaceous sediments are present in the rift basins (Kemp and Barrett, 1975; Truswell and Drewry, 1984). A recent short seafloor drill core from the Amundsen Sea region of West Antarctica recovered a mid-Cretaceous (~92−84 Ma) paleosol formed at a paleolatitude of ~82°S during the early phases of rifting with Zealandia (Gohl et al., 2017; Klages et al., 2020), when atmospheric CO_2 was estimated be ~1000 ppm (Foster et al., 2017). This paleosol contained in situ fossil tree roots, and fossil pollen and spores that indicate a diverse temperate lowland rainforest biome flourishing in about 4 months of complete polar night darkness and at mean annual temperatures of 13°C with precipitation of 1120 mm/yr. The reconstructed temperate climate at this high latitude

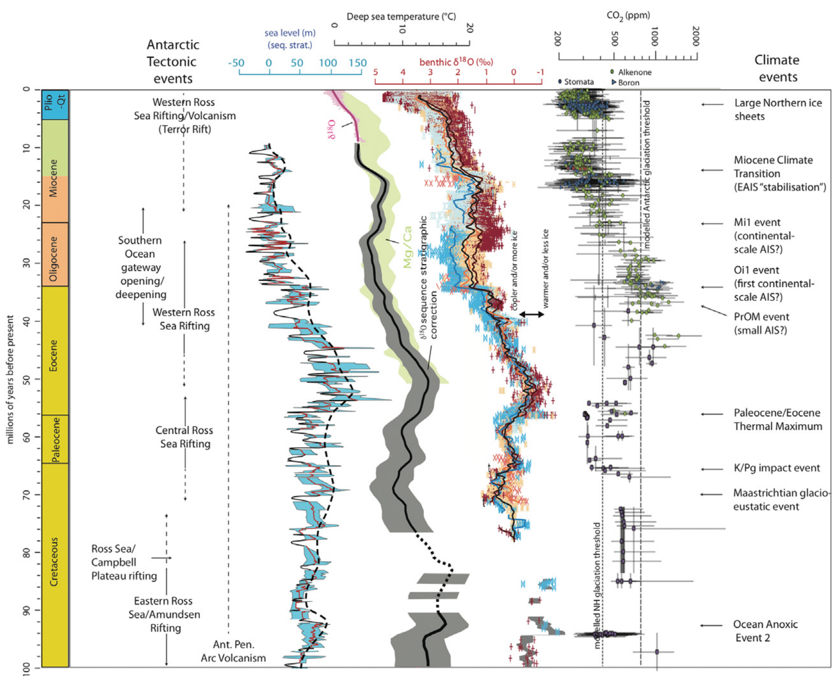

FIGURE 3.3 Chronostratigraphic summary of far-field sea level records (Kominz et al., 2008), climate proxies (deep sea temperature and $\delta^{18}O$; Cramer et al., 2009), atmospheric CO_2 (Foster et al., 2017) and relevant Cenozoic climate and tectonic events discussed in text also shown.

requires elevated atmospheric carbon dioxide levels and a vegetated land surface without major Antarctic glaciation (Klages et al., 2020).

The Eocene epoch was the last period when atmospheric CO_2 exceeded three to five times preindustrial concentrations (Anagnostou et al., 2016; Foster et al., 2017; Jagniecki et al., 2015; Liu et al., 2009; Pagani et al., 2011, 2005) (Fig. 3.3). Ocean modelling studies indicate that poleward heat transport in the Eocene was similar to today, but polar sea-surface temperatures (SSTs) were up to ~14°C warmer, appearing to preclude significant ice sheets in Antarctica (Hollis et al., 2019, 2012; Huber et al., 2004). An ice-free and vegetated Antarctica may have also exerted a significant control on the global carbon cycle by thawing of organic-rich permafrost soils during rapid and extreme warming events (hyperthermals), including the Paleocene-Eocene Thermal Maximum (PETM) (DeConto et al., 2012). Isotope studies on molluscs in the Antarctic Peninsula region suggest SSTs reached ~15°C in the early Eocene, cooling to ~5°C by the Late Eocene (Ivany et al., 2008). Similar SSTs are estimated from ODP Leg 113 stable isotope proxies (Kennett and Stott, 1990). Proxies from early Eocene erratics in the Ross Sea and offshore strata in Wilkes Land indicate much warmer summer temperatures (~25°C), frost-free winters (~10°C) and SSTs >15°C warmer than present, despite polar winter darkness (Askin, 2000; Bijl et al., 2013; Levy and Harwood, 2000; Pross et al., 2012).

Most modelling studies fail to produce extreme Eocene temperatures at high latitudes, unless CO_2 levels were significantly higher than current proxy records suggest (Caballero and Huber, 2013; Hollis et al., 2019, 2012, 2009). This implies that models might be undersensitive and lack some processes critical for simulation of polar climates. In contrast to the apparent warmth of the Eocene, sea level records from low-latitude passive margins in the Paleocene to Eocene record large amplitude variations (~40 m), which could relate to episodic growth of substantial ice sheets on Antarctica and/or mantle dynamics affecting these relative sea level records (Kominz et al., 2008; Miller et al., 2020). If eustatic in origin, these far-field sea level records contradict established models of Cenozoic cryosphere evolution and expansion of the Antarctic ice sheets at 34 Ma due to the development of the ACC (Kennett, 1977). However, they have never been fully tested against semicontinuous direct records proximal to the Antarctic continent.

Short cores containing ice transported clasts collected in the Sabrina Coast and Prydz Bay regions of East Antarctica and the Weddell Sea suggest the presence of some marine-terminating glaciers in the early Eocene to late Eocene (Carter et al., 2017; Gulick et al., 2017; Passchier et al., 2017; Shevenell et al., 2017). This evidence of earlier glacial advances is supported by radiolarian assemblages indicative of surface cooling at high latitudes in the Southern Ocean that also coincide with a positive oxygen isotopic excursion at ~37 Ma (the Priabonian Oxygen Isotope Maximum) (Pascher et al., 2015; Scher et al., 2014). Whether these were local mountain glaciers or ice sheets, prior to the Eocene/Oligocene boundary, it is clear from a range of proxy records around the margin that the late Eocene was significantly cooler than the mid Eocene. Temperate coastal pollen assemblages have been recorded from drill cores in the Weddell Sea, Ross Sea, Wilkes Land and Prydz Bay regions (Anderson et al., 2011; Cooper and O'Brien, 2004; Pross et al., 2012; Raine and Askin, 2001; Warny and Askin, 2013).

3.3.2 The Eocene-Oligocene transition and continental-scale glaciation of Antarctica

High-resolution deep sea $\delta^{18}O$ records, palaeontological studies and modelling experiments suggest the first continental-scale ice sheets were triggered at the Eocene/Oligocene boundary by an optimally cold orbital configuration (Coxall et al., 2005), following cooling due to the tectonic opening of Southern Ocean gateways (Bijl et al., 2013; Kennett, 1977) and decreasing atmospheric CO_2 below a threshold value (DeConto et al., 2008; Galeotti et al., 2016). This cooling also led to significant shifts in Southern Ocean planktic ecosystems (Houben et al., 2013). Once initiated, models suggest that ice sheet hysteresis behaviour, relating largely to height-mass balance and albedo feedbacks, ensured that the first ice persisted as a nucleus, allowing the ice sheet to expand and contract in response to orbital forcing throughout the Oligocene (DeConto and Pollard, 2003).

In the Antarctic Peninsula region, shallow sediment cores dated at $\sim 36 \pm 1$ Ma contain pollen and leaf wax biomarkers indicative of a significant cooling and drying prior to the Eocene/Oligocene boundary (Feakins et al., 2014). A similar cooling signal between the Eocene and Oligocene is identified in the Ross Sea, with a shift to shorter chain length leaf wax biomarkers reflecting a vegetation response to cooling climate (Duncan et al., 2019). Late Eocene cooling and drying is further supported by geochemical and clay mineral evidence from drill cores in Prydz Bay indicating reduced chemical weathering and enhanced physical weathering by glacial activity after 34.4 Ma, but with periods of ephemeral glaciation interpreted between 36 and 34.4 Ma (Forsberg et al., 2008; Hambrey et al., 1991; Passchier et al., 2017). Late Eocene palynological assemblages at Site 1166 in Prydz Bay indicate stunted *Nothofagus* rainforest, reflecting a cool to cold temperate environment at sea level (Macphail and Truswell, 2004a,b). Thermochronological studies from Prydz Bay also indicate greatly enhanced erosion by the EAIS in that region since 34 Ma (Thomson et al., 2013).

Paleotopographic reconstructions derived from tectonic, seismic and drilling studies reveal that West Antarctica and the East Antarctic marine basins were largely above sea level at 34 Ma (Paxman et al., 2019; Wilson et al., 2012). Therefore Antarctica could hold more terrestrial ice in the Oligocene than it can today, even though the climate was warmer than present (Wilson et al., 2013).

This is because the cooling threshold required for the development of a high elevation terrestrial-based ice sheet is lower than that of a marine-based ice sheet, which is highly sensitive to changes in oceanic heat flux. Consequently, models indicate a largely terrestrial West Antarctica could potentially accommodate an extra $\sim$13 million km^2 of grounded ice (i.e. $\sim$30 m SLE) during the early Oligocene, while the increased buttressing provided by a larger WAIS also leads to a larger and higher EAIS (Bart et al., 2016; Colleoni et al., 2018; Wilson et al., 2013) (Fig. 3.4). In addition, marine ice sheets also displace some of their mass in the ocean, so even if the volumes of a marine-based vs terrestrial-based ice sheet are the same, the resulting sea level changes are less for marine-based ice sheets (Gasson et al., 2016a).

However, these reconstructions present maximum and minimum estimates for the amount of subaerial land at the Eocene/Oligocene boundary, and Coenen et al. (2020) suggested that microfossils and biomarkers indicate marine embayments and lowlands in West Antarctica in the late Eocene, which favour the minimum topographic reconstructions of Paxman et al. (2019) and Wilson et al. (2012). However, an important caveat with this is that the modelled reconstructions have a very coarse (and smoothed) resolution. A more complex topography that included narrow marine embayments formed during rifting could have existed. These topographic reconstructions are also critical in assessing the role of glacial isostatic adjustment (GIA) on regional vs global sea level changes (e.g., Stocchi et al., 2013; Whitehouse et al., 2019).

Constraining Antarctica's paleotopography is critical for determining Antarctic Ice Sheet (AIS) contributions to eustatic sea level variability and ice volume throughout the Cenozoic era. Recent syntheses of seismic datasets constrained by geological data obtained from on-land outcrops and drill cores have provided significant advances in understanding the role that paleotopography has played on AIS history and offshore sediment deposition (Colleoni et al., 2018; Hochmuth et al., 2020a,b; Levy et al., 2019; Paxman et al., 2019). Furthermore, the accumulation of sediment through erosion and sedimentation in offshore basins is a fundamental control on ice sheet dynamics in its own right, and modellers are increasingly recognising the importance of this process on the long-term evolution of the AIS (Pollard and DeConto, 2020).

3.3.3 Transient glaciations of the Oligocene and Miocene

During the earliest Oligocene (and potentially late Eocene), marine-terminating glaciers episodically extended beyond the present-day coastline around much of the margin, with sediment core evidence of this in the Prydz Bay, Sabrina Coast, Wilkes Land and Ross Sea regions (Barrett, 1989; Escutia and Brinkhuis, 2014; Galeotti et al., 2016; Hambrey et al., 1991; Kulhanek et al., 2019; Levy et al., 2019). A high-resolution assessment of the sedimentology in the Cape Roberts Project drill cores indicated a stepped evolution of the EAIS expansion between 34 and 31 million years ago, with smaller, oscillatory terrestrial ice sheets varying at orbital timescales when atmospheric CO_2 levels were >600 ppm. However, at 32.8 Ma, a large, more stable continental-scale ice sheet formed at a time when proxies suggest CO_2 fell below 600 ppm (Galeotti et al., 2016).

In Prydz Bay and Wilkes Land, late Eocene to early Oligocene diamictites were recovered from the continental shelf, but are interpreted as glaciomarine deposits indicative of marine-terminating glaciers, rather than grounding of ice sheets on the outer continental shelf (Escutia et al., 2011a; O'Brien et al., 2001). However, determining whether or not Antarctic ice sheet expansion resulted in a ice advancing to the coastline in all sectors of Antarctica remains equivocal

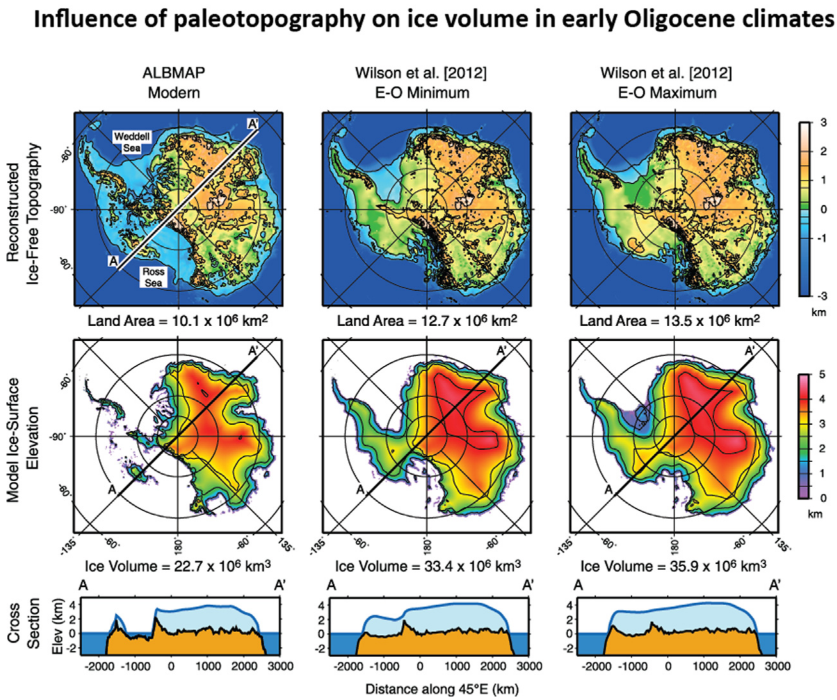

FIGURE 3.4 Top row: (left) Modern topography of West Antarctica; (middle) Minimum elevation of reconstructed E/O topography of West Antarctica, based tectonic history, seismic stratigraphic interpretations and drill core observation. (right) Maximum elevation of reconstructed E/O topography of West Antarctica using the same methodology. Maximum and minimum reconstruction accounting for uncertainties in the various datasets used to compile the paleotopographies. Middle and Bottom rows: (left) modelled ice sheet volume on topographies show in top row under an E/O boundary climate state (700 ppm CO_2) indicating a lack of ice in West Antarctica as marine ice sheet does not form in this warmer-than-present climate state. (middle) Reconstructed E/O topography of West Antarctica, with modelled ice sheet volume run in same climate as shown in top middle panel. (right) Reconstructed E/O topography of West Antarctica, with modelled ice sheet volume run in same climate as shown in top right panel.

from geological datasets. Evidence of a marine-terminating ice sheet grounding on the continental shelf comes from: (1) sedimentological data from the deep-sea margin of Antarctica which indicates only presence (rather than size) of marine-terminating glaciers; (2) sites in close proximity to the TAM [e.g., CIROS-1 and Cape Roberts Project (CRP)]; and (3) continental shelf regions in Wilkes Land and Prydz Bay. However, these records are highly discontinuous and potentially record smaller-scale alpine glacial advances or are hard to distinguish between glaciomarine and subglacial sedimentation (Cooper and O'Brien, 2004; Escutia et al., 2011a; Galeotti et al., 2016).

Consequently, further drilling campaigns in targeted regions are required to test the hypothesis of continental-wide expansion of the Antarctic ice sheets near the Eocene/Oligocene boundary, as implied by deep sea records and model-based experiments (Fig. 3.3). Drill core records from the Antarctic margin can also provide valuable constraints on relative sea level records in order to test sea-level models relating to EAIS growth. Such data-model comparisons suggest a near-field increase in relative sea level occurred, as a consequence of glacial isostatic adjustment and gravitational attraction as the EAIS grew (Stocchi et al., 2013). Increased spatial resolution in proximal marginal areas of drill cores is required to fully test these models and the full extent of Antarctic ice sheet growth across the continent.

Orbital pacing of Oligocene ice sheet variability is recorded from numerous locations around the East Antarctic margin, including the Ross Sea (Barrett, 2007, 1989; Galeotti et al., 2016; Naish et al., 2001), and offshore from Wilkes Land and Dronning Maud Land (Hartman et al., 2018; Hauptvogel et al., 2017; Salabarnada et al., 2018). The Oligocene-Miocene boundary (23 Ma) is characterised by an isotopic excursion of ~1‰ attributed to an abrupt increase in Antarctic ice volume driven by changes in Earth's orbital parameters (Barrett, 1989; Flower et al., 2006; Mawbey and Lear, 2013; Naish et al., 2001; Zachos et al., 1997) and a decrease in atmospheric CO_2 (Pagani et al., 2005). Deep Sea Drilling Project (DSDP) Site 270 records a phase of proximal glaciomarine sedimentation on the outer Ross Sea continental shelf at ~24.5 Ma, inferred to be the consequence local advances of ice caps nucleating on nearby subaerial basement (De Santis et al., 1995; Kulhanek et al., 2019) (for details see Naish et al., 2021, this volume).

A comprehensive synthesis of geological drill core data and the seismic stratigraphy in the Ross Sea was conducted by Levy et al. (2019), who compared these data to orbital scale timeseries analysis on deep sea oxygen isotope records. In their study, the authors noted a large increase in the sensitivity of benthic $\delta^{18}O$ records to obliquity pacing (40-kyr orbital cycles relating to the tilt of the Earth's axis) during the latest Oligocene. This increased sensitivity coincided with direct evidence of AIS advance onto the Ross Sea continental shelf – as determined by seismic unconformities and sedimentary facies in drill cores, as well as evidence from global proxies of lower atmospheric CO_2 conditions following the Oligocene/Miocene boundary (Foster and Rohling, 2013; Foster et al., 2017). As obliquity is an important regulator of latitudinal temperature gradients, and therefore the wind-driven ocean currents that strongly influence marine ice sheet mass balance, these results suggest increased frequency of orbitally paced marine-terminating ice sheet advances and retreats in this region following the Oligocene/Miocene boundary (Levy et al., 2019).

Following the periodic transient glaciations during the Oligocene to early Miocene, both near- and far-field proxy data indicate a period of sustained warmth, referred to as the Miocene Climatic Optimum (MCO; ~17−15 Ma; Flower and Kennett, 1994; Shevenell et al., 2008) (for more detail see Levy et al 2021), this volume. At this time, changes in global carbon cycling occurred (e.g., Holbourn et al., 2015; Vincent and Berger, 1985), average global temperatures were ~3°C warmer than present, and while polar amplification is suggested from proxy data, models require atmospheric CO_2 in the range of 460−580 ppmv (Feakins et al., 2012; Lewis et al., 2008; Shevenell and Kennett, 2004; Warny et al., 2009; You et al., 2009).

The ANDRILL site AND-2A was recovered from the Western Ross Sea and was interpreted to record TAM tidewater outlet glaciers overriding and/or calving near the site (Fielding et al., 2011; Passchier et al., 2011). At 15.7 Ma, a diatomite with abundant pollen, algae and other biomarkers suggests a warmer than present (Mean Summer Temperature of ~10°C) climate during the MCO (Feakins et al., 2012; Warny et al., 2009). A compilation of sedimentological and geochemical evidence from the AND-2A drill core combined with modelling experiments suggest retreat of the EAIS to its terrestrial margin during peak warm interglacials of the MCO (Gasson et al., 2016a; Levy et al., 2016). Further offshore, IODP Site U1521 recovered a thick interval of diatom-rich mudstone deposited during the MCO (McKay et al., 2019), while offshore of Wilkes Land marine sediments demonstrates a relative lack of ice rafted debris, with temperate pollen assemblages of *Nothofagidites* and *Podocarps* indicative of mean summer on-land temperatures of >10°C (Sangiorgi et al., 2018). On-land outcrops in the Dry Valleys provide evidence of voluminous outbursts of subglacial meltwater derived from the EAIS margin prior to 14 Ma (Lewis et al., 2006; Sugden and Denton, 2004), while a tundra vegetation and wet-based alpine glaciation persisted at high elevations in the TAM until at least 14.07 Ma (Lewis et al., 2008).

The Middle Miocene Climate Transition (MMCT) is identified by a ~1‰ enrichment in the $\delta^{18}O$ record of deep sea benthic foraminifera at 13.8 Ma (Flower and Kennett, 1994; Holbourn et al., 2014; Kennett, 1977; Shevenell and Kennett, 2004), with sea level and temperature reconstructions implying the majority of this $\delta^{18}O$ enrichment is related to ice sheet expansion (John et al., 2004; Shevenell et al., 2008; Wright et al., 1991) (for more detail see Levy et al. 2021, this volume). This isotopic excursion is associated with rapid cooling to dry-based glaciation and aridification of the high elevation regions of the TAM, alongside inferred extinction of alpine tundra vegetation (Lewis et al., 2008, 2007). Consequently, this expansion has commonly been inferred to represent the development of a permanent and relatively stable EAIS (Sugden, 1996).

This idea of a stable EAIS since ~14 Ma was intensely debated throughout the 1980s and 1990s on the basis of Pliocene-age marine diatoms observed in the Transantarctic Mountain Sirius Group deposit. These diatoms were inferred to have been sourced from Pliocene-age marine strata deposited in the Wilkes Land subglacial basin and transported into the TAM via a subsequent readvance of the EAIS (Webb et al., 1984), implying this subglacial basin was deglaciated in the Pliocene (see review by Barrett, 2013 for details on this debate). Subsequent studies suggest the diatoms were windblown from isostatically uplifted Pliocene marine strata in the coastal regions of the Ross Sea and incorporated into the surface layers of the Sirius Group after deposition and are therefore more indicative of a Pliocene WAIS retreat (McKay et al., 2008). This hypothesis was recently expanded by model experiments indicating potential windblown pathways may have been more widespread and Pliocene-aged marine diatoms could have been sourced from widespread uplifted marine sediments along the margin of the EAIS, as well as the WAIS (Scherer et al., 2016).

A glacial unconformity observed in seismic records from the Ross Sea, RSU4, is constrained to have formed between 16 and 14 Ma and suggests substantial marine-based ice advance of the EAIS into the Ross Sea associated with the MMCT (Anderson and Bartek, 1992; Bart, 2003; De Santis et al., 1995). Resolving the timing of this unconformity was a primary objective of the recent IODP Expedition 374 (McKay et al., 2019). In Prydz Bay and Wilkes Land (Sites 1165 and U1356), greatly increased deposition of gravel and pebble-sized ice rafted debris from 14.1 to 13.7 Ma provides direct evidence for ice expansion of the EAIS at the MMCT (Pierce et al., 2017).

The ANDRILL sites AND-1B and AND-2A in the Western Ross Sea recovered several diamictite-rich deposits with a maximum age of 13.57 Ma, interpreted to represent a phase of Antarctic ice sheet expansion in the Ross Embayment, potentially during the MMCT (Fielding et al., 2011; Levy et al., 2016; McKay et al., 2009; Passchier et al., 2011). A depositional change observed in seismic profiles from the Ross Sea around this time has been attributed to EAIS and WAIS expansion (De Santis et al., 1999). In the Wilkes Land region, a depositional shift in the channel levee systems on the continental margin is interpreted to have been associated with expansion of the EAIS to the shelf edge at the MMCT (Escutia et al., 2011a; Sangiorgi et al., 2018). Decreasing sedimentation rates and increased ice rafted debris deposition after 14.5 Ma on the East Antarctic margin in Prydz Bay potentially signifies reduced erosion by the EAIS under the influence of a cooler glacial regime (Florindo et al., 2003), although ODP Site 1166 recovered sediments of this age containing benthic foraminifers recycled from Eocene shallow water sediments, suggesting physical erosion of the continental shelf continued through this period (Cooper and O'Brien, 2004). At this time, a hiatus or condensed sequence that spans most of the middle Miocene (<6 m/Ma, 15−8 Ma) has been reported along the Pacific Margin of the Antarctic Peninsula (Hernández-Molina et al., 2017).

Following the MMCT, several other Miocene glaciations inferred from $\delta^{18}O$ excursions probably occurred between 13 and 8 Ma (Holbourn et al., 2013; Miller et al., 1991), but geological records of this time period are sparse in Antarctica. In the Antarctic Peninsula and Wilkes Land region, pollen contained in continental shelf drill cores suggest tundra vegetation may have persisted until 12.8−11 Ma (Anderson et al., 2011; Sangiorgi et al., 2018). This implies that at lower latitudes and/or low elevations, climate conditions may have allowed vegetation to persist well into the late Miocene. Biomarker evidence in the Dry Valleys and sparse pollen data from DSDP Site 274 in the northwestern Ross Sea hints at coastal refugia of vegetation persisting into the early Pliocene, although unequivocal evidence of this occurring is still lacking (Fleming and Barron, 1996; Ohneiser et al., 2020).

An increased abundance of hemipelagic sediments and ice rafted debris in the Weddell Sea was originally interpreted as representing the development of the first major 'marine-based' WAIS advance occurring at ~8 Ma (Kennett and Barker, 1990). Late Miocene interglacials (11−6 Ma) in AND-1B are represented by terrigenous facies that are similar to those deposited widely in proximal glaciomarine setting in Greenland today, such as outwash gravels and coarse inclined sand beds interpreted as glaciomarine fan systems, and mudstones that contain intervals of rhythmically laminated sand/silts formed by large volumes of turbid subglacial meltwater discharge (McKay et al., 2009). Although such facies exist in some Late Pleistocene and modern sediments, they are generally thin (<1 m) and sparsely distributed (Mckay et al., 2009; Prothro et al., 2018). In contrast, these facies in late Miocene interglacial intervals in AND-1B are >10 m thick, indicating elevated levels of subglacial meltwater discharge relative to Plio-Pleistocene times, which contain diatom ooze that are relatively starved of terrigenous sediment supply (McKay et al., 2009; Rosenblume and Powell, 2019). Similar sedimentary facies are observed in the middle to late Miocene Fisher Bench Formation from the Pagodroma Group in the Prydz Bay region of East Antarctica, while seismic sequences and short cores near Totten Glacier also provide clear evidence that elevated subglacial meltwater discharge was widespread during the late Miocene around East Antarctica, with a warmer subpolar style glacial regime relative to the Pliocene (Donda et al., 2020; Gulick et al., 2017; Hambrey and McKelvey, 2000).

Recent global temperature reconstructions indicate a significant late Miocene cooling event between 7 and 5.4 Ma (Herbert et al., 2016), broadly corresponding to a reduction in the presence of sedimentary facies associated with large turbid subglacial meltwater discharge around the East Antarctica (Gulick et al., 2017; Hambrey and McKelvey, 2000; McKay et al., 2009;

Rosenblume and Powell, 2019). Despite this inferred warmth and surface melt in East Antarctica in the late Miocene, cosmogenic nuclides in sand grains from AND-1B suggest minimal surface exposure of these grains prior to subglacial transport to the offshore drillsite, indicating the EAIS had not experienced significant on-land retreat of its margin within the past 8 Myr (Shakun et al., 2018). During the latest Miocene, and coveal to this cooling event, a shift in the development of glacial margin sequences along the Pacific Margin of the Antarctic Peninsula marks the time that regular ice advances began to reach the shelf break (Larter and Barker, 1989, 1991b; Larter et al. 1997; Hernández-Molina et al., 2017).

3.3.4 Pliocene to Pleistocene

The Pliocene and Pleistocene history of the AIS has been an area of intense study over the past decade, and here we only provide a first-order summary of recent developments in understanding, with a focus on how this history may manifest itself in the sedimentary basins of the Antarctic margin. Levy et al. (2021) and Wilson et al. (2021) provide a detailed review of the Pliocene and Pleistocene history of the AIS and linkages to global records. Even more extensively studied is the Last Glacial Maximum (LGM) deglaciation, which has recently been reviewed by the Reconstruction of Antarctic Ice Sheet Deglaciation (RAISED) consortium (The RAISED Consortium, 2014), and is covered in detail by Siegert et al. (2021). For conciseness, the LGM and last deglaciation histories are not repeated in this chapter, except where relevant context for the deeper time records is provided.

During the early to mid-Pliocene warmth, global sea levels are thought to have been 20 ± 10 m above present-day levels, indicating a reduction/collapse of both the Greenland Ice Sheet and the WAIS, and potentially large parts of the marine-based sectors of the EAIS (Dumitru et al., 2019; Grant et al., 2019; Miller et al., 2012; Naish and Wilson, 2009). Although the exact timing of the subsidence of West Antarctica remains equivocal, seismic stratigraphic arguments suggest that between the late Miocene and Pliocene, there was a major shift in the style of ice sheet erosion. In West Antarctica, and parts of East Antarctica, it is inferred that larger, cold polar, marine ice sheets led to increased erosion and overdeepening of the continental shelf (Bart and De Santis, 2012; Bart and Iwai, 2012; Cooper and O'Brien, 2004; De Santis et al., 1995; Hernández-Molina et al., 2017). This eroded continental shelf sediment was subsequently redeposited to the continental slope to rise, resulting in the development of large trough mouth fan and mass transport systems (O'Brien et al., 2007; Rebesco et al., 2006). This overdeepening would have increased the sensitivity of the ice sheets margin to Marine Ice Sheet Instability (MISI) processes (Bart et al., 2016; Colleoni et al., 2018). Currently, it remains uncertain how diachronous overdeepening of the continental shelf was across the late Miocene to Pliocene, as tectonic drivers of sedimentary basin development played a role alongside the climatic or glaciological processes. However, as discussed in later region-specific sections of this chapter, it is clear there was a significant shift in stratigraphic architecture around the Antarctic margin during the late Neogene that appears to be associated with more frequent occurrences of marine ice sheet advances.

Sedimentary facies from the AND-1B drill core indicate numerous orbitally-paced advances of the WAIS to the mid-continental shelf during the early Pliocene (Naish et al., 2009). This is supported by seismic stratigraphic evidence of truncated glacially eroded surfaces that extended to continental shelf edge (Alonso et al., 1992; Anderson et al., 2018; Bart, 2001). Coastal diatom oozes indicate significant sediment starvation during Pliocene interglacials, implying reduced surface and subglacial meltwater from the adjacent coastline relative to the late Miocene (McKay et al., 2009), an observation that is mirrored in outcrops from the Prydz Bay region, implying a shift towards cold polar glaciation in the Pliocene around the EAIS margin (Hambrey and McKelvey, 2000; Whitehead et al., 2004). AND-1B also records periodic retreats of the WAIS that continued through the Plio-Pleistocene until at least 1.0 Ma, and although other proximal ice sheet and distal sea level/ice core records suggest WAIS may have collapsed since this time (as recently as the last interglacial), there is a lack of direct Antarctic records to confirm this (Hillenbrand et al., 2002; McKay et al., 2012b; Scherer et al., 1998). Surface waters during the warmest interglacial of the Pliocene in AND-1B indicate greatly reduced sea ice in the Ross Sea, and diatom species that today live north of the Polar Front, implying sea surface temperatures were 4°C–5°C warmer than present (McKay et al., 2012a; Riesselman and Dunbar, 2013). In the Wilkes Land and Prydz Bay region, similar microfossil-derived sea surface temperatures and open water conditions suggest migration of the Polar Front southward during the Pliocene (Bohaty and Harwood, 1998; Escutia et al., 2009; Taylor-Silva and Riesselman, 2018; Whitehead and Bohaty, 2003). Warmer than present waters were also reconstructed during Marine Isotope Stage 31 at ~1 Ma (Beltran et al., 2016; Scherer et al., 2008; Villa et al., 2008), when a significant deglaciation of the WAIS was proposed (Naish et al., 2009; Scherer et al., 2008). Offshore provenance and ice rafted debris data suggests the marine-terminating margin of the EAIS fluctuated greatly at orbital timescales and periodically retreated significantly inland during the Pliocene (Bertram et al., 2018; Cook et al., 2013; Hansen et al., 2015; Passchier, 2011; Patterson et al., 2014; Williams et al., 2010) while continental shelf deposits in Wilkes Land (IODP Site 1358) show advances and retreats of the ice sheet from the continental shelf edge at these times (Reinardy et al., 2015).

Global cooling and the onset of Northern Hemisphere glaciation at ~2.7 Ma corresponded with a continued cooling trend in Antarctica and increasing seasonal sea ice persistence/extent around the continental margin (Armbrecht et al., 2018; Cortese and Gersonde, 2008; Escutia et al., 2009;

Kennett and Barker, 1990; McKay et al., 2012a; Riesselman and Dunbar, 2013; Taylor-Silva and Riesselman, 2018). Cosmogenic isotope dating studies around the EAIS margin suggest a thicker ice sheet existed during glacials in the late Pliocene and early Pleistocene, compared to late Pleistocene glacials. This is interpreted to represent a shift to cooler, more arid conditions (i.e., less precipitation of snow) in the late Pleistocene (Jones et al., 2017; O'Brien et al., 2007; Suganuma et al., 2014; Yamane et al., 2015). Despite this cooling, provenance indicators from Site 1361 offshore of Wilkes Land provide evidence that some inland retreat of the marine-based EAIS margin occurred during Marine Isotope Stages 11, 9 and 5, (~400, 320 and 120 ka, respectively), although the exact extent of EAIS retreat remains difficult to constrain from offshore provenance studies (Wilson et al., 2018). A novel method to constrain the extent of the last major inland retreat of the EAIS has recently been presented using the uranium isotopic composition of carbonate precipitates in morainal deposits and indicates a ~700 km retreat inland of the Wilkes Land margin occurred during Marine Isotope Stage 11 (Blackburn et al., 2020). During the last interglaciation of Marine Isotope Stage 5, ice core evidence combined with far-field sea level fingerprinting and modelling experiments suggests substantial ice loss driven by oceanic warming in the Weddell Sea sector of the WAIS, although it remains equivocal if this corresponded to full marine-based WAIS collapse (Clark et al., 2020; Turney et al., 2020).

The most accessible geological records in Antarctica capture the retreat of the ice sheets since the Last Glacial Maximum and consequently has been heavily studied by a range of offshore (e.g., shallow sediment cores, multibeam bathymetric surveys) and onshore studies (e.g., mapping and cosmogenic nuclide dating of moraines). Given the breadth of studies in this time period and that such studies are generally not captured by geological drilling methods, we do not discuss post-LGM glacial retreat in detail in this chapter (unless it is relevant to the deeper time records) and the reader is referred to Siegert et al. (2021).

3.4 Regional seismic stratigraphies and drill core correlations, and future priorities to reconstruct Antarctica's Cenozoic ice sheet history

Extensive seismic reflection data have been acquired by many nations around Antarctica, and a compilation of almost all multichannel profiles are available in stack version at the SCAR Seismic Data Library System for Cooperative Research (SDLS) (https://sdls.ogs.trieste.it), established and endorsed in 1991 by SCAR (Report 9) and the Antarctic Treaty (ATCM Recommendation XVI-12). This cooperative library has sparked many successful collaborations and the exchange of data between scientists of all SCAR countries and beyond. The existence and structure of SDLS allowed to maximise reuse of existing data and strategically collect new data where necessary, often coordinating data collection between countries. This has reduced costs and logistic effort for data collection and also minimises unnecessary exposure of possible environmental impacts through seismic data acquisition. There are currently data from 153 surveys with over 336,000 km on seismic lines from 16 countries included in the SDLS (Fig. 3.1). This represents ~87% of the known multichannel seismic reflection data collected in Antarctica since the late 1970s.

The seismic stratigraphic framework above the acoustic basement was defined regionally by the ANTOSTRAT (Antarctic Offshore Acoustic Stratigraphy) project for the Ross Sea, Antarctic Peninsula, Weddell Sea, Prydz Bay and Wilkes Land in the mid-1990s (Brancolini et al., 1995; Cooper et al., 2011, 2008) and represented one of the precursor programs for ACE, PAIS, PRAMSO and for the circum-Antarctic paleobathymetric reconstructions. However, the ages of the ANTOSTRAT unconformities on the continental shelf, rise and abyssal plain have been only partially constrained by drilling, mainly in the Ross Sea and Prydz Bay (see synthesis by Bart and De Santis 2012; Cooper et al., 2008), the Antarctic Peninsula (Barker and Camerlenghi, 2002) and Wilkes Land (Escutia et al., 2011a). In addition to continental shelf drilling, partial age control of continental rise unconformities has allowed several region-to-region correlations to be made (Close, 2010; Donda et al., 2007; Hernández-Molina et al., 2017; Hochmuth et al., 2020a,b; Hochmuth and Gohl, 2019; Leitchenkov et al., 2007, 2015; Lindeque et al., 2016, 2013; Rebesco et al., 2006; Sauermilch et al., 2019). In the frame of the Palaeotopographic-Palaeobathymetric Reconstructions PAIS subcommittee, these have allowed for updated paleodepth contour maps of the main seismic horizons across all the Antarctic margin and Southern Ocean from the Eocene-Oligocene Boundary to modern times to be presented (Hochmuth et al., 2020a,b). Such data helps inform models restoring the Antarctic margin paleotopography since the Eocene, by measuring the volume of sediment that had been transported offshore by erosive ice sheets. However, such models also need to consider the compaction of the sediments, as well as the lithosphere isostatic subsidence, in addition to the tectonic and thermal history that can only be verified by deep geological drilling (Paxman et al., 2019; Wilson et al., 2012). All these reconstructions represent a significant step forward, but gaps still remain and areas where maps are extrapolated need to be verified by future seismic survey and drilling campaigns. Despite these remaining uncertainties, over the past decade we have gained an increasingly detailed view of the morphological and tectonic evolution of the Southern Ocean, including the opening and deepening of the Tasmanian and Drake gateways that allowed for the establishment of the ACC.

In this section, we summarise the seismic stratigraphy of major sedimentary basins around the Antarctic margin, how the integration of this stratigraphic architecture with geological drilling may inform on the long-term climate and ice sheet evolution described above, and how future campaigns could be conducted to resolve outstanding aspects of this history.

3.4.1 Ross Sea

The Ross Sea contains the most well-defined seismic stratigraphic framework for Antarctica's continental shelves, with a dense network of seismic profiles that have been constrained by numerous geological drilling projects since the 1970s (Fig. 3.5). A significant number of regional, large-scale geophysical exploration surveys of the Ross Sea continental margin architecture were conducted in the 1980s and 1990s, but during the last two decades, a series of cruises collecting closely spaced grids were conducted, in order to reconstruct the WAIS and EAIS dynamics across the Late Cenozoic (Anderson et al., 2018; Bart, 2003; Bart and De Santis, 2012; Bart et al., 2011; Böhm et al., 2009; Chow and Bart, 2003; Kim et al., 2018; Mosola and Anderson, 2006; Sauli et al., 2014). Recent work focused on understanding the relationship between the ocean circulation, the morphology of the sea floor, the processes affecting the sub-ice shelf cavities and the ice sheet dynamics, in the present day and since the LGM (Ashley et al., 2020; Gales et al., 2021; Tinto et al., 2019).

Although numerous different frameworks have been proposed over this time, for simplification purposes, the synthesis below largely adopts the ANTOSTRAT nomenclature (e.g., ANTOSTRAT Ross Sea atlas of Brancolini et al., 1995), but discusses these with caveats relating to basin-wide correlations of these sedimentary packages and erosive surfaces. In this framework, eight major Ross Sea Sequence (RSS) units bounded by seven major Ross Sea Unconformities (RSU) are mapped across the Ross Sea (Brancolini, et al., 1995), although subdivision of these sequences has been conducted in subsequent studies (Fig. 3.6). These sequences are largely defined by studies in the Eastern and Central basins of the Ross Sea, and represent major steps in Antarctica's tectonic and climatic evolution, whereas in the active rift zones of the Western Ross Sea, different nomenclatures exist (Fielding et al., 2008; Levy et al., 2012, 2019; Pekar et al., 2013, Sauli et al., 2021). These differences arise due to the difficulties of correlation between basins, as well as the potential for significant diachronism relating to the complex history of Cenozoic rifting, subsidence, sedimentation and ice sheet expansion across the Ross Sea (Fig. 3.7). Work combining seismic, magnetic and gravity data highlight the complex structural evolution of the western Ross Sea during the late Cenozoic, with the diachronous propagation of rifting southwards between 46 and ~11 Ma, with a prominent pulse of rifting in the early Miocene (~17 Ma) (Davey et al., 2016; Ferraccioli et al., 2009; Fielding et al., 2008; Granot and Dyment, 2018; Granot et al., 2013). Late Miocene and Pliocene subsidence was associated with intense volcanism (Lisker et al., 2014; Wenman et al., 2020), and recent extensional tectonics

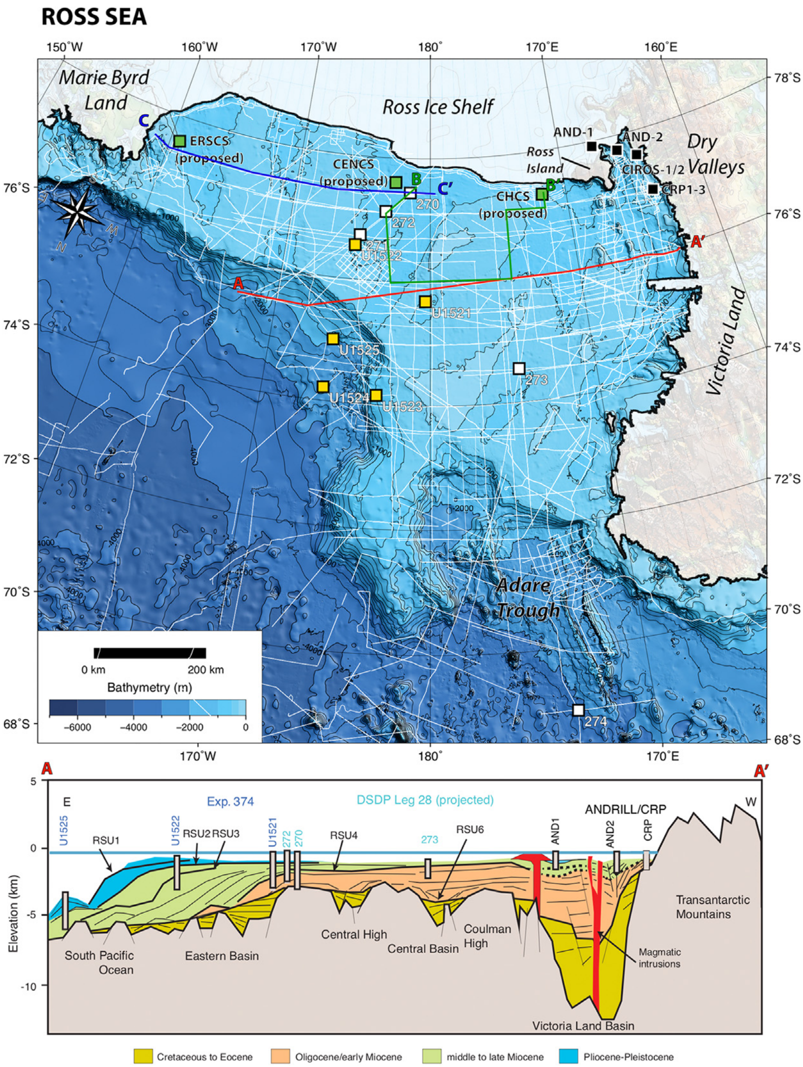

FIGURE 3.5 (Top) Overview map of Ross Sea sector with existing seismic lines (white lines) and drill sites. DSDP Leg 28 sites are shown as white squares, ice-platform drilling projects as black squares (CRP, CIROS, ANDRILL) and IODP Expedition 374 sites as yellow squares. Future proposed sites discussed in text are shown as green squares. Seismic tracks are from the SCAR Antarctic Seismic Data Library System (SDLS) and additional survey information. Bathymetry is from Bathymetric Chart of the Southern Ocean (Arndt et al., 2013) and subglacial topography from BedMachine Antarctica dataset (Morlighem et al., 2020). Track lines of the seismic profiles shown in bottom panel and Fig. 3.6 are marked with bold red (A−A′), green (B−B′) and blue (C−C′) lines, respectively. (Bottom) Ross Sea seismic stratigraphy showing major unconformities (RSU6,4-1) and associated shifts in the geometry of sedimentary packages on the continental shelf, and previous drilling (see upper panel for transect line). DSDP Leg 28, ANDRILL, CRP and Expedition 374 sites. *Adapted from McKay, R.M., De Santis, L., Kulhanek, D.K., IODP Expedition 374 Science Team, 2019. Proceedings of the International Ocean Discovery Program, vol. 374, https://doi.org/10.14379/iodp.proc.374.2019.*

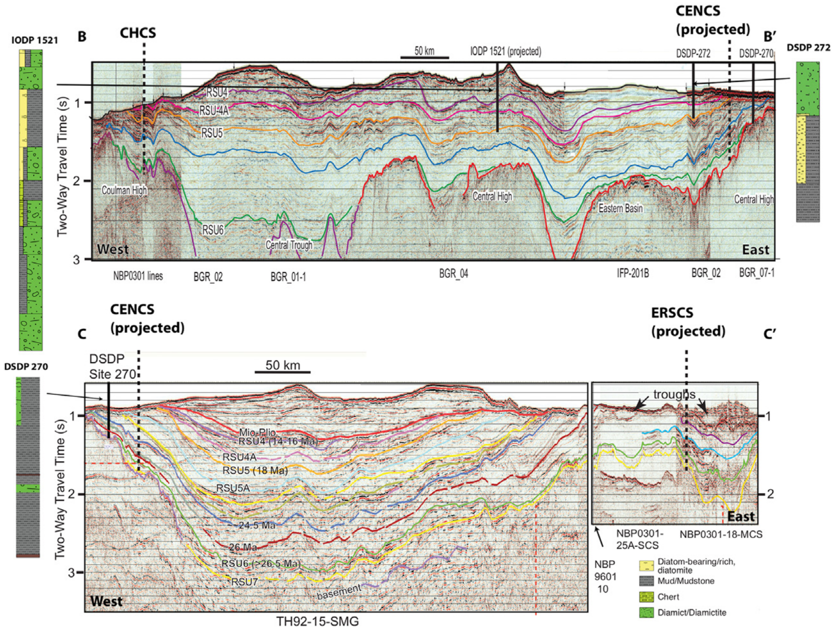

FIGURE 3.6 Detailed seismic cross sections and correlations of major unconformities and ties to DSDP Leg 28 sites (Sites 270, 272) compiled for IODP pre-proposal 998 (Table 3.1) from: (Top) the Central Trough to western flank of the Eastern Basin (Line B-B' in Fig. 3.5); (Bottom) the western flank to Eastern Flank of the Eastern Basin (Line C-C' in Fig. 3.5), based on correlations presented by Sorlien et al. (2007). Approximate location of proposed (projected) future drill sites discussed in text is shown. Seismic line numbers used to construct profile and are available in SDLS are labelled for each section and are available in SDLS. Vertical exaggeration in both lines is large (> 80x). *Note*: Labels are at base of upper section and top of lower section. *Drill core lithologies are based on data from Hayes, D.E., Frakes, L.A., et al., 1975. Initial Reports of the Deep Sea Drilling Project, vol. 28. US Government Printing Office. Available from: http://deepseadrilling.org/28/dsdp_toc.htm, Kulhanek, D.K., Levy, R.H., Clowes, C.D., Prebble, J.G., Rodelli, D., Jovane, L., et al., 2019. Revised chronostratigraphy of DSDP Site 270 and late Oligocene to early Miocene paleoecology of the Ross Sea sector of Antarctica. Global and Planetary Change 178, 46–64. Available from: https://doi.org/10.1016/j.gloplacha.2019.04.002, McKay, R.M., De Santis, L., Kulhanek, D.K., IODP Expedition 374 Science Team, 2019. Proceedings of the International Ocean Discovery Program, vol. 374, https://doi.org/10.14379/iodp.proc.374.2019.*

affecting the sea floor has been reported in the western Ross Sea (Geletti and Busetti, 2011; Hall et al., 2007; Sauli et al., 2021). This tectonic system appears to be associated with the presence of mud volcanoes and pockmarks fed by fluids/gas seeping migrating upward along faults. Similar morphological mounds of possibly carbonatic and/or volcanic origin also occur within the Terror Rift, close to volcanic centres including Franklin Island (Lawver et al., 2012).

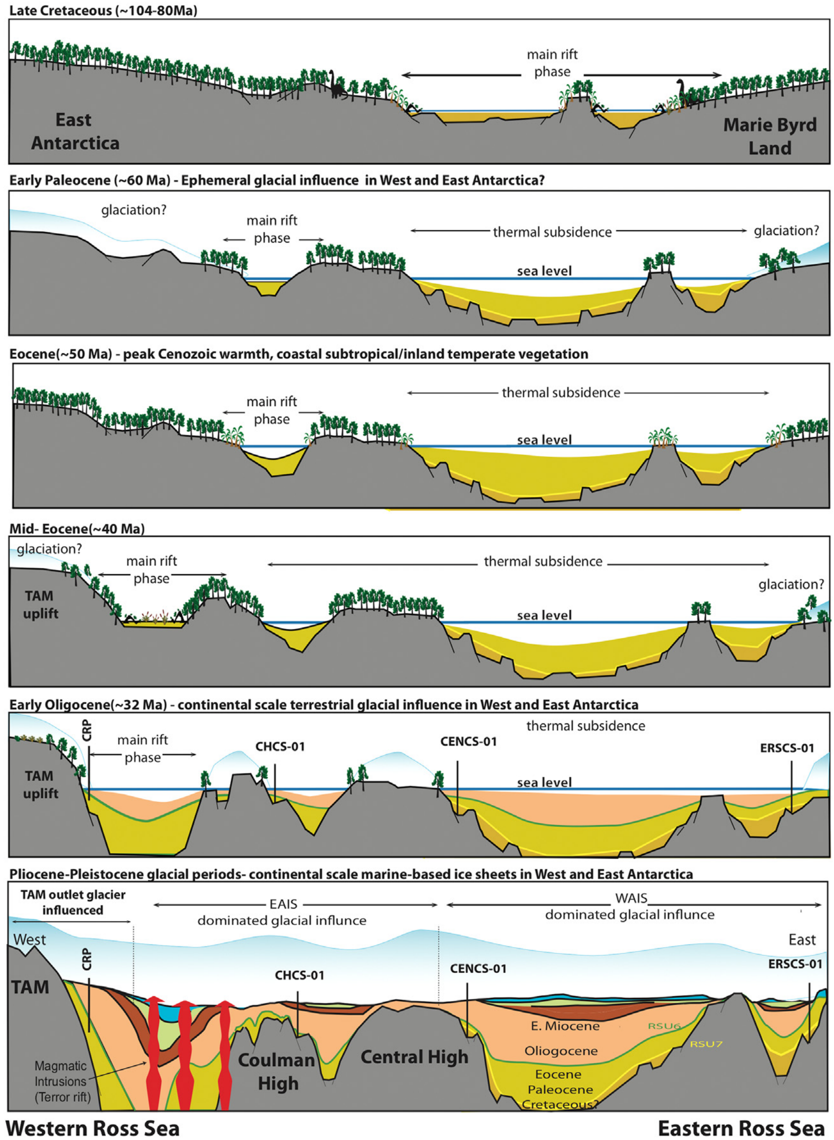

FIGURE 3.7 West Antarctic Rift System (WARS) history in the Ross Sea and relationship to basin infill and ice sheet/TAM outlet glacier influences through time. The history is based on the rift model presented by Wilson and Luyendyk (2009), and the profile shown in Fig. 3.6. Targeted drilling in a proposed E−W transect across the continental shelf is intended to assess the timing of active rift termination and will obtain high-resolution climate records back to the onset of rifting (~Late Cretaceous).

The geological basement depth in the Ross Sea is reconstructed by combining seismic profile interpretation with inversion of gravity data (Brancolini et al., 1995; Decesari et al., 2007; Ji et al., 2018; Luyendyk et al., 2001; Tinto et al., 2019). The oldest and deepest ANTOSTRAT unit in the Ross Sea is RSS-1, which consists of graben-bound rift-fill strata and is separated into two units, representing early- (RSS-1 Lower) and late-rift (RSS-1 Upper) sequences bounded by unconformity RSU7. These units are likely to be diachronous across basins, a consequence of rifting propagating toward the west (Luyendyk et al., 2001; Wilson and Luyendyk, 2009). Unit RSS-1-lower is likely Late Cretaceous in age in the Eastern Basin and is characterised by dipping and disrupted reflectors. RSS-1-lower may represent a fluvial terrestrial setting and potentially provides a unique opportunity to sample terrestrial Antarctic environments during the Cretaceous (Luyendyk et al., 2001). RSU7 is inferred to have formed during regional extension caused by the break-up of the Gondwana continent (Decesari et al., 2007; Luyendyk et al., 2001), although glacial erosion or relative sea level changes could also be responsible. Unit RSS-1-upper is a thicker sequence of flat lying, faulted strata onlapping onto RSU7, and inferred to contain marine strata deposited during marine transgression across thermally subsiding crust (Decesari et al., 2007).

RSU6 is a prominent seismic unconformity across the Ross Sea, but its origin and age is enigmatic. It is possible that RSU6 was cored at CRP and CIROS-1 (Figs. 3.5 and 3.7), but its age at these sites is highly ambiguous due to extensive unconformities truncated by alpine TAM glaciation. In addition, the occurrence of faults bounding the western Ross Sea basins (Sauli et al., 2021) makes correlations to the broader Ross Sea seismic stratigraphy tenuous (Davey et al., 2000). DSDP Site 270 provides a minimum constraint for RSU6 of >26.5 Ma, but this site cored into a basement high and likely postdates RSU6. However, correlation of this onlapping surface onto the basement high suggests DSDP Site 270 provides a constraint for the onset of sedimentation following RSU6 at 26.5 Ma in this locality (Kulhanek et al., 2019) (Fig. 3.6). An earlier Oligocene age (>28 Ma) is consistent with the hypothesis that RSU6 represents the transition from the Eocene 'greenhouse' to early Oligocene 'icehouse' and has been proposed to be related to early Oligocene sea level falls associated with ice sheet growth (Anderson and Bartek, 1992; Bartek et al., 1991; De Santis et al., 1995), but drilling will help constrain whether climatic, tectonic or glacial driver are responsible for the origin of RSU6. However, GIA theory and experiments indicate initial ice sheet growth would result in rising sea levels in the near-field Antarctic and falling sea levels away from the ice grounding zone, in the peripheral bulge (Stocchi et al., 2013). Depending on the ice sheet proximity and mass, the depositional response and resulting stratigraphic architecture could lead to widespread disconformities and stratigraphic truncations, or maximum flooding surfaces containing highly condensed sections. In the Western Ross

Sea, RSU6 is possibly amalgamated over some of the structural highs with the older Coulman High Major Unconformity (CHMU), which separates rift fill strata (RSS-1) from overlying post-rift, glaciomarine strata of RSS-2 and was the proposed target for the ANDRILL-Coulman High project (Rack et al., 2012). The ages of pre-CHMU strata are likely younger than the pre-RSU6 strata (RSS-1) in the Central and Eastern Ross Sea. This truncated surface is likely diachronous across the Ross Sea and also likely to be younger in the Western Ross Sea than in the Eastern Basin based on the inferred propagation of the rifting and subsidence histories from east to west (Wilson et al., 2012). Consequently, the origin of RSU6 remains ambiguous and needs to be assessed by future geological drilling.

Overlying RSU6, glacially-influenced marine sediments dominate RSS-2. This unit provides a record of the early Oligocene to early Miocene history of the Antarctic ice sheets, although it has only been sparsely sampled. The CRP and CIROS-1 drill cores obtained discontinuous records of RSS-2 that indicate the Victoria Land basin was influenced by deposition from local TAM alpine glaciers and trunk glaciers directly connected to teh EAIS and incised through the TAM since the earliest Oligocene (Barrett, 2007; Galeotti et al., 2016). DSDP Site 270 only sampled the latest Oligocene in the upper part of RSS-2, but included a discontinuity near the O/M boundary (Kulhanek et al., 2019; Levy et al., 2019). Much of the early history of WAIS expansion in the central to eastern Ross Sea is currently unsampled, despite seismic evidence of large WAIS expansion sometime during the early to late Oligocene (Sorlien et al., 2007). This provides a compelling target for future drilling campaigns, either via ice shelf drilling platforms such as the ANDRILL project (Levy et al., 2016), ship-based systems such as the JOIDES Resolution, or through IODP Mission Specific Platforms. As noted earlier, expansion of the WAIS during the relatively warmer climates (compared to today) of the early Oligocene is possible if West Antarctica was more elevated at that time (Wilson et al., 2013) (Fig. 3.4). Consequently, the ice sheet evolution in the Ross Sea is hypothesised to be strongly-coupled to the tectonic and subsidence history of West Antarctica, rather than climate forcing alone (Colleoni et al., 2018; Hochmuth and Gohl, 2019; Paxman et al., 2019; Wilson et al., 2013). Several large truncations are noted across the Ross Sea during the Oligocene to early Miocene (RSU5 and RSU4a) and are interpreted as phases of localised advances of marine-terminating ice caps nucleating on basements highs that remained subaerially exposed at this time (De Santis et al., 1995). Similar erosional surfaces are noted in the ANDRILL and Cape Roberts Project cores during this time period, suggesting advances of marine-terminating EAIS outlet glaciers extended into the Western Ross Sea during the late Oligocene and early Miocene (Levy et al., 2019). A recent proposal (998-pre) was submitted to IODP to drill three continental shelf sites in the Ross Sea (sites CHCS, CENCS, ERSCS in Fig. 3.6). The three sites are located along an E—W longitudinal-transect designed to capture the integrated history of tectonic, climate and glacial influences from both East and

West Antarctica (Fig. 3.7). By drilling sequences between RSU7 and RSU4, the specific objectives are: (1) to obtain direct evidence of the earliest ice sheets in East and West Antarctica expanding into the Ross Sea; (2) to obtain geological reconstructions of 'pre-icehouse' climates at high latitudes in Antarctica during the Late Cretaceous to Eocene; and (3) to constrain the timing of late rift phases in the Ross Sea to resolve mechanisms of crustal extension in the Ross Sea, in order to test hypotheses of global plate tectonic models and understand tectonic controls on ice sheet evolution. The proposed sites are intended to constrain the pre-RSU5 stratigraphy in the Ross Sea.

The recent IODP Expedition 374 obtained excellent records post-dating 18 Ma (RSS-3 and younger) in the Central Ross Sea and was successful in refining the post-RSU5 stratigraphy (McKay et al., 2019) (Figs. 3.5 and 3.6) and a revision of the depth and age of the RSU5 is ongoing, but is constrained to be ~18 Ma at the base of U1521 (McKay et al., 2019; Pérez et al., 2021; Sauli et al., 2021). These cores will document the evolution of the marine-based ice sheets in the Ross Sea, as glacial erosion resulted in progradation of the continental shelf (older strata are generally aggradational), followed by a transition from a seaward dipping shallow continental shelf to an overdeepened (i.e. landward deepening) continental shelf. Site U1521 drilled through a thick seismic sequence of progradational foresets above RSU5, after ~18 Ma, recovering a ~300 m interval of diamictites interbedded with thin mudstone layers suggestive of the input of a large volume of glacially eroded material by marine-terminating glaciers or ice sheets. This new evidence of marine-terminating glaciers discharging large volumes of sediment in the early Miocene is consistent with sedimentary evidence from coastal drill cores from the Cape Roberts and AND-2A drilling projects. However, the Early Miocene diamictites in U1521 are overlain by ~120 m of diatom-rich muds, provisionally dated at 16.7 to 15.8 Ma and inferred to relate to ice sheet retreat during the MCO and a sustained period of seasonally ice-free surface waters that allowed for diatom production and accumulation (McKay et al., 2019). Facies sequences at these sites are indicative of glacial depositional systems characterised by sediment-laden melt water plumes originating from marine-terminating glaciers of the EAIS, or outflow of glacifluvial sediments during periods when the EAIS had retreated on-land (Fielding et al., 2011; Levy et al., 2019; Naish et al., 2001; Passchier et al., 2011). Seismic profiles indicate the presence of deep channels that are associated with these strata and are indicative of the discharge of large volumes of subglacial outwash in warmer-than-present glacial regimes (Bart and De Santis, 2012; Chow and Bart, 2003; De Santis et al., 1995; McKay et al., 2019). On land, geologic and geomorphic studies indicate that this period was associated with a wet-based style of glaciations experiencing significant surface melt (Lewis et al., 2007, 2006; Smellie et al., 2011).

Truncation of glaciomarine foresets defines RSU4, which provides the first seismic evidence of an expanded grounded ice sheet advancing across much of the outer western Ross Sea. This surface is interpreted as an expansion of a grounded ice stream originating from the west (i.e., East Antarctica) in the central Ross Sea between 16 and 14 Ma, and work is ongoing on IODP Exp374 Site U1521 to refine the exact timing and magnitude of this event and the provenance of the grounded ice sheet (Anderson and Bartek, 1992; Colleoni et al., 2018; De Santis et al., 1995; Kim et al., 2018; McKay et al., 2019; Pérez et al., 2021; Ten Brink et al., 1995).

Unconformity RSU3 provides the first clear evidence of major cross-shelf paleotroughs, associated with enhanced progradation of the continental shelf further in the Eastern Ross Sea (Bart and De Santis, 2012; Chow and Bart, 2003; De Santis et al., 1995). This is interpreted as an expansion of the marine-based WAIS, which likely coalesced with ice derived from the EAIS to create a continental shelf wide advance of ice across the Ross Sea (De Santis et al., 1995, 1999). Resolving the age of RSU3 was a primary focus of IODP Expedition 374 Site U1522, with preliminary age models indicating a late Miocene hiatus associated with RSU3 between ~9 and 5.5 Ma (McKay et al., 2019). Meltwater and outwash features are rare in strata younger than RSU3, and, where present, are greatly reduced in scale when compared to Pleistocene examples (c.f., Simkins et al., 2017). Above RSU3, progradational seismic facies are progressively thinner and less common (Fig. 3.5), suggesting gradual sediment starvation as the ice sheets transited to a colder glacial regime, and marine-based ice sheet expansions eroded and truncated preexisting sediment infill on the outer shelf.

Paleobathymetric reconstructions suggest the RSU2 surface (Pliocene age) is associated with the establishment of an overdeepened continental shelf in the Ross Sea (De Santis et al., 1999). This overdeepening likely occurred as a result of an increasingly marine setting over much of West Antarctica due to extensive Plio-Pleistocene glacial erosion, following Cretaceous to Neogene rifting. This must have also occurred on the background of a cooling climate that allowed expansion of marine-based ice sheets. Such expansions across the Ross Sea acted to erode continental shelf sediments in units below RSU3. Most of this sediment was transported to the continental shelf break and redeposited in the form of large trough-mouth fans on the upper slope (Bart, 2003; Colleoni et al., 2018; Cooper et al., 2008; De Santis et al., 1999; Kim et al., 2018).

Several large canyons exist on the continental rise of the Ross Sea, acting as conduits funnelling cascading High Salinity Shelf Water from the continental shelf into the abyssal ocean to form Antarctic Bottom Water. On the flanks of these canyon systems are thick levee deposits that contain high-resolution archives of oceanographic change. In the central Ross Sea, the late Pliocene to Pleistocene intervals of these levees were cored at sites U1524 and U1525 by IODP Expedition 374 (McKay et al., 2019). In addition to this, the upper slope and outermost continental rise display mounded drift deposits emplaced during the Neogene to Pleistocene (Kim et al., 2018). These drifts are associated with easterly currents of the Antarctic Slope Current, and one of these drifts was the target of IODP Expedition 374 Site U1523 (McKay et al., 2019). Analysis of this site and nearby gravity cores covering the Plio-Pleistocene will allow changes in the strength of this current to be reconstructed, which is important as this current is thought to regulate water mass (and therefore heat and nutrient) exchange between the continental shelf and offshore waters (Kim et al., 2020; McKay et al., 2019).

On the continental shelf, seismic facies above RSU2 consist of massive tabular sheets generally displaying an aggradational pattern, interpreted as till sheets deposited by the increased frequency of marine-based ice sheet advances (Accaino et al., 2005; Alonso et al., 1992; Böhm et al., 2009). These facies are also associated with widespread deposition of low-relief, asymmetrical Grounding Zones Wedges deposited at the margin of a marine-based ice sheet over the Plio-Pleistocene (Bart et al., 2011; Bart and De Santis, 2012; Bart and Owolana, 2012; Batchelor and Dowdeswell, 2015). Coastal tidewater glaciers built morainal features in the Victoria Land offshore (Sauli et al., 2014). Above RSU1 (0.8 Ma?), sediment packages on the shelf edge show distinctive aggrading or backstepping (rather than prograding), indicating that most sediment delivered from land by marine-based ice sheets was reworked and sequestered on the outer shelf or continental slope/rise (Bart and Tulaczyk, 2020; De Santis et al., 1999; Shipp et al., 1999). Anderson et al. (2018) highlight a disconnect over the past 0.8 Ma between the frequency of advances noted in outer shelf seismic facies (two advances) and those recorded in the mid-shelf site AND-1B core (eight advances). A critical point of difference in these locations is that AND-1B was recovered from an actively forming flexural moat around the volcanic centre of Ross Island, providing continued development of accommodation space to protect deposited strata from glacial erosion (Horgan et al., 2005; Naish et al., 2009). Consequently, this disconnect may indicate, that either, not all glacial periods of the late Pleistocene represent shelf wide expansion, or that the outer shelf sequences in RSS-8 represent amalgamations of numerous glacial advances, with the largest advances eroding evidence of previous expansion.

A high priority ambition for the drilling community is to obtain records of ice sheet retreat during Plio-Pleistocene interglacials near the present-day grounding line of the WAIS, with the primary goal of acquiring records of WAIS extent during late Quaternary 'super-interglacials' of the past 400 kyrs, which were characterised by warmer than usual conditions, both in Antarctica and globally (McKay et al., 2016). Drilling in this region is critical to ground-truth the full extent of WAIS retreat during these warmer interglacials and allows for a complete transect from the outer to inner continental shelf to be developed (Fig. 3.8). Such a transect would enable a better understanding of ocean–ice interactions that may have influenced past retreat events. Although several sediment cores have been collected from hot water drill access holes in the Siple Coast region of the Ross Sea, they have

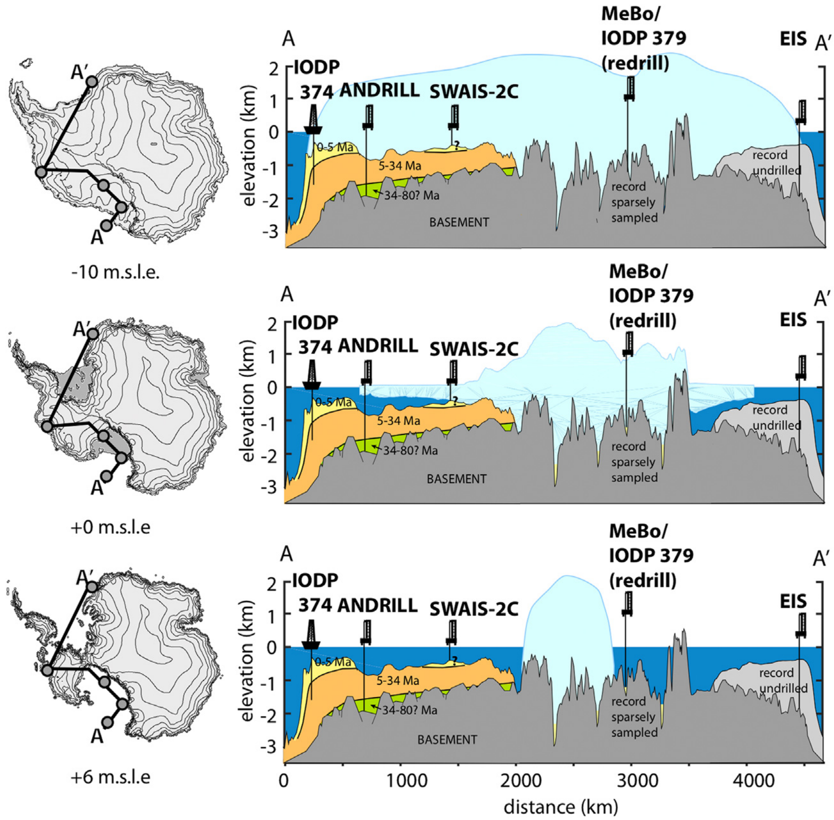

FIGURE 3.8 Transect across West Antarctica showing three possible ice sheet configurations, and the southward extension of transect-based drilling strategy (circles in maps) to obtain direct records of its past climatic history. Past drill sites from ANDRILL and Expedition 374 are shown, alongside proposed SWAIS 2C (International Continental Drilling Program; ICDP) drill sites and Ekström Ice Shelf sites, as well as undrilled IODP Expedition 379 continental shelf sites that remain viable future targets. *Modified from McKay, R.M., Barrett, P.J., Levy, R.S., Naish, T.R., Golledge, N.R., Pyne, A., 2016. Antarctic Cenozoic climate history from sedimentary records: ANDRILL and beyond. Philosophical Transactions of the Royal Society A 374 (2059), 20140301. Available from: https://doi.org/10.1098/rsta.2014.0301.*

yet to penetrate the LGM diamict (Kingslake et al., 2018; Priscu et al., 2019; Scherer et al., 1998). To overcome this problem, New Zealand researchers (Antarctic Research Centre at Victoria University of Wellington, and GNS Science) are currently building an integrated hot water/rock drilling system capable of recovering ~200 m of sediment in places where the combined depth of the ice shelf (or sea ice) and water column is <1000 m thick. The sediment/rock drill is similar in functionality to the ANDRILL system, but is lighter weight and its smaller footprint is designed to be capable of deep field deployment within the constraints of existing Antarctic science support programmes. The combined rig, drill pipe and casing package weighs ~30 tonnes and can undertake soft sediment coring using hydraulic piston and punch corers. For hard rock drilling, it will use off-the-shelf diamond-bit rotary coring technology capable of rates of recovery approaching 100%, as was the case for ANDRILL. It is anticipated that this system will drill at the grounding line of the Kamb Ice Stream (KIS) and Crary Ice Rise (CIR), to obtain Neogene and Quaternary sediments – as part of a proposed Intercontinental Drilling Program (ICDP) project (SWAIS 2C) project from 2021 onward.

3.4.2 Amundsen Sea

The Amundsen Sea continental shelf and rise (Fig. 3.9) developed after the Cretaceous break-up of Zealandia from West Antarctica (see Section 3.2), but the paleoenvironment from the Cretaceous to the Neogene in the Amundsen Sea sector remains poorly sampled. The first drill cores from the shelf were collected during a MeBo seabed drilling expedition in 2017 (Gohl et al., 2017). A drill core from the inner/middle shelf showed evidence for a temperate rainforest and swamp environment formed in a rift basin in the middle Cretaceous, with a ~40-Myr hiatus separating these sediments from an overlying sandstone formation of late Eocene age (Klages et al., 2020). More analyses of core samples from the other MeBo drill sites, which according to preliminary age estimates span various time slices from the Oligocene to Holocene (Gohl et al., 2017), are in progress. In terms of paleoclimate-related and glacially-driven sedimentary processes in the Neogene and Quaternary, this region is dominated by sediment erosion, transport and deposition driven mainly by the large outlet ice streams of the Pine Island, Thwaites, Haynes, Pope and Smith glaciers of the eastern Amundsen Sea Embayment. As well as these, many smaller glaciers drain ice from the elevated central Marie Byrd Land and feed into the Dotson Ice Shelf and the various segments of the Getz Ice Shelf of the central and western Amundsen Sea.

The analysis of seismic lines crossing the slope and shelf, most of them collected since 2000 (Dowdeswell et al., 2006; Graham et al., 2009; Hochmuth and Gohl, 2013; Klages et al., 2014, 2015; Lowe and Anderson, 2002; Uenzelmann-Neben et al., 2007; Weigelt et al., 2012, 2009), resulted in a seismic stratigraphic model (Gohl et al., 2013) very much analogous to the dated Ross Sea shelf stratigraphy with a similar seismic reflection signature (Fig. 3.9). However, deep drill sites currently do not exist on the Amundsen Sea shelf and this was a key focus of IODP Expedition 379, but a near 'worst-case scenario' sea ice season during the drilling window in 2018/19 precluded access of the drill ship to the continental shelf (Gohl et al., 2021). However, the proposal targets remain viable and important drilling targets for the future and will assist in validating these correlations to the

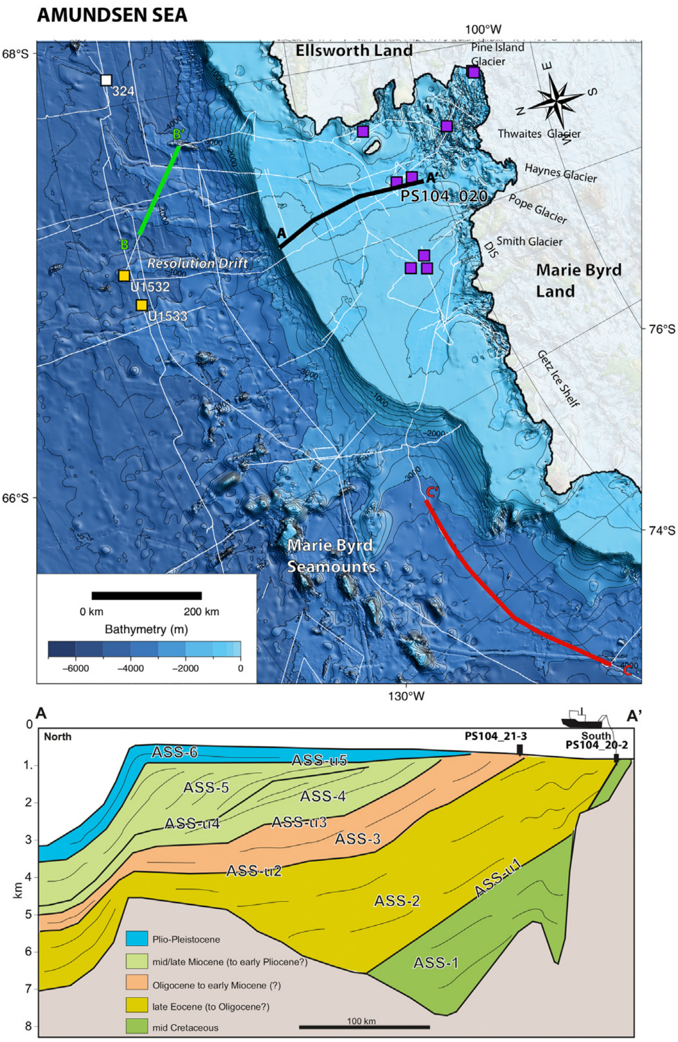

FIGURE 3.9 (Top) Overview map of Amundsen Sea sector with existing seismic lines (white lines) and drill sites, including DSDP Leg 35 Site 324 (white square), IODP Expedition 379 sites U1532 and U1533 (yellow squares) and MeBo seabed drill sites (purple squares), including Site PS104_20−2 (Gohl et al., 2017; Klages et al., 2020). Seismic tracks are from the SCAR Antarctic Seismic Data Library System (SDLS) and additional survey information Bathymetry is from Bathymetric Chart of the Southern Ocean (Arndt et al., 2013) and subglacial topography from BedMachine Antarctica dataset (Morlighem et al., 2020). Segments of seismic profiles shown in Figs. 3.10 are marked with bold green (B−B′) and red (C−C′) lines, respectively. (Bottom) Seismic stratigraphy and major unconformities (discussed in text) across the Amundsen Sea Embayment shelf (track-line shown as a black bold line (A−A′) in top panel), using updated age constraints from Klages et al. (2020). Most of the seismic stratigraphy is still undated as deep drill holes do not exist on the shelf. *(Bottom) Modified from Gohl, K., Uenzelmann-Neben, G., Larter, R.D., Hillenbrand, C.-D., Hochmuth, K., Kalberg, T.,et al., 2013. Seismic stratigraphic record of the Amundsen Sea Embayment shelf from preglacial to recent times: evidence for a dynamic West Antarctic ice sheet. Marine Geology 344, 115−131. Available from: https://doi.org/10.1016/j.margeo.2013.06.011.*

Ross Sea (Fig. 3.8). This will determine whether the ice sheet histories in these regions are fundamentally different, with local influences by tectonic processes potentially playing as an important role as climate and oceanographic processes. Existing seismic coverage indicates the total pre-glacial to glacial sediment cover on the shelf is up to 7 km thick in places. Based on the observation of glacially-driven truncational unconformities (surfaces ASS-u4 and above; Fig. 3.9), an early advance of grounded ice onto the continental inner to middle shelf is interpreted to have not occurred prior to the Miocene. A large proportion of the present outer shelf consists of a 70 km broad zone of prograding sequences that were deposited after transport by advancing grounded ice (Gohl et al., 2013; Hochmuth and Gohl, 2019, 2013).

Studies of the large number of samples from conventional coring systems, and geomorphological studies, have yielded a reasonably detailed record of the ice retreat in the Amundsen Sea since the LGM. These works were comprehensively synthesised by Larter et al. (2014) as part of the RAISED consortium project, although numerous new studies have provided new insights (Klages et al., 2017, 2014; Kuhn et al., 2017; Smith et al., 2017). Combined, these works indicate that the WAIS retreated rapidly from the outer shelf at the LGM (about 18 ka) to the inner shelf at about 10 ka, where it halted until the current retreat from coastal locations started in the mid-20th century (Hillenbrand et al., 2013; Klages et al., 2017; Larter et al., 2014; Smith et al., 2017, 2014). Sedimentary, geochemical and microfossil proxies from post-LGM sediment cores on the continental shelf suggest incursions of relatively warm Circumpolar Deep Water onto the shelf forced deglaciation during the early Holocene, as well as ice shelf thinning since the mid-20th century (Hillenbrand et al., 2017; Minzoni et al., 2017). Circumpolar Deep Water incursions have been identified as the main driver for present ice shelf cavity melting in the Amundsen Sea embayment (e.g., Nakayama et al., 2013; Scambos et al., 2017). Present research and future drilling in this region are consequently focusing on testing the hypothesis that Circumpolar Deep Water incursions onto the shelf were the main driver of WAIS retreat during past warm periods of the Quaternary and Neogene (Gohl et al., 2021).

Similar to the continental shelf, the coverage of seismic lines on the continental rise and deep sea of the Amundsen Sea has increased in recent years (Fig. 3.9), although large unsurveyed areas still exist, in particular in the central and western Amundsen Sea. A single transect along the rise from the Ross Sea to the Amundsen Sea was used to establish the first seismic stratigraphic record on the full sedimentary cover for the western Amundsen Sea with the identification of distinct pre-glacial, transitional and full glacial sequences (Fig. 3.10) (Lindeque et al., 2016). The seismic stratigraphy was derived by long-distance correlation to the Ross Sea chronostratigraphic record based on the shelf drill sites of DSDP Leg 28 (e.g., De Santis et al.,

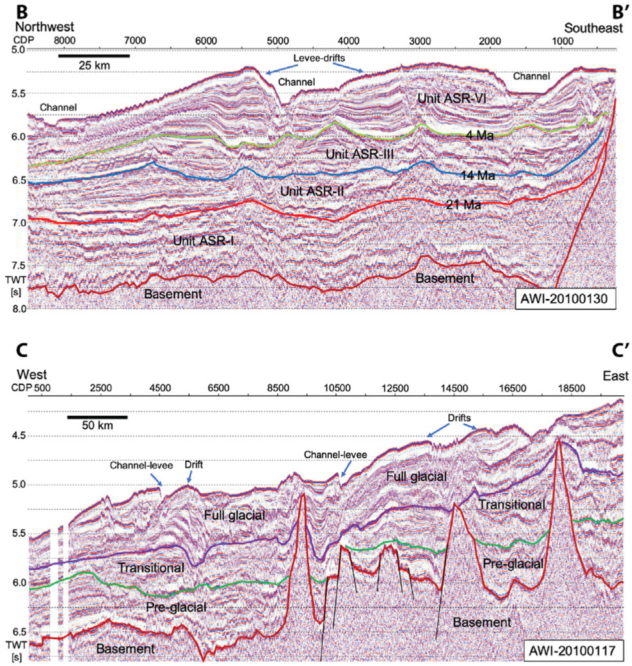

FIGURE 3.10 (Top) Section of seismic profile AWI-20100130 from the eastern Amundsen Sea rise crossing major sediment drifts and adjacent deep-sea channels. The long-distance correlation and interpretation of key horizons and units is slightly modified from Uenzelmann-Neben and Gohl (2014). Section location is marked in Fig. 3.9 as a bold green line (B−B′). (Bottom) Section of seismic profile AWI-20100117 from the western Amundsen Sea rise with interpretation of three distinct pre-glacial (Late Cretaceous to late Eocene), transitional (late Eocene to mid-Miocene) and full glacial (mid-Miocene to present) units, slightly modified from Lindeque et al. (2016). Section location is marked in Fig. 3.9 as a bold red line (C−C′).

1999; Hayes et al., 1975). The transitional period includes the late Eocene to mid-Miocene when grounded ice first expanded onto the continental shelves, while the full glacial period describes the interval from the mid-Miocene to Quaternary, with intensified ice advances onto the outer shelves. No apparent difference in the deep-sea sedimentation transport processes or temporal shift in deposition between the Amundsen Sea and Ross Sea is observed. Additional new seismic data were collected on a Russian expedition in 2019 and will help quantify the extent of the depositional sequences in the western Amundsen Sea.

The continental rise of the eastern Amundsen Sea is dominated by large contourite drifts, some of them rising several hundred metres above the surrounding seafloor (Nitsche et al., 2000; Scheuer et al., 2006a,b; Uenzelmann-Neben, 2018; Uenzelmann-Neben and Gohl, 2014, 2012; Yamaguchi et al., 1988) (Fig. 3.10). Most drift systems are elongated in a north–south direction and flanked by deep-sea channels eroded by turbidity currents carrying suspended detritus supplied by downslope transport processes from the slope and shelf. The suspended particles were entrained in strong bottom currents and were subsequently deposited on the flanks of the channels to form the drifts. Seismic analyses with first estimates of a chronostratigraphy by long-distance and jump correlation of seismic horizons to DSDP and ODP drill sites in the Bellingshausen Sea and Ross Sea indicate that early drift formation by enhanced bottom-current activity began in the Eocene/Oligocene. Drift formation intensified in the Miocene, likely caused by expansion of the WAIS during global cooling, increased sea-ice cover and, as a result, the formation of Antarctic Bottom Water and enhanced bottom-current flow (Uenzelmann-Neben and Gohl, 2012).

Although only two sites on the continental rise and none on the shelf could be drilled during IODP Expedition 379 in 2019 (Fig. 3.1), almost continuous sequences spanning the latest Miocene to Pleistocene, deposited with high sedimentation rates, were recovered from the lower and upper western flank of the Resolution Drift (Gohl et al., 2021). The cores from both sites recovered predominantly glaciomarine, fine-grained terrigenous sediments intercalated with pelagic and hemipelagic deposits that, in the younger parts of the cores, contain more biogenic material. The records show an interplay of glacially transported shelf sediments that were transported downslope to the continental rise by gravitational processes and redistributed across the rise by turbidity and bottom currents. Although IODP Expedition 379 was unable to retrieve cores from the shelf, the drill records from the continental rise reveal the timing of glacial advances across the shelf and, thus, the existence of a large ice sheet in West Antarctica for prolonged time periods since the late Miocene. Detailed analyses of the IODP Expedition 379 core samples and data are in progress (Gohl et al., 2021).

In contrast to the Amundsen Sea continental shelf, information from conventional sediment cores from the continental slope and rise is sparse. Dowdeswell et al. (2006) reported debris and grain flow deposits presumably of LGM age from three short cores collected on the continental slope. In a long gravity core from the continental rise (Hillenbrand et al., 2002), thick beds of turbidites and contourites deposited during late Pleistocene glacial periods alternate with thin beds of foraminifera-bearing, bioturbated muds deposited during interglacials. A condensed, but well dated core from a seamount location on the continental slope retrieved sediments mainly consisting of pelagic material, i.e. planktic foraminifera and iceberg-rafted debris. Notably, this record did not provide evidence for a WAIS collapse during the last 800 ka (Hillenbrand et al., 2002). By comparing palaeoceanographic data from a core recovered from the same seamount location to other Southern Ocean cores, Williams et al. (2019) found evidence that deep- and bottom-water mass formation varied between the different sectors of the Antarctic margin during glacial periods of the last 800 ka. Hillenbrand et al.

(2009) analysed Pleistocene to Holocene glacial-interglacial cycles in a sediment core recovered from the Resolution Drift (site located to the south of the two IODP Expedition edition 379 drill core sites) and found, based on proxies for biological productivity and lithogenic sediment supply, that in the Amundsen Sea the interval from Marine Isotope Stage (MIS) 15 to MIS 13 (621−478 ka) was a single prolonged interglacial period, during which the WAIS may have collapsed. A palaeoceanographic study on the same core by Konfirst et al. (2012) concluded that after the end of the Mid-Pleistocene Transition (MPT) at ca. 620 ka the Amundsen Sea low pressure system shifted farther south during interglacial periods than during earlier interglacials, thereby increasing Circumpolar Deep Water upwelling onto the shelf. Recent provenance studies provide information about the sub-ice geology and drainage systems in the hinterland that may allow past ice sheet retreat events to be identified in offshore sediments (Simões Pereira et al., 2018, 2020).

3.4.3 Bellingshausen Sea and Pacific coastline of Antarctic Peninsula

The continental margin in the Bellingshausen Sea and along the west side of the Antarctic Peninsula is a former active margin where subduction of successive ridge crest segments proceeded from southwest to northeast (Eagles et al., 2009; Larter and Barker, 1991a) (Fig. 3.11). The arrival of each ridge crest segment at the margin was followed by 1−4 million years of uplift and then long-term subsidence (Bart and Anderson, 1995, 2000; Hernández-Molina et al., 2017; Larter and Barker, 1991b; Larter et al., 1997). Along the Pacific margin northeast of Alexander Island, multichannel seismic profiles show that outer shelf sequences are separated from NE-SW trending mid-shelf basins by the Mid-shelf High (Gambôa et al., 1990; Kimura, 1982; Larter et al., 1997). On the outer shelf aggrading sequences without a distinct paleo-shelf edge are unconformably overlain by prograding sequences with an abrupt paleo-shelf edge (Fig. 3.12). This change is observed all along the Pacific margin (Bart and Anderson, 1995; Jin et al., 2002; Larter and Barker, 1989, 1991b; Larter et al., 1997) and west along the margin of the Bellingshausen Sea (Nitsche et al., 1997). Above a widespread unconformity within the prograding sequences there is less progradation than in the earlier units. Four lobes along the margin where the extent of progradation is greater represent late Quaternary and earlier termini of paleo-ice streams (Bart and Anderson, 1995; Larter et al., 1997). Marguerite Trough, the pathway of the largest paleo-ice stream on the Pacific margin northeast of Alexander Island during the late Quaternary, reaches the margin between two of these lobes as a consequence of lateral migration of the outer part of the trough (Bart and Anderson, 1995; Hernández-Molina et al., 2017; Ó Cofaigh et al., 2005a).

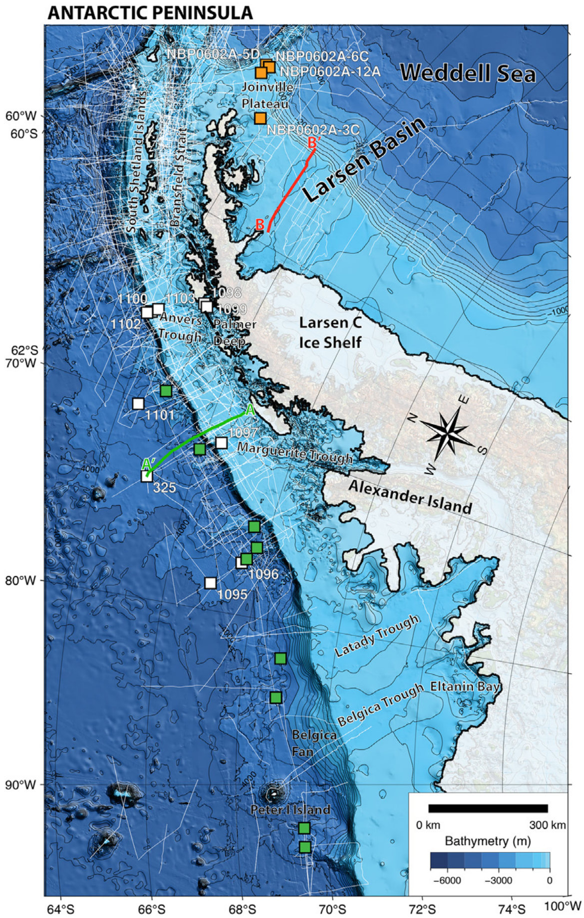

FIGURE 3.11 Overview map of Bellingshausen Sea and Antarctic Peninsula sector with existing seismic lines (white lines), drill sites and topographic features mentioned in text. Bathymetry is from Bathymetric Chart of the Southern Ocean (Arndt et al., 2013) and subglacial topography from BedMachine Antarctica dataset (Morlighem et al., 2020). Drill sites, including DSDP Leg 35, ODP Leg 178 sites (white square), and SHALDRIL drill sites (orange squares; NBP0602A). IODP Proposal 732-FULL2 sites are shown as dark green squares.

A relatively steep continental slope along the Pacific margin northeast of Alexander Island, with typical maximum gradients of 13°−17° and a zone of rugged topography near its base, make it difficult to trace seismic units between the continental shelf and rise (Hernández-Molina et al., 2017; Larter and Cunningham, 1993). The upper continental rise hosts large sediment drifts that are up to 250 km long (Rebesco et al., 1996, 1997, 2002). These are separated by large turbidity current channels, with up to 1 km of relief

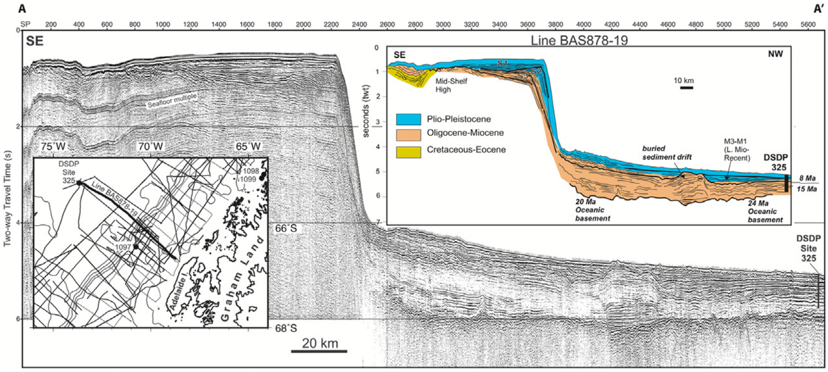

FIGURE 3.12 Seismic profile BAS878-19, and interpretation (insert) through correlation to DSDP Site 325 across the Bellingshausen Sea continental shelf and rise. Profile line as green line A–A′ is shown in Fig. 3.11. *Modified after Cooper, A.K., Brancolini, G., Escutia, C., Kristoffersen, Y., Larter, R., Leitchenkov, G., et al., 2008. Cenozoic climate history from seismic reflection and drilling studies on the Antarctic continental margin. In: Florindo, F., Siegert, M. (Eds.), Antarctic Climate Evolution, vol. 8. Elsevier, pp. 115–234.*

between the drift crests and the channel thalwegs (Larter et al., 2016a; Rebesco et al., 2002). The channels originate from networks of tributaries at the base of the continental slope, which have generated the rugged topography there (Amblas et al., 2006; Rebesco et al., 2002). The drifts developed after an earlier period of sediment accumulation in a lower energy regime that infilled depressions in basement and aggraded over most of the continental rise, resulting in a low relief paleo-seabed (Larter and Cunningham, 1993; Rebesco et al., 1997, 2002). However, Hernández-Molina et al. (2006) identified a buried sediment drift of early Miocene age that formed to the northeast of a group of seamounts near DSDP Site 325 (Fig. 3.12).

The dominant features on the broad southern Bellingshausen Sea continental shelf west of Alexander Island are the Belgica and Latady troughs, the former being >100 km wide. These troughs were the pathways of two very large paleo-ice streams that deposited extensive prograded sequences on the outer shelf and constructed large trough mouth fans on the continental slope (Dowdeswell et al., 2008; Larter et al., 2016b; Nitsche et al., 1997, 2000; Ó Cofaigh et al., 2005b; Scheuer et al., 2006). The slope on the fans is much less steep than along the part of the margin to the northeast, mostly between 1° and 2°. The slope is steeper again to the west of the Belgica Fan, where the shelf is narrower. One more large sediment drift extends from this western part of the margin towards Peter I Island, near the boundary between the Amundsen and Bellingshausen seas.

Scientific drilling in this subregion was conducted on DSDP Leg 35 in 1974 and on ODP Leg 178 in 1998 (Barker et al., 1999; Hollister et al., 1976) (Fig. 3.1). Of the sites drilled during Leg 35, Site 325 was the only one that provides useful chronostratigraphic constraints on the long-term evolution of the margin (Fig. 3.12). Drilling penetrated close to latest Oligocene oceanic basement on the central continental rise, but the single hole was only spot cored. Later correlations along seismic lines connecting the site to the margin showed that prograded sequences on the outer shelf are all younger than a condensed unit or hiatus from 15 to 8 Ma at Site 325 (Hernández-Molina et al., 2017; Larter and Barker, 1991b). Correlations to the sediment drifts on the upper continental rise showed that they started to develop during the condensed interval or hiatus at Site 325, but their growth accelerated in the late Miocene (Hernández-Molina et al., 2017; Rebesco et al., 1997, 2002).

During ODP Leg 178, two sites were drilled on the continental shelf (albeit with poor core recovery) and three sites on the continental rise, which provided detailed constraints on the late Miocene to recent evolution of the margin. Results from sites 1097 and 1103, on the outer shelf in the axes of Marguerite Trough and Anvers Trough, respectively, showed that progradation started at around 8 Ma, but also confirmed that the earlier late Miocene aggradational units were glacially influenced (Bart et al., 2005, 2007; Eyles et al., 2001). Two further sites, 1098 and 1099, were drilled on the inner shelf in the 1400-m deep Palmer Deep basin, recovering postglacial and Holocene successions of centennial to millennial scale resolution, ~47 and ~108 m thick, respectively (Barker et al., 1999; Domack et al., 2001; Ishman and Sperling, 2002; Leventer et al., 2002; Shevenell and Kennett, 2002). Continental rise sites 1095, 1097 and Site 1101 drilled into sediment drifts that contained continuous, expanded sedimentary records extending back to the earliest late Miocene. At Site 1095, on the distal part of one of these drifts (Drift 7), sedimentation rates were highest in the late Miocene and decreased progressively through the Pliocene and Quaternary. No sites have been drilled in the mid-shelf basins west of the Antarctic Peninsula or in the Bellingshausen Sea. Configuration of seismic reflectors on the northwest flank of the Antarctic Peninsula mid-shelf basins suggests deposition in them pre-dates uplift of the mid-shelf high (Larter et al., 1997). Therefore, they probably contain a record of early Neogene to Paleogene, possibly extending to Cretaceous, climate history of the Antarctic Peninsula.

DSDP Site 324, at 69°03.21′S, 98°47.20′W, where Pliocene and Quaternary sediments were recovered by spot coring to 199 m below sea floor (mbsf), has sometimes been described as being in the southern Bellingshausen Sea (Hollister et al., 1976). However, its location is >300 km west of Peter I Island, and so actually in the Amundsen Sea. The earliest indication of ice rafted debris in cores recovered by scientific drilling in this subregion is in latest early Miocene sediments at Site 325, with none having been found in three cores from earlier intervals in the early Miocene at the same site. This suggests that any marine-terminating glaciers existing before this time were rare, although there is local evidence of marine-terminating

Oligocene glaciers on the South Shetland Islands (Birkenmajer, 1991; Dingle and Lavelle, 1998; Troedson and Smellie, 2002). The start of deposition of prograded units on the outer shelf at around 8 Ma suggests that this was the time of onset of frequent grounded ice advances to the shelf edge, i.e. this was the time of transition from a glacially-influenced to a fully glacial regime on the continental marine margin (Hernández-Molina et al., 2017). The widespread unconformity within the outer shelf prograding sequences above which there is less progradation may have resulted from deeper erosion during glacial periods with lower sea levels after the Late Pliocene increase in the volume of Northern Hemisphere ice sheets (Larter and Barker, 1989, 1991b). The limited age control available from the outer shelf drill sites is consistent with this interpretation.

The large sediment drifts on the continental rise have formed beneath a bottom current that flows southwest along the margin (Giorgetti et al., 2003). However, the position of the buried early Miocene drift identified by Hernández-Molina et al. (2006) in relation to a group of seamounts implies a bottom current that flowed in the opposite direction at that time, and therefore suggests a reversal of bottom current flow along the continental rise during the middle or late Miocene. The observation from Site 1095 that accumulation rates of dominantly terrigenous sediments on the continental rise were highest in the late Miocene and decreased progressively through the Pliocene and Quaternary suggests that most erosional overdeepening of the inner shelf and cross-shelf troughs occurred during the late Miocene. However, from a synthesis of ODP Leg 178 diatom assemblage data (Bart and Iwai, 2012) proposed that such overdeepening occurred later, in the earliest Pliocene. Seismic correlations from Site 1095 and 1096 to the large trough mouth fans in the Bellingshausen Sea suggest the highest rates of sediment accumulation in them occurred during the Pliocene (Scheuer et al., 2006). The observation that fairly high rates of terrigenous sedimentation on the continental rise in this subregion were sustained through the Pliocene before declining during the Quaternary suggests that the early Pliocene warm period did not result in a long interruption between grounded ice advances across the continental shelf. In relation to this observation it is interesting to note that most model simulations for the warmest part of the Pliocene show an ice sheet or ice caps remaining on the spine of the Antarctic Peninsula (e.g., Pollard et al., 2015; Smellie et al., 2009). This is a consequence of the fact that the spine of the Peninsula has an average elevation of around 2000 m, maintaining low temperatures over its summit plateau and leading to high snow accumulation rates from maritime air masses moving across it (Turner et al., 2002). The high accumulation rates enable rapid and extensive ice sheet growth during cold periods, even if they are of relatively short duration.

The evidence of sustained terrigenous sediment supply to the continental rise through the Pliocene is just one striking example of the potential of the records in the sediment drifts. Complete recovery of the continuous, expanded records they contain will provide new insights into details of the

Miocene to Recent glacial history of the Antarctic Peninsula and the Bellingshausen Sea sector of the WAIS. The results of Leg 178 combined with new seismic profiles, have guided the development of a new IODP proposal that was approved for drilling but is awaiting scheduling (732-Full2). The aim of this new proposal is to obtain ultra-high precision chronostratigraphic control that can be established using palaeomagnetic methods (Channell et al., 2019), to evaluate the past history and stability of the WAIS and Antarctic Peninsula Ice Sheet. This will enable, for example, determination of the conditions in, the duration of, and rate of change through, glacial periods and deglacial transitions into Pliocene and Quaternary interglacials.

3.4.4 The Northern Antarctic Peninsula and South Shetland Islands

This subregion includes the Bransfield Strait and the continental margin around the South Shetland Islands (Fig. 3.11). Bransfield Strait is a 2000 m deep rift basin that is actively extending at 7 mm/yr (Dietrich et al., 2004). The time of initial extension and the oldest age of basin sediments are uncertain, but most studies suggest a probable onset between ~6 Ma (Larter and Barker, 1991a) and 3.3−4 Ma (Barker and Dalziel, 1983; Lodolo and Pérez, 2015). Gambôa et al. (1990) speculated that Bransfield Strait may have opened earlier, during the early Miocene and have been continuous with mid-shelf basins to the southwest. A new investigation of the crustal structure of the Bransfield rift and associated volcanic edifices has been conducted recently involving combined use of a large number of land and ocean bottom passive seismometers and marine surveys (Almendros et al., 2020).

From multichannel seismic data, Gambôa et al. (1990) identified ‘rift’ and ‘drift’ sequences in Bransfield Strait. ‘Drift’ sequences prograde the shelf and are about 1 km thick. In single channel seismic data, Jeffers et al. (1990) defined four glacio-eustatic units within the ‘drift’ sequences, and interpreted all four as being younger than 3 Ma. Prieto et al. (1999) used different single channel seismic data to define eight seismic units that comprise interfingering slope and basinal deposits within the ‘drift’ sequences. They interpret the slope units as having been deposited directly from grounded ice during glacial periods, and the basinal units as having been deposited by mass flow processes during deglaciations and interglacial periods. García et al. (2008) interpreted data from a multichannel seismic survey in the context of comprehensive multibeam bathymetry coverage of Bransfield Strait (Gràcia et al., 1997; Lawver et al., 1996). They highlighted changes through time in the post-rift succession to increased aggradation over progradation and to more localised sediment delivery to the basin. From single channel seismic data, Banfield and Anderson (1995) identified sediment mound features that they infer to be glacial grounding moraines in up to 1000 m water depth on the southeastern flank of Bransfield Strait. They speculated that mounds at ~700 m depth mark the maximum ice advance during the LGM. Deep troughs with mega-scale lineations are incised into the shelf and are interpreted as the paths of paleo-ice streams (Banfield and Anderson, 1995; Canals et al., 2002), while the Bransfield Basin contains an expanded Plio-Pleistocene section that to date has not been targeted for drilling.

Multichannel seismic profiles across the continental slope NW of the South Shetland Islands reveal a forearc basin, with more than 1.5 km sediments, that is bounded to the NW by a small accretionary prism (Maldonado et al., 1994). The prism overthrusts trench-fill sediments that may have been deposited rapidly and are up to 1 km thick (Kim et al., 1995; Maldonado et al., 1994). The only scientific drilling in the South Shetland Islands region was done at SHALDRIL Site 1 in Maxwell Bay, where an expanded succession of Holocene diatomaceous muds, ~105 m thick, overlying a clay-rich diamicton was recovered (Milliken et al., 2009).

3.4.5 The Eastern Margin of the Antarctic Peninsula

This subregion, which includes the Weddell Sea margin of the Antarctic Peninsula and Larsen Basin, is a passive margin that originally formed in the Jurassic during initial opening of the Weddell Sea (Fig. 3.11). Multichannel seismic reflection data show at least 8 km of sediment at the base of the northernmost part of the continental slope, overlying likely Early Cretaceous age basement (Barker and Lonsdale, 1991). Seismic data farther south are sparse as there is persistent sea ice cover throughout most austral summers (Parkinson, 2019).

Four main seismic stratigraphic units are identified from single channel seismic reflection data over a wide area of the shelf and upper slope (Anderson et al., 1992; Sloan et al., 1995), (Fig. 3.13): Unit 4, acoustic basement, interpreted as Jurassic and younger volcanic rocks; Unit 3, parallel to sub-parallel seaward-dipping reflections; Unit 2, prograding sequences with truncated foresets that downlap onto Unit 3; Unit 1, aggrading reflections. The northern continental slope has plastered contourite drift deposits up to 900 m thick, thought to have been deposited by bottom currents flowing northward along the western limb of the Weddell Gyre (Pudsey, 2002). Reflectors within the older part of Unit 3 are observed close to Seymour Island where Late Cretaceous to Oligocene sediments with similar dips crop out (Anderson et al., 1992, 2011). The only scientific drilling in this subregion was carried out through the SHALDRIL project, which used a lightweight drill rig installed over a moonpool on RV *Nathaniel B Palmer* during two cruises in early 2005 (cruise NBP0502) and 2006 (cruise NBP0602A; sites shown in Fig. 3.11). The holes drilled in this subregion were all relatively shallow, with the maximum depth below sea floor from which cores were recovered being 31.4 m at site NBP0602A-5. Anderson et al. (2011) presented a synthesis of the SHALDRIL

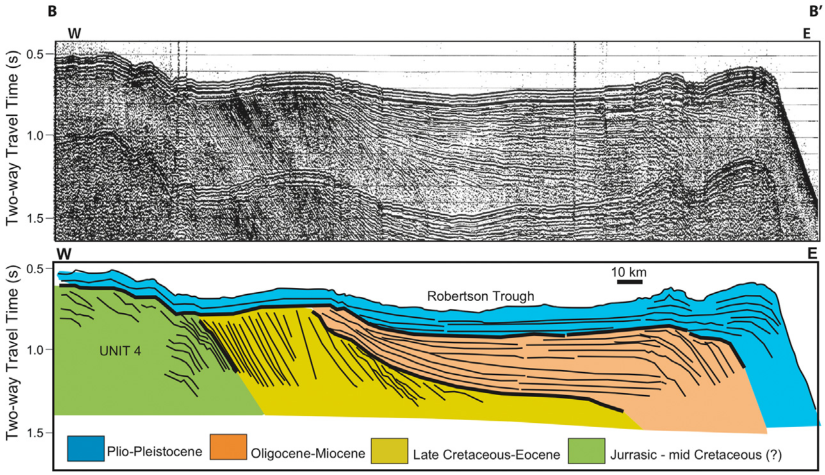

FIGURE 3.13 Seismic profile and interpretation across the Larsen Basin continental shelf. Profile line as red line B–B′ is shown in Fig. 3.11. *Modified from Sloan, B.J., Lawver, L.A., Anderson, J.B., 1995. Seismic stratigraphy of the Larsen Basin, Eastern Antarctic Peninsula. In: Cooper, A.K., Barker, P.F., Brancolini, G. (Eds.), Geology and Seismic Stratigraphy of the Antarctic Margin. American Geophysical Union, pp. 59–74.*

results, which provide the only offshore chronostratigraphic constraints in this region. Sediments of late Eocene age were recovered at SHALDRIL Site 3, above a prominent unconformity. The unconformity is probably within sediments that correlate with seismic Unit 3 described above. The other SHALDRIL sites in the subregion are located near the northeastern corner of the Joinville Plateau on seismic profiles in which stratigraphic units have not been correlated with those identified further south. The late Eocene age (37–34 Ma) of the sediments recovered at SHALDRIL Site NBP0602A-3 is consistent with previous interpretations of seismic Unit 3 as consisting of Late Cretaceous to Oligocene marine shelf deposits (Sloan et al., 1995; Smith and Anderson, 2010). Seismic Unit 2 has been interpreted as Miocene to Pliocene in age and seismic Unit 1 as Pliocene to recent.

The seismic units on the profiles through the SHALDRIL sites near the northeastern corner of the Joinville Plateau exhibit rather uniform seismic facies and contain reflectors that are truncated near the sea floor and dip fairly consistently at a low-angle towards the continental margin. NBP0602A sites 12, 5 and 6 were at locations progressively nearer to the continental shelf break and recovered sediments of late Oligocene (28.4–23.3 Ma), middle Miocene (12.8–11.7 Ma) and early Pliocene age, respectively. Seismic profiles suggest the Joinville Plateau is characterised by a late Oligocene to Pliocene sediment wedge containing no large unconformities, with contour currents and glacimarine sedimentation dominating deposition in this region since at least the Late Oligocene, and a lack of a grounded Antarctic Peninsula Ice Sheet until early

Pliocene (Smith and Anderson, 2010). SHALDRIL site NBP0602A-5 penetrated an unconformity between middle Miocene sediments below and early Pliocene sediments above, similar to those recovered at site NBP0602A-6. Smith and Anderson (2010) used regional seismic stratigraphic ties to the SHALDRIL cores to constrain an expanded Plio-Pleistocene section in James Ross Basin. They identified 10 unconformity bounded units, suggesting this area could yield an excellent Pliocene to Pleistocene record of climate-ice sheet conditions if it was to be drilled in the future.

Results from analysis of the SHALDRIL cores indicate progressive cooling and increasing glacial influence in the northern Antarctic Peninsula region since the late Eocene (Anderson et al., 2011). In the late Eocene, despite palynological evidence of diverse flora similar to that in forested parts of southern Chile and New Zealand today, rare ice-rafted pebbles and sand grain surface textures suggest some tidewater glaciers were also present. The late Oligocene cores had a markedly greater content of ice-rafted sand grains and indications that seasonal sea ice may have been present. The recovered middle Miocene sediments ($\sim$12.8 Ma) contain diverse ice-rafted pebbles from local and distant sources and provide clear indications of sea ice presence. However, palynological analyses show that tundra vegetation still persisted in this subregion at this time, and therefore persisted through the Middle Miocene Climate Transition, but evidence of this vegetation is absent in the cores by early Pliocene time, by which time there had certainly been grounded ice advances across the northernmost continental shelf. Sand grains in Pleistocene sediments recovered in SHALDRIL NBP0602A-5 exhibit greater grain roughness and more abundant glacial surface textures relative to the middle Miocene and early Pliocene sediments, suggesting a further intensification of glaciation.

The SHALDRIL results show that the sedimentary units on the continental shelf in this subregion contain a rich record of Cenozoic climate change and cryospheric evolution that is accessible to shallow drilling. However, the existing cores are from condensed sections spanning only a limited number of time windows, and therefore only provide a tantalising glimpse of the long-term climate in this region. These cores, alongside extensive seismic data in this region, show there are accessible strata that clearly present opportunities for further shallow drilling expeditions, perhaps using remotely-operated sea-floor drilling systems. However, any such expeditions will be vulnerable to the variable sea ice conditions in this region, so a wide range of alternate sites would be required to mitigate against this risk.

3.4.6 The South Orkney Microcontinent and adjacent deep-water basins

This subregion includes the South Orkney Microcontinent (SOM) and the adjacent deep-water Jane and Powell basins (Fig. 3.14). The SOM extends about 350 km from east to west and 250 km from north to south and is

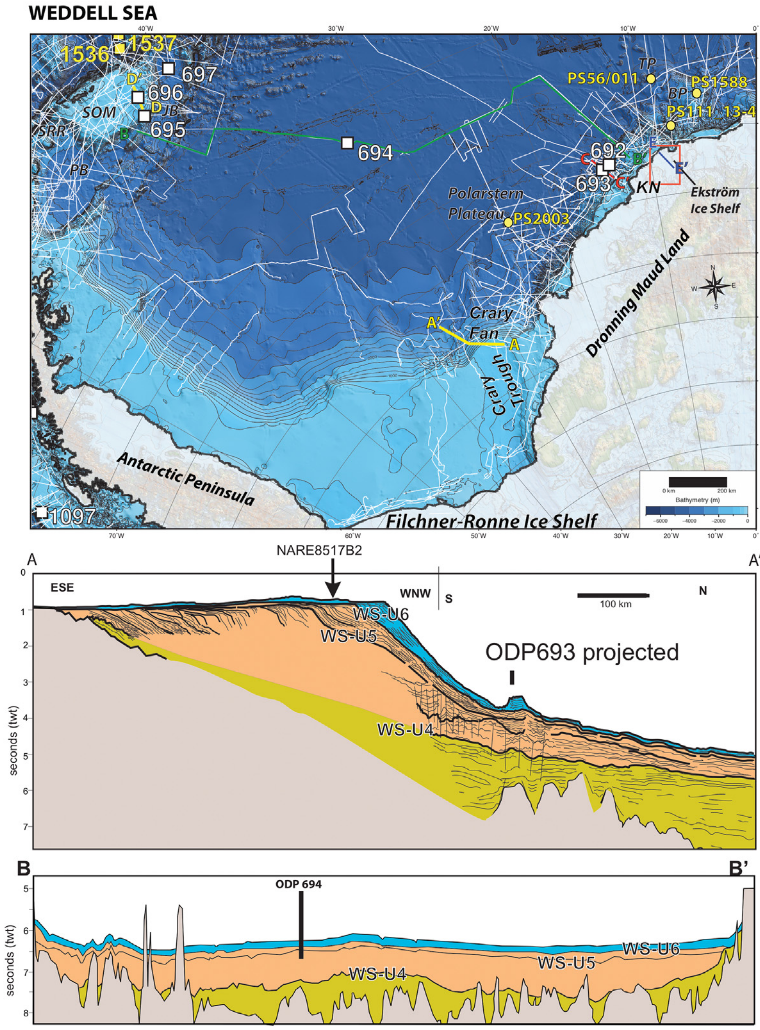

FIGURE 3.14 (Top) Location map of Weddell Sea sector with existing seismic lines (white lines). Yellow sites indicate sediment cores and the Red box shows the Ekström Ice Shelf area for pre-site drilling investigations (*BP*, Bungenstock Plateau; *KN*, Kapp Norvegia; *SSR*, South Shetland Rise; *TP*, Torge Plateau; *SOM*; South Orkney Microcontinent; *JB*, Jane Basin; *PB*, Powell Basin). Seismic tracks are from the SCAR Antarctic Seismic Data Library System (SDLS) and additional survey information. Bathymetry is from Bathymetric Chart of the Southern Ocean (Arndt et al., 2013) and subglacial topography from BedMachine Antarctica dataset (Morlighem et al., 2020). Bold green line (B−B′) shows seismic line for figure in bottom panel. Segments of seismic profiles shown in Figs. 3.15 and 3.16 are marked with red line (C−C′) and blue line (D−D′), respectively. (Middle) Interpretation of seismic lines BGR86-11 and BGR86-12 (available on the SDLS), shown as profile A−A′ in upper panel. Crossing line NARE8517B2 was used to check the depth of the unconformities WS4 and WS5. (Bottom) Interpretative line drawing of the seismic image and the sequences identified by Lindeque et al. (2013). Unconformities WS-U4 and WS-U6 were correlated to drill sites around Antarctic to about 34 and 5 Ma, respectively, although these units may be diachronous across the basin (Hochmuth et al., 2020a,b; Lindeque et al., 2013). *(Middle) From Cooper, A.K., Brancolini, G., Escutia, C., Kristoffersen, Y., Larter, R., Leitchenkov, G., et al., 2008. Cenozoic climate history from seismic reflection and drilling studies on the Antarctic continental margin. In: Florindo, F., Siegert, M. (Eds.), Antarctic Climate Evolution, vol. 8. Elsevier, pp. 115−234. Lower panel modified from Lindeque, A., Martos Martin, Y., Gohl, K., Maldonado, A., 2013. Deep-sea pre-glacial to glacial sedimentation in the Weddell Sea and southern Scotia Sea from a cross-basin seismic transect. Marine Geology 336 (0), 61−83. Available from: https://doi.org/10.1016/j.margeo.2012.11.004.*

underlain by Mesozoic metamorphic and sedimentary rocks (Dalziel, 1984; Thomson, 1981). Offshore, the SOM includes four Cenozoic sedimentary basins (King and Barker, 1988) with up to 5 km of sediment (Busetti et al., 2001, 2002; Harrington et al., 1972). Powell Basin (up to 3600 m deep) formed as the SOM rifted and drifted away from the tip of the Antarctic Peninsula in late Eocene to early Miocene time (Catalán et al., 2020; Coren et al., 1997; Eagles and Livermore, 2002; King and Barker, 1988; Lawver et al., 1994; Rodríguez-Fernández et al., 1997). Opening of Jane Basin (up to 3300 m deep) probably began later (Lawver et al., 1991, 1994) and may have continued until the middle Miocene (Bohoyo et al., 2002; Eagles and Jokat, 2014; Maldonado et al., 1998).

From single channel seismic data on the SOM, King and Barker (1988) defined pre-rift, syn-rift and post-rift units (S3, S2 and S1, respectively) (Fig. 3.15). The post-rift sediments are less than 1 km thick (e.g., Busetti et al., 2001, 2002) and were drilled at ODP Site 695 (1300 m water depth) and ODP Site 696 (600 m water depth) (Fig. 3.15). They comprise Oligocene or early Miocene to Quaternary terrigenous sediments, with rare coarse-grained ice rafted debris until the late Miocene (~8.7 Ma) and common ice rafted debris thereafter. Middle Miocene to Quaternary sediments are hemipelagic and diatomaceous muds and oozes (Barker and Kennett, 1988; Barker et al., 1988). ODP Site 696 also sampled syn-rift late Eocene sandy mudstones (S2) that have nannofossil assemblages and clay minerals suggesting a relatively warm climate, and palynoflora indicating temperate beech forests and ferns on the northern Antarctic Peninsula. However, the same late Eocene sediments also contain ice-rafted sand grains of the southern Weddell Sea provenance, indicating that tidewater glaciers were present in that area even before the Eocene-Oligocene climate transition (Carter et al., 2017). The occurrence of autochthonous glaucony in these sediments indicates that they were deposited during a transgressional event just before the Eocene-Oligocene climate transition (López-Quirós et al., 2019). Other results from ODP sites 695 and 696 suggest intermittent glaciation with little sea ice during most of the Miocene and a persistent ice cap to sea level on the Antarctic Peninsula since the late Miocene. Herron and Anderson (1990) place the maximum late Quaternary grounding line advance at the 300 m isobath, and consider open-marine conditions to have existed over the SOM since 6000 years BP based on single-channel seismic and seafloor core data. A detailed bathymetric compilation confirmed a laterally extensive break of slope across the middle of the SOM shelf at this depth, and reexamination of a seismic profile crossing it suggests this represents deposition at a former grounding zone (Dickens et al., 2014).

In Powell Basin, post-early-rift sediments are up to 3 km thick. King et al. (1997) identified two seismic units with low reflectivity below and high reflectivity above. They interpreted the change as recording the onset of glacial-interglacial cyclicity in the supply of coarse detritus to the basin in

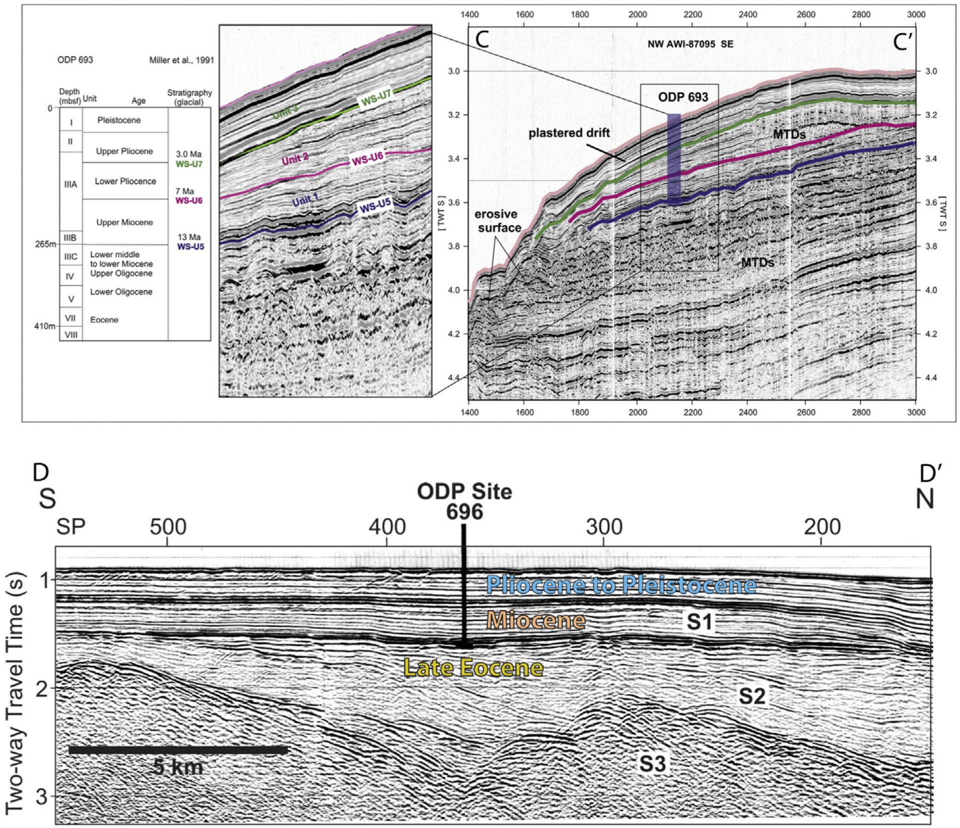

FIGURE 3.15 (Top) Seismic profile NW AWI-87095 on the continental slope in the Eastern Weddell Sea. The interpreted glacial key horizons constrained by ODP site 693. Seismic line (B−B′) and drill site location shown in Fig. 3.14; *MTDs*, Mass Transport Deposits. (Bottom) Seismic profile AMG845-18 over the South Orkney Microcontinent in the Western Weddell Sea, with location of ODP site 696. *(Top) Modified from Huang, X., Jokat, W., 2016. Middle Miocene to present sediment transport and deposits in the Southeastern Weddell Sea, Antarctica. Global and Planetary Change 139, 211−225. Available from: https://doi.org/10.1016/j.gloplacha.2016.03.002. (Bottom) Modified from Barker, P.F., Kennett, J.P., Scientific, P., 1988. Weddell sea palaeoceanography: preliminary results of ODP Leg 113. Palaeogeography, Palaeoclimatology, Palaeoecology 67 (12), 75−102.*

the late Miocene. A similar upward change in reflectivity is observed in Jane Basin (Maldonado et al., 1998). The reflectivity change may also be due to silica diagenesis (e.g., Lonsdale, 1990; Volpi et al., 2003). Rodríguez-Fernández et al. (1997) interpreted four seismic units in Powell Basin, which they characterised as pre-rift, syn-rift, syn-drift and post-drift. Maldonado et al. (2006) defined five seismic units in Jane Basin and neighbouring ocean basins, and related changes in seismic characteristics since the middle Miocene to variations in bottom water flow. ODP Site 697 was drilled in Jane Basin (Fig. 3.14) to ~323 mbsf, and recovered mainly early Pliocene and younger hemipelagic sediments with ice rafted debris throughout; however, ice rafted debris is abundant only near the base of the sequence (Barker and Kennett, 1988; Barker et al., 1988). Other seismic studies of Powell Basin (e.g., Coren et al., 1997; Kavoun and Vinnikovskaya, 1994; Viseras and Maldonado, 1999) focus on the post-early Oligocene rift history of the basin, but are limited in paleoclimate interpretations by the lack of drilling data.

Results from the ODP Leg 113 sites in this subregion show that the sedimentary units on the SOM and in the adjacent basins hold valuable long-term records of Cenozoic climate change and development of glaciation in this key area near the outflow of the Weddell Gyre and the Southern Boundary of the ACC. In particular, the succession holds good records of the conditions prior to the Eocene-Oligocene climate transition that are accessible by drilling, and records of the transition itself are probably present in some locations. The ice rafted debris in these sediments also provides evidence of the development of glaciation in the southern Weddell Sea as icebergs transported around the Weddell Gyre are carried across and around the SOM (Weber et al., 2019, 2014).

In 2019 IODP Expedition 382 drilled three sites in basins to the immediate north of the SOM, in the Pirie and Dove Basin. These sites are situated in the primary pathway of icebergs discharged from the Weddell Sea margin of the WAIS and EAIS and will allow researchers working on those cores to reconstruct ice sheet and oceanographic dynamics in this sector of Antarctic back to ~6 Ma (Weber et al., 2019). This will complement similar resolution records influenced by WAIS ice dynamics recently captured by IODP Expeditions 374 and 379, in the Ross Sea and Amundsen Sea, as well as the marine-based margin of Wilkes Land (Patterson et al., 2014). Future scientific drilling in this region could target earlier Eocene sedimentary records and more expanded records of some later periods.

3.4.7 East Antarctic Margin

The EAIS holds the world's largest freshwater reservoir with an equivalent of ~52 m sea level rise (Fretwell et al., 2013). It was long argued that the EAIS remained stable on million-year timescales (e.g., Sugden et al., 1993), supported by ice-sheet models requiring unlikely warming ($>10°C$) before exhibiting ice mass loss (e.g., Huybrechts, 1993). The last decade, however, has seen a significant increase in ice mass discharge in east Antarctica (Rignot et al., 2019; Shen et al., 2018), with the Wilkes Land loosing 51 ± 13 Gt/yr of ice between 2009 and 2017, which accounts for 20% of the total mass loss of Antarctica during this period (Rignot et al., 2019). Furthermore, for the last four decades, the cumulative contribution to sea level from East Antarctica is not far behind that of West Antarctica. These observations point to East Antarctica as a major participant in the ice mass loss from Antarctica in addition to the rapid mass loss reported from West Antarctica (Rignot et al., 2019).

The most recent Antarctic bed topography reconstruction by Morlighem et al. (2020) (Fig. 3.2) shows the glaciers with the most potential of becoming unstable draining through deep throughs with inland-sloping bedrock topography. In East Antarctica, these include glaciers draining through the Wilkes Subglacial Basin, Queen Mary Land and glaciers feeding the eastern Filchner Ice Shelf. Conversely, the Totten Glacier and Moscow University glaciers draining through the Aurora Subglacial Basin, and glaciers feeding the Amery Ice Shelf (except along the East Lambert Rift) are shown to have stabilising slopes beneath them and therefore would have to retreat several km inland before reaching a zone of retrograde bed. In Enderby and Queen Maud Land, the drainage basins are mostly above sea level and glaciers flow over prograde bed slopes, except along a narrow coastal margin, and are hence more protected from MISI processes. These findings signal the relevance of understanding past East Antarctica's marine ice sheet dynamics for assessing their response to ongoing climate change and to better determine Antarctica's future contribution to sea-level change.

3.4.7.1 Weddell Sea

The Weddell Sea comprises a wide, deeply-incised continental shelf, that is currently characterised by heavy sea ice cover on the outer continental shelf, and the Filchner-Ronne Ice Shelf (FRIS) on the inner shelf, which is the largest ice shelf on Earth by volume (Akhoudas et al., 2020; Arndt et al., 2013). This extensive ice cover has precluded detailed surveying by seismic vessels and drilling on the continental shelf, so most seismic studies and drill cores are restricted to offshore regions (Figs. 3.1 and 3.14). In the southeastern Weddell Sea, the Filchner Depression/Crary Trough represents a glacially carved seafloor depression that drained a large portion of the marine-based sector of the EAIS in the Recovery Ice Stream catchment. Model-based experiments suggest this sector of the EAIS is the most sensitive to oceanic warming, and potentially susceptible to threshold behaviour under moderate levels of oceanic warming ($\sim 1°C-2°C$) (Golledge et al., 2017). Such warming could occur rapidly in this region, if there is a shift in wind-driven advection of modified Circumpolar Deep Water into Filchner Depression/Crary Trough on the continental shelf, via the southern limb of the Weddell Gyre (Hattermann, 2018; Hellmer et al., 2012).

Kristoffersen and Jokat (2008) previously described the regional seismic stratigraphy of the Weddell Sea continental shelf/slope/rise in the first edition of Antarctic Climate Evolution (Florindo and Siegert, 2008). Broadly, the principal stratigraphic features in the Weddell Sea sedimentary basins are prograding wedges of glacigenic sediments along the entire continental shelf margin. A large trough-mouth fan (Crary Fan) north of the Filchner Depression/Crary Trough extends into much of the continental rise to abyssal plain of the southeastern Weddell Sea and is associated with a complex channel-levee and gully system (Gales et al., 2016, 2014, 2012). The present-day sedimentary depositional system in the Weddell Sea can be split into three geomorphological regions (Jerosch et al., 2016): (1) the continental margin in the southern and eastern region is heavily influenced by downslope transport of sediments near the glaciated continental shelf edge, with offshore channel-levee and contourite systems (Michels et al., 2002); (2) slowly accumulating hemipelagic sediments of mostly terrigenous origin further offshore in the central and northern Weddell Gyre; and (3) hemipelagites and contouritic sediment drifts in the north-western Weddell Sea (Vernet et al., 2019).

Very few multichannel reflection seismic surveys have explored the southern Weddell Sea since the review by Kristoffersen and Jokat (2008), partly because of increasing difficulties to fulfil environmental protection restrictions, but also due to the pervasive ice conditions in this region. However, ongoing data interpretation and review papers have provided new results for paleoenvironmental changes in the Weddell Sea area, with implications for understanding the evolution of Antarctica's cryosphere and global impacts of climate change. Here, we provide an update on scientific knowledge about (1) Gondwana break-up, Weddell Sea opening and the pre-ice-sheet depositional environment from mainly geophysical research and (2) the Eocene-Oligocene transition and younger geological units that have been sampled by drilling. A wealth of studies have been undertaken on deglaciation processes (from LGM, to recent), and these are discussed in more detail by Siegert et al. (2021) and by Hillenbrand et al. (2014). We also discuss some outstanding scientific questions that could be addressed by future geoscientific drilling based on recent seismic surveys beneath the Ekström Ice Shelf (EIS).

3.4.7.1.1 Gondwana break-up, Weddell Sea opening and pre-ice-sheet depositional environment

U-Pb zircon studies revealed that the southern side of Dronning Maud Land has a protracted late Neoproterozoic/early Palaeozoic metamorphic overprint, accompanied by igneous activity, most likely related to the East African-Antarctic Orogen (Jacobs et al., 2017). The lack of preserved Mesozoic–Cenozoic sediments and structures in central Dronning Maud Land has limited our understanding of the post-Pan-African evolution of this important part of East Antarctica (Sirevaag et al., 2018). Vibroseismic site surveys conducted for planned drilling studies to improve this understanding have been conducted below the Ekström Ice Shelf (Kuhn and Gaedicke, 2015; Smith et al., 2020) and show a possible outcrop of the syn-rift volcanic Explora Wedge unit at the seafloor (Fig. 3.16). A recent synthesis of ship-based and aeromagnetic surveys has provided new insights into the reconstruction of the spreading history of the Weddell Sea area (Eagles and Jokat, 2014). The separation of Antarctica from former South Africa in the Dronning Maud Land area has been assumed to have occurred between 82 and 159 Ma (Kristoffersen et al., 2014). In the southern Weddell Sea in front of the FRIS, a failed rift system is observed, and oceanic crust in the centre of this failed rift has a minimum age of 145/148 Ma (magnetic chron M19/M20) and maximum age of 160 Ma (Jokat and Herter, 2016).

The Weddell Sea formed as a consequence of the break-up of the Gondwana super-continent in Jurassic times. This break-up was associated with massive, but short-lived volcanic activity, that possibly formed the Explora Wedge (Kristoffersen et al., 2014). Dredges have recovered organic rich marine sediments, indicating temperate climate conditions, and a belemnite of likely early Cretaceous age from the slopes of the Wegener Canyon (from 2700 to 3250 m water depth). This is very close to ODP Site 693, where upper Cretaceous marine sediments were drilled at the borehole base

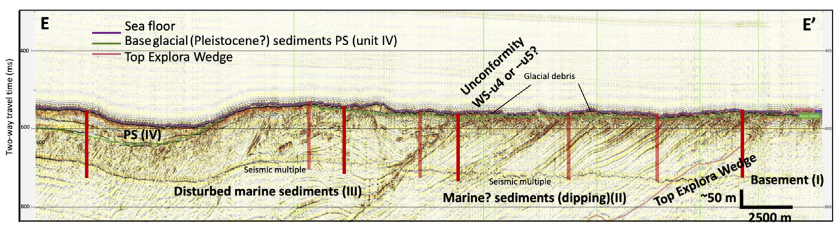

FIGURE 3.16 Vibroseis seismic profile from below the Ekström Ice Shelf. Four seismic units were detected: continental basement (I) with the Explora Wedge and overlying unconformity (red line). Seismic unit II could include the oldest post-rift sediments (Jurassic–Cretaceous) in the Dronning Maud Land area and is interpreted as a shallow marine (or terrestrial?) environment. An angular unconformity separates this from seismic unit III that indicates more turbulent deposition (drifts?, canyon infill?), interpreted as being deposited after initiation of the EAIS (younger than 34 Ma?). (Plio-?) Pleistocene sediments (Unit IV) stratified parallel to the seafloor occur in the most northern part of the profile. Whole seismic units could be sampled at four (up to 200 m deep) drill-coring sites (vertical red lines) for bedrock and covering sediment characterisation. Four additional drill cores (transparent red) would allow coverage of the entire sedimentary sequences. Seismic line (E-E′) location shown in Fig. 3.14.

(Kennett and Barker, 1990; Fütterer et al., 1990), suggesting significant potential for obtaining longer-term Mesozoic records in this region. Continued seafloor spreading led to expansion of the Weddell Sea between the Cretaceous and the Eocene, but a lack of geological sampling of this stratigraphy do not allow any further reliable statements about the sedimentary and oceanographic environment during this period. However, some inferences can be made from intraregional seismic correlations (Lindeque et al., 2013; Maldonado et al., 2006; Pérez et al., 2021), geologic data (Carter et al., 2017; Mackensen and Ehrmann, 1992) and modelling results (Douglas et al., 2014; Ladant et al., 2014; Wilson et al., 2012) that suggest a proto-Weddell Gyre existed throughout much of this period. Model experiments indicate that deep convection was more intense prior to the opening of the Drake Passage, but changed to a more stagnant stage when the Drake Passage opened (Ladant et al., 2018).

3.4.7.1.2 The Eocene-Oligocene transition and paleoenvironment during increasing glacial conditions

After the opening of Drake Passage at ~34−35 Ma, the Weddell Sea became tectonically passive with approximately the same topography as it has today (Vernet et al., 2019). The opening of Drake Passage allowed the ACC to develop and has long been thought to be a key factor in ice sheet expansion across the Antarctic continent (Kennett, 1977). On the continental rise and abyssal plain of the Weddell Sea, a prominent unconformity (WS-U4) marks these changes, inferred to coincide with the Eocene/Oligocene boundary but has yet to be constrained by drilling (Lindeque et al., 2013) (Fig. 3.14). A correlation of the deep water Weddell Sea seismic stratigraphy to ODP/IODP/DSDP drill cores in the Southern Ocean and Antarctic margin was conducted by Huang et al. (2014) and Hochmuth et al. (2020a,b). This work presented a state-of-the-art reconstruction of sediment accumulation in the Southern Ocean with time slice presentations of back-stripped sediment accumulation maps. It highlights that the failed rift basin in the Weddell Sea contains the thickest sequence of pre-Oligocene sediments on the Antarctic margin, with thicknesses reaching more than 7 km (Jokat and Herter, 2016; Leitchenkov and Kudryavtsev, 2000), whereas extensive fluvial erosion is inferred for the southeastern Weddell Sea (Hochmuth et al., 2020a,b). Between 34 and 14 Ma, sediment accumulation rates increased slowly and were most focussed in regions where there was enhanced erosion by expanding glacial systems on the continental margin of the eastern Weddell Sea (34−24 Ma), Ronne (24−21 Ma) and Filchner (21−14 Ma) shelf areas.

Unconformity WS-U5 is constrained by ODP Site 693 to between 15 and 13 Ma (Huang and Jokat, 2016; Kennett and Barker, 1990), correlating with the MMCT (Fig. 3.15). After this time, sedimentation rates increased significantly in the Weddell Sea, and stronger bottom-water currents formed expansive contouritic drifts (Hochmuth et al., 2020a,b).

Particularly high sedimentation rates from ODP Leg 113 cores are reconstructed for the period between 14 and 3 Ma in the Crary Fan area, and between 5 Ma and recent on the continental slope and rise offshore from Dronning Maud Land (Barker et al., 1988; Hochmuth et al., 2020a,b; Huang and Jokat, 2016; Huang et al., 2014; Kennett and Barker, 1990). This suggests increased expansion of marine-terminating ice sheets delivering sediment to the continental shelf edge at these times. Highest last glacial sedimentation rates of up to 300 cm/kyr were recovered in sediment cores from the southern Weddell Sea on the Crary Fan rise (Sprenk et al., 2014; Weber et al., 2011). These data suggest that if sea ice-related risks for drilling vessels could be mitigated, there is excellent potential to obtain Neogene to Quaternary archives in this high-latitude, polar region for decadal and perhaps annual resolution of sedimentation relating to ice dynamics, oceanic process and depositional history. This is in contrast to very low sedimentation rates in the northern abyssal plain (Geibert et al., 2005; Honjo et al., 2008; Howe et al., 2007). Seafloor plateaus on the abyssal plain, such as the Polarstern or Torge Plateaus (Arndt et al., 2013; Bart et al., 1999; Kuhn et al., 2002), and sediment starved slopes like the Bungenstock Plateau provide low but continuous pelagic sedimentation that are covered with biogenic sediments (Abelmann et al., 1990). Gravity cores from the Torge, Bungenstock and Polarstern Plateaus collected sediment dating back to the lower Pliocene (ca. 4.5 Ma) and show a shift from biogenic opal rich to carbonate-rich sediments near the Pliocene/Pleistocene boundary (Hillenbrand and Ehrmann, 2005). This shift is suggested to be related to oceanic cooling and freshening by enhanced meltwater input (higher ice volume dynamics), increased sea-ice coverage, less general overturning circulation due to more Antarctic Bottom Water formation, or a deeper carbonate compensation depth and higher alkalinities as observed during late Pleistocene glacial periods (Rickaby et al., 2010).

3.4.7.1.3 Recent geophysical survey beneath the Ekström Ice Shelf and future directions for drilling

Satellite gravimetry data comparisons to vibroseis measurements conducted on the Ekström Ice Shelf (EIS) have enabled an improved bathymetry to be developed below the Dronning Maud Land ice shelves. These interdisciplinary observations have been conducted as part of a site survey for future potential geological drilling below the EIS, and 615 km of high-resolution vibroseismic lines were collected on the ice shelf between 2010 and 2018 (Eisermann et al., 2020; Kuhn and Gaedicke, 2015; Smith et al., 2018, 2020) (Fig. 3.16). Vibroseismic profiles near the calving front on the ice shelf indicate onlapping strata in a ~1000 m thick dipping sedimentary sequence covering the continental basement (Kristoffersen et al., 2014). Although the seismic data are currently unpublished, preliminary analysis indicates three distinct sedimentary units above the continental basement. The volcanic Explora Wedge is interpreted to likely form the top of this basement and dips $\sim 20°$ to the north (Kristoffersen et al., 2014) (Fig. 3.16).

A well stratified seismic interval (unit II) overlies the basement and dips in the same direction and is hypothesised to have been deposited in a quiet, shallow marine environment after the Weddell Sea opening during the Jurassic. A clear unconformity with a steeper dipping angle cross cuts unit II and is overlain by irregularly folded, but clearly stratified sediments (unit III) that outcrop on the seafloor in the northern part of the profiled area. This unconformity is tentatively interpreted to represent the WS-U4 ($\sim$Eocene/Oligocene boundary) or WS-U5 ($\sim$14 Ma) surface discussed above. The uppermost seismic unit (IV) shows deposition and bedding parallel to the seafloor and could have been deposited during interglacials (or glacials?) through the Plio-Pleistocene. Glacial debris and diamicton covers the older sequences in an up to 10-m-thick layer on the seafloor. Depending on the utilised drilling technology, a drilling plan that revolved around five cores penetrating 200 m below the seafloor would enable sampling of all the identified seismic units, allowing a tectonic and climate history to be reconstructed in this region for key 'snapshot' time periods since the Jurassic. This would provide a history of early sedimentation after the rifting and EAIS build up, alongside a reconstruction of associated variability of productivity and oceanographic changes related to past climates. Accompanied drilling further to the north would enable more comprehensive changes of Weddell Gyre dynamics and Antarctic Bottom Water formation during Cenozoic glacial/interglacial cycles.

High-quality Plio-Pleistocene records from this sector of the margin would also build on the excellent high-resolution long sediment cores collected further north in the Scotia Sea during 2019 by IODP Expedition 382. This recent IODP expedition aimed to capture millennial scale resolution records of ice rafted debris deposition from cores in the 'Iceberg Alley' region of the Weddell Gyre/ACC confluence (Weber et al., 2019). Sedimentary records deposited at locations along the pathways of the returning Weddell Gyre surface currents that pass over Dronning Maud Land and the Weddell Sea Deep Water overflow to the Scan Basin in the Scotia Sea (Pérez et al., 2014) are connected to the IODP Expedition 382 sites and offer unique opportunities for reconstructing past changes in bottom water flow and iceberg discharge in these areas. With hot-water drilling required to access the seafloor below the EIS, this drilling should be complimented by a deployment of instrumentation to obtain an oceanographic time series observing upwelling of modified Warm Deep Water onto the shelf and in the deepest part of the glacially eroded trough below the EIS. This will help constrain processes associated with ocean-cryosphere interaction in the cavity of this ice shelf, supplementing similar measurements below the Fimbul Ice Shelf to the east (Hattermann, 2018; Hattermann et al., 2012, 2014), as well as enabling a better understanding of the relevance of the paleoclimate records and model experiments in this region.

3.4.7.2 Prydz Bay

Prydz Bay overlies a rift structure that extends about 500 km into the interior of the continent and has channelled drainage at least since the early Cretaceous (Arne, 1994). It presently contains the Lambert Glacier-Amery Ice Shelf drainage system that drains more than 16% of the EAIS. As with the Aurora Basin, this drainage basin extends to the Gamburtsev Mountains, a subglacial range in which the Cenozoic ice sheets may have nucleated (Bo et al., 2009). An extensive grid of seismic surveys exists in this region, with age constraints provided by the two ODP Legs 119 and 188 (Fig. 3.17). The offshore paleoclimate records and seismic stratigraphic framework in this region are

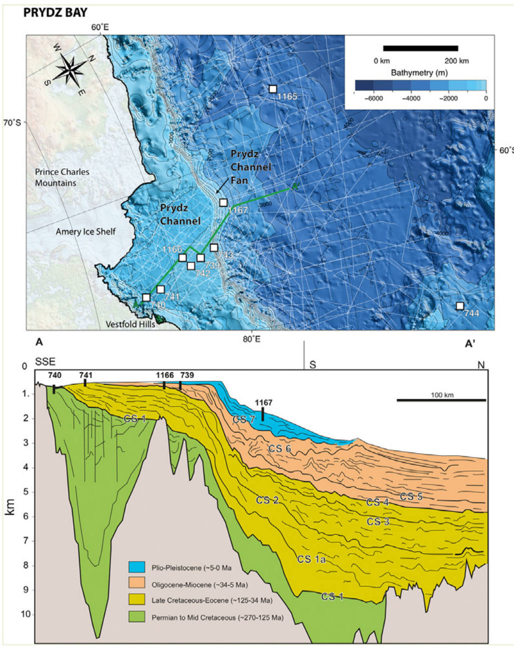

FIGURE 3.17 (Top) Location map of Prydz Bay sector with existing seismic lines (white lines) and drill sites (white boxes). Seismic tracks are from the SCAR Antarctic Seismic Data Library System (SDLS) and additional surveys. Bathymetry is from Bathymetric Chart of the Southern Ocean (Arndt et al., 2013) and subglacial topography from BedMachine Antarctica dataset (Morlighem et al., 2020). (Bottom) Interpretive seismic section across Prydz Bay shelf, continental slope and continental rise based on Russian seismic lines RAE 5702, 5701 and 5206. See bold green line A−A′ in upper panel for section trackline. *Adapted from Cooper, A.K., Brancolini, G., Escutia, C., Kristoffersen, Y., Larter, R., Leitchenkov, G., et al., 2008. Cenozoic climate history from seismic reflection and drilling studies on the Antarctic continental margin. In: Florindo, F., Siegert, M. (Eds.), Antarctic Climate Evolution, vol. 8. Elsevier, pp. 115−234. with annotated seismic horizons from Leitchenkov, G., Galushkin, Y., Guseva, Y., Dubinin, E., 2020. Evolution of the Sedimentary Basin of the Continental Margin of Antarctica in the cooperation sea (from results of numerical modeling). Russian Geology and Geophysics 61 (1), 6878. Available from: https://doi.org/10.15372/RGG2019079.*

further constrained by a wide range of on-land field studies and exposure dating. Two Phanerozoic phases of enhanced denudation are inferred for the Prince Charles Mountains, with an initial phase of 1.6−5.0 km of focussed erosion during the initial rift phase in the early Palaeozoic, followed by 1−4.5 km of erosion during rifting reactivation in the early Cretaceous (Lisker et al., 2003). Zircons and hornblendes recovered from Eocene fluvial sediments draining from the Gamburtsev mountains in ODP Leg 188 Site 1166 provide $^{40}Ar/^{39}Ar$ dates of ~519−530 Ma, indicative of a continental origin for the Gamburtsev mountains as opposed to a younger volcanic origin (van de Flierdt, 2008). Veevers (2008) examined zircons for U-Pb ages and Hf isotopes from Permian to Cenozoic sediments from across the Prince Charles Mountains and Prydz Bay and identified clusters of ages between 700−460 Ma, 1200−900 Ma and smaller clusters as old as 3350 Ma, suggesting the region comprises a core complex of Grenville age (1200−900 Ma) rocks surrounded by fold belts formed by the assembly of Gondwana (700−460 Ma).

3.4.7.2.1 Early Cenozoic greenhouse and earliest glacial phase in late Eocene

The formation of the Lambert Graben and Prydz Bay basin during the Carboniferous to early Cretaceous provided sedimentary depocentres prior to the inferred onset of Cenozoic glaciation near the Eocene/Oligocene boundary, and both basins contain up to 9.0 km of rift-fill sediment (Arne, 1994; Leitchenkov et al., 2020, 2018, 2014; Lisker et al., 2005). Seismic reflection data show Mesozoic sequences of parallel, moderately continuous reflectors (Figs 3.17 and 3.18), which were penetrated at ODP Sites 740, 741 and 1166.

ODP Site 740 intersected interbedded sandstone, siltstone and mudstone with reddish coloration (Barron and Larsen, 1989), interpreted as fluvial flood plain deposits (Turner, 1991). The age of this unit remains unknown, but could be as old as Triassic (Mcloughlin and Drinnan, 1997a,b; Truswell, 1991). Multichannel seismic data highlights a thick (up to 5 km), faulted and high-velocity (up to 5.2 km/s) unit underlying these red beds (Leitchenkov et al., 2020, 2015). This sequence predates the main phase of break-up-related crustal extension and is thought to correlate with the Permian-Triassic sediments of the northern Prince Charles Mountains. This indicates the reddish beds in ODP Site 740 are likely to be early Cretaceous or Late Jurassic in age. The base of ODP sites 741 and 1166 recovered Turonian-Santonian(?) (94−84 Ma) and middle Aptian age (125−113 Ma) sediments, respectively, and contain siltstone and sandstone interbeds with minor coal. These strata are interpreted as probable delta plain to lagoonal in origin, and palynomorph assemblages from ODP Site 1166 indicate a conifer-dominated woodland vegetation, consistent with a cool, humid climate (Macphail and Truswell, 2004a,b).

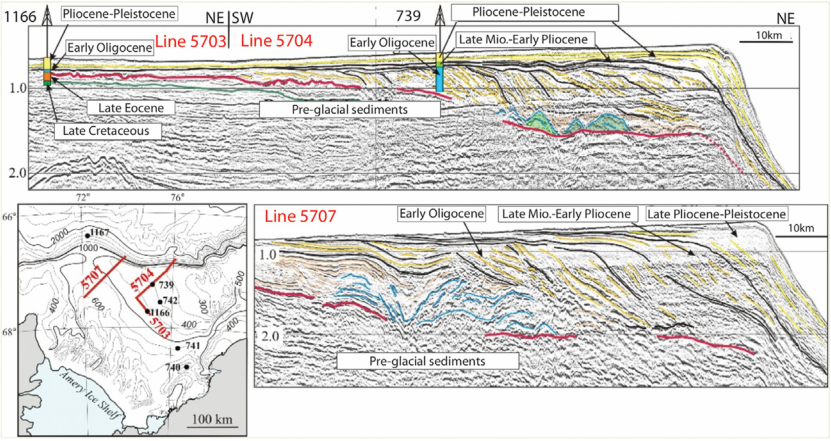

FIGURE 3.18 Seismic lines showing shelf and upper slope development during the Cenozoic in Prydz Bay. Prograding clinoforms developed in the Oligocene with episodes of shelf and slope erosion. *From Leitchenkov, G., Galushkin, Y., Guseva, Y., Dubinin, E., 2020. Evolution of the Sedimentary Basin of the Continental Margin of Antarctica in the cooperation sea (from results of numerical modeling). Russian Geology and Geophysics 61 (1), 6878. Available from: https://doi.org/10.15372/RGG2019079.*

The continental rise offshore of Prydz Bay contains up to 7 km of post-rift sediments (Fig. 3.17) (Mizukoshi et al., 1986; Stagg et al., 2005, 2004). The lowermost seismic stratigraphic unit has parallel, mostly continuous, reflectors typical of deep-ocean deposition that probably occurred during pre-ice-sheet times (Kuvaas et al., 2005; Kuvaas and Leitchenkov, 1992; Leitchenkov et al., 2015, 2007; Mizukoshi et al., 1986). Nine seismic horizons were identified from the continental slope and rise (Fig. 3.17) starting from horizon CS1, which corresponds to the top of rift fill unit. Horizons CS1a, CS2 and CS3 bounding early post-rift units likely formed in response to tectonic, ocean circulation and climate changes in the Southern Ocean prior to the onset of major glaciation at about 34 Ma, which is marked by Horizon CS4 (Leitchenkov et al., 2015, 2007) (Fig. 3.17).

Although syn-glacial strata (post-Eocene) are nearly absent on much of the inner shelf, they are up to 1.5 km thick on the outer shelf, and up to 2.8 km thick on the continental rise (Leitchenkov et al., 2015). In Prydz Bay, ODP Sites 739, 742 and 1166 recovered sediments deposited immediately before major glaciation (Barron et al., 1991; Cooper and O'Brien, 2004). Seismic correlations to these cores indicate that poorly sorted sands overlie an undulating erosion surface, suggesting a period of erosion possibly related to a relative low stand of sea level (Erohina et al., 2004) (Fig. 3.18). These sands fine upsection into mudstone containing lonestones, marine diatoms and dynocysts (O'Brien et al., 2001). An integrated bio-(diatoms, palynomorphs) and magneto-stratigraphic age model developed for ODP Sites 739, 742 and 1166 indicates the late Eocene to early Oligocene intervals of these sites form a relatively continuous succession from 36 Ma (C16.1n) to 33 Ma (C13n) (Macphail and Truswell, 2004a,b; O'Brien et al., 2001; Passchier et al., 2017). Sand-grain surface textures in fluvial sands from Hole 1166A suggest erosion and breakage by glaciers, implying the presence of at least valley glaciers in the hinterland of Prydz Bay prior to the arrival of ice-rafted debris offshore (Strand et al., 2003).

3.4.7.2.2 Oligocene–Miocene ice-sheet development

The early glacial section of the shelf comprises tabular units that pinch out shoreward due to inner-shelf erosion, and extend seaward into prograding slope deposits (Cooper et al., 1991). The paleo-continental shelf edges for these units are better defined upsection, as the foreset strata steepen seaward (Fig. 3.18). On the outer shelf, the early glacial time is characterised by crosscutting mounded seismic facies, indicative of migrating grounding line fans formed at the front of meltwater rich glaciers (Leitchenkov et al., 2015). Several separate foreset packages interpreted as representing ice advances are identified on the shelf, the oldest of which occurs 50–100 km landward of the present-day shelf break. The foresets range in age from late Oligocene to late Miocene (early Pliocene?) based on correlations to ODP Site 739 (Leitchenkov et al., 2015). Shelf-edge clinoforms developed during the Oligocene, with foresets interrupted by numerous erosion surfaces (Fig. 3.18).

ODP sites 739, 740, 741, 742 and 1166 on the continental shelf recovered probable subglacial and glaciomarine diamicts, with thin interbedded diatomaceous mudstones deposited during warm episodes (Erohina et al., 2004; Hambrey et al., 1991). The drilling and seismic evidence indicates glacial advance across the Prydz Bay continental shelf during cold episodes, probably reaching the shelf edge. Over-compacted horizons indicate periods of glacial erosion and ice loading during the early Oligocene, Miocene and Plio-Pleistocene (O'Brien et al., 2001; Solheim, 1991). Prior to the late Miocene, the Prydz Bay shelf prograded uniformly across its width, with the bulk of the ice and entrained sediment coming from the southern end of the bay (i.e. from the Lambert Graben). The Prydz Bay continental slope became progressively steeper from the early phase of glaciation in the early Oligocene, to reach angles of as much as 8° on the present slope (Figs. 3.17 and 3.18).

On the continental rise, a pre-ice-sheet unit is overlain by another unit exhibiting channel-levee geometries. The nature of the change in geometry and the tracing of reflectors to the shelf drill sites suggest that this change originated from the glacial expansion and increased sediment supply in the early Oligocene (Kuvaas and Leitchenkov, 1992). Overlying the channel-levee complexes are thick mounds and sediment waves that show evidence of modifications by bottom currents although sediment waves may also form under influence overspill of turbidite flows and flow stripping from the main channels (Huang et al., 2020) (Fig. 3.17).

ODP Site 1165 drilled a thick mound of lower Miocene and younger contourite sediments with turbidites only in the upper 5 m (Cooper and O'Brien, 2004). The surface marking the base of the mounded sequences was dated as being early Miocene and was interpreted as representing a shift from low relief submarine fans to highly mounded deposits. However, no obviously lithological change is noted across this boundary, and interbedded bioturbated claystone with ice rafted debris and claystones with silt laminae are described above and below this surface. The facies associations suggest that sediment was delivered by turbidity currents and subsequently entrained and redeposited by deep sea contour currents, while the interbeds represent Milankovich-scale forcing of paleoenvironmental processes relating to ice rafting, biogenic sediment supply, oxygenation of bottom waters and current speed (Williams and Handwerger, 2005). At the middle Miocene (14−16 Ma), a shift from laminated contourites to alternating hemipelagic and pelagic facies occurs, with the alternation interpreted to represent Milankovitch cycle modulation of biological productivity relating to sea ice state and ice sheet extent (Cooper and O'Brien, 2004; Florindo et al., 2003; Grutzner et al., 2003). At this time, recycled microfossils increase significantly, suggesting the start of intense erosion by ice sheets of sediments on the continental shelf.

3.4.7.2.3 The Polar Ice Sheet (late Miocene(?)−Pleistocene)

In the early Pliocene, ice flow regimes changed and ice was focused into an ice stream on the western side of Prydz Bay, cutting a cross-shelf trough, the Prydz Channel (Taylor et al., 2004). The ice stream delivered basal debris to the shelf edge, where the debris built a trough mouth fan on the upper continental slope (O'Brien and Harris, 1996; O'Brien and Leitchenkov, 1997; O'Brien et al., 2004). On the banks adjacent to Prydz Channel, vertical aggradation of subglacial debris produced tabular units while glacial erosion overdeepened the inner shelf. The inferred early Pliocene base of the Prydz Channel Fan is the prominent unconformity mapped as reflector A by Mizukoshi et al. (1986) and reflector PP-12 by O'Brien et al. (2004).

While drilling and seismic evidence indicate that glaciers periodically advanced to the continental shelf edge in Prydz Bay during cold episodes of the Pliocene and early Pleistocene, evidence of warmer-than-present episodes and reduced ice extent also exists. Sediments in the Prince Charles Mountains indicate open-water fjordal environments in the Miocene to Pliocene, and an ice sheet margin that retreated several hundred kilometres inland from its present position (Hambrey and McKelvey, 2000; Whitehead, 2003; Whitehead et al., 2004). Lower Pliocene marine diatomite in the

Vestfold Hills, on the eastern side of Prydz Bay, contains evidence of temperatures 4°C warmer than today (Quilty et al., 2000; Whitehead et al., 2001). Diatoms in ODP sites 1166 and 1165 suggest reduced sea ice during the Pliocene (Whitehead et al., 2005), with silicoflagellates indicating higher surface water temperatures (Escutia et al., 2005; Whitehead and Bohaty, 2003). Calcareous nannoplankton at ~1.1 Ma indicates warmer conditions at that time (Pospichal, 2003).

ODP Site 743 was drilled into the eastern, steep part of the slope, and recovered diamict, while ODP Site 1167 was drilled into the Prydz Fan, and recovered muddy, pebbly sands and diamicts, interpreted to be deposited by slumping of subglacial debris delivered to the shelf edge by past expansion of the EAIS (Huang et al., 2020; O'Brien et al., 2001; Passchier, 2003). ODP Site 1167 also recovered thin mudstone units deposited during periods of reduced ice extent. More than 90% of the fan was deposited before the mid-Pleistocene, and only three advances of the Amery Ice Shelf to the shelf edge are constrained for the late Pleistocene (O'Brien et al., 2004). The seismic stratigraphy of the margin reflects the decrease of sediment supply from the continental shelf in the late Pliocene and the increase of influence of bottom currents in reworking fine grained material, leading to the formation of sediment drifts and sediment waves on the rise (Huang et al., 2020). Clay mineralogy, magnetic properties and clast composition at ODP Site 1167 show changes suggesting that the Pleistocene peak of erosion and ice volume in the Lambert-Amery drainage system occurred in the early Pleistocene (O'Brien et al., 2004). Oxygen isotope measurements on foraminifera from ODP Site 1167 also suggest that sedimentation was reduced after the mid-Pleistocene, with the last ice advance to the shelf edge at about Marine Isotope Stage 16 (612–698 ka; Lisiecki and Raymo, 2005). However, the stratigraphic record is fragmentary because hiatuses are common, which leads to a tentative identification of isotope stages (Theissen et al., 2003).

The late Pleistocene saw the Amery Ice Shelf grounding zone moving seaward to a position in mid-shelf during glaciations with grounded ice likely on the adjacent banks and an ice shelf in Prydz Channel (Domack et al., 1998). This landward shift in ice sheet margin extent during glacials is inferred to be the consequence of several factors including overdeepening of the inner shelf that acted to restrict marine-based ice sheet advance after the mid-Pleistocene; shifts in orbital influences on ice sheet mass balance at the Mid-Pleistocene Transition; and increased aridity due to late Pleistocene cooling may have also contributed to reduced ice extent (O'Brien et al., 2007; Suganuma et al., 2014).

3.4.7.3 East Antarctic Margin – Sabrina Coast

The low-lying, glacially sculpted Aurora Subglacial Basin (ASB) contains ~3–5 m sea level equivalent of marine-based ice (Fig. 3.19), and its

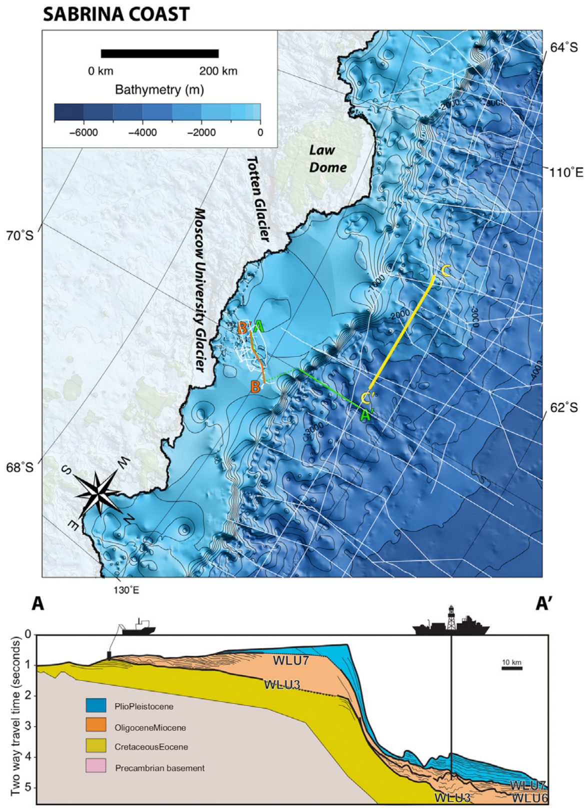

FIGURE 3.19 (Top) Overview map of Sabrina coast region of East Antarctica with existing seismic lines (white lines). No drill sites exist in the region, which is the focus of two planned drilling projects on the continental shelf and rise (see text for details). Seismic tracks are from the SCAR Antarctic Seismic Data Library System (SDLS) and additional surveys. Seismic track-lines in lower panel (orange line B′−B and green line A−A′) and Fig. 3.20 (yellow line C−C′) are shown. Bathymetry is from Bathymetric Chart of the Southern Ocean (Arndt et al., 2013) and subglacial topography from BedMachine Antarctica dataset (Morlighem et al., 2020). (Bottom) Sabrina Coast seismic stratigraphy showing major unconformities using the nomenclature for the Wilkes Land margin (WLU3 to WLU7) and associated shifts in the geometry of sedimentary packages on the continental shelf, and previous drilling (see upper panel for transect line). Profile is constructed from seismic lines 10 and 21 presented by Gulick et al. (2017) and RAE5103, with a tentative correlation between these lines based on Donda et al. (2020).

broader catchment drains ice from the Gamburtsev Mountains to the Sabrina Coast (Aitken et al., 2016; Fretwell et al., 2013; Greenbaum et al., 2015; Young et al., 2011a). The Totten Glacier is one of the catchment's largest marine-terminating outlet glaciers (Khazendar, 2013). Its grounding line is presently influenced by warm subsurface (<400 m) ocean waters and it is experiencing East Antarctica's largest mass loss (Li et al., 2016; Rintoul et al., 2016; Roberts et al., 2017). The ASB catchment consists of several overdeepened basins (Aitken et al., 2016; Young et al., 2011a) and hosts an active subglacial hydrological system that drains meltwater to the ocean (Wright et al., 2012), suggesting that regional ice may be susceptible to progressive retreat and changing subglacial hydrology. Models suggest significant ASB catchment mass loss is possible under some Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathways, but there are large differences in the scale of this change between models (DeConto and Pollard, 2016; Golledge et al., 2015). Furthermore, model experiments indicate that both the Wilkes Subglacial Basin and ASB are more sensitive to atmospheric warming than other sectors of the EAIS (Golledge et al., 2017). Consequently, identifying regional climate threshold responses to oceanic and/or atmospheric warming from geological archives remains a high priority to provide important constraints on model-based interpretations and to allow assessment of the potential future sensitivity of this region to atmospheric vs oceanic influences on ice sheet mass balance.

On the Sabrina Coast continental shelf, three seismic megasequences were defined by Gulick et al. (2017). Chronostratigraphy of these megasequences was constrained by short piston cores targeting locations where seismic reflectors outcroped at the seafloor (Fernandez et al., 2018; Gulick et al., 2017; Montelli et al., 2020; Smith et al., 2019). Megasequence I (Ms-1) consists of low to moderate amplitude seaward-dipping discontinuous to continuous reflectors. Clinoforms imaged on the middle shelf indicate enhanced sediment supply to the margin, and terrestrial palynomorphs and benthic foraminifers from sediment cores that penetrated outcropping reflectors stratigraphically below and above the uppermost clinoform (Fig. 3.19) suggest a latest Paleocene and early to middle Eocene age range for the uppermost feature (Gulick et al., 2017; Smith et al., 2019). A series of discontinuous moderate- to high-amplitude reflectors at the top of Ms-I and the presence of lonestones in recovered sediments indicate that marine-terminating tidewater glaciers were present at the coastline by the early-to-middle Eocene, well before continental-scale ice sheets were thought to have been established. The top of Ms-1 is defined by a sharp erosive surface in the seismic data and is interpreted as an initial ice advance across the continental shelf, but is currently undated (Fig. 3.19; Gulick et al., 2017). Above this surface, Ms-II consists of strata with parallel high-amplitude reflectivity and prograding strata that are interrupted by ten undated erosive surfaces (Fig. 3.20; Gulick et al., 2017). Five of these surfaces display prominent tunnel valleys, providing evidence of a grounded ice sheet with a substantial meltwater channel system, that in turn implies climates warm enough for surface-derived subglacial meltwater (Fig. 3.20; Gulick et al., 2017; Ó Cofaigh, 1996). Thus, seismic and sedimentologic data from Ms-II suggest that meltwater-rich glaciers advanced and retreated across the shelf at least 10 times between the early to middle Eocene and the late Miocene. Ms-II is truncated by a regional

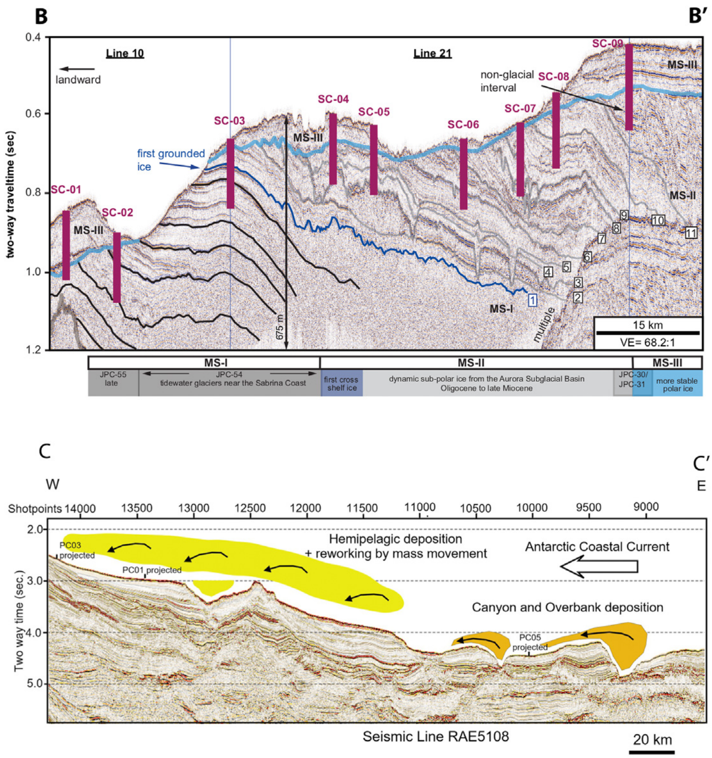

FIGURE 3.20 (Top) Composite seismic line with pre- to pro-glacial Megasequence I (Ms-I; black), meltwater-rich glacial Ms-II with grounded ice-eroded surfaces (initial, dark blue horizon; subsequent, grey) overlain by a non-glacial interval and regional unconformity (light blue horizon), and polar glacial Ms-III. Proposed drill sites are indicated in red (sites SC-01 to SC-09). (Bottom) Seismic line RAE5108 [profile shown in Fig. 3.19 as orange line (B−B′)]. Suspended sediment supplied by turbidity currents passing down continental rise canyon are entrained by alongslope currents building sediment ridges adjacent to the canyons. These channel levee and drifts provide ideal drilling target to obtain continuous offshore oceanographic records adjacent to the Sabrina Coast, complimenting the less continuous direct ice sheet records from proposed drilling on the continental shelf (see text and Fig. 3.19 for details). *(Top) Modified from Gulick, S.P.S., Shevenell, A.E., Montelli, A., Fernandez, R., Smith, C., Warny, S., et al., 2017. Initiation and long-term instability of the East Antarctic Ice Sheet. Nature 552, 225. (Bottom) From O'Brien, P.E., Post, A.L., Edwards, S., Martin, T., Caburlotto, A., Donda, F., et al., 2020. Continental slope and rise geomorphology seaward of the Totten Glacier, East Antarctica (112°E-122°E). Marine Geology 427, 106−221. Available from: https://doi.org/10.1016/j.margeo.2020.106221.*

landward-dipping unconformity. Diatom data from short sediment cores that penetrated the unconformity indicate diatomites of late Miocene to earliest Pliocene age overly the regional unconformity (Gulick et al., 2017; Montelli et al., 2020). Above the regional unconformity, late Miocene to recent glacial to glaciomarine sediments of variable (≤110 m) thickness are preserved in

Ms-III. Inter-till reflectors suggest glacial variability in the catchment since the late Miocene (Fernandez et al., 2018). However, subglacial meltwater features are absent, suggesting a late Miocene change in ice sheet thermal regime (sub-polar to polar) (Fig. 3.20; Gulick et al., 2017).

A tentative correlation between the shelf and rise seismic sequences (Fig. 3.19; schematic section of the margin, modified from Donda et al., 2020) suggests that the boundary between the pre-glacial and ice sheet growth phases is the seismic horizon WL3. This major erosional unconformity is inferred to be related to the onset of glaciation, thus marking the transition from the greenhouse to the ice-house era. There is evidence that WL3 is Late Eocene in age (Leitchenkov et al., 2015). Based on the tentative shelf-rise correlation, WL3 correlates to the boundary between Ms-I and Ms-II megasequences of Gulick et al. (2017), which has been interpreted as providing the first preserved evidence of grounded ice on the Sabrina Coast shelf in the Late Eocene (ca. 38 Ma).

The progressive increase of the sediment input from the continent as recorded on the continental rise deposits is consistent with the existence of a fluvial-like drainage system possibly related to the nucleation of the EAIS in the Gamburtsev Mountains (DeConto and Pollard, 2003) and the arrival of marine-terminating glaciers near the Sabrina Coast by the Mid-Eocene (Donda et al., 2020; Gulick et al., 2017). Since then, sediments on the continental rise record the widespread occurrence of gravity-driven processes and, in general, the dominance of downslope processes. This change should be related to the growth of a continental-scale ice sheet, similarly to Prydz Bay and western Wilkes Land (Donda et al., 2020). The occurrence of highly fluctuating, warm-based outlet glaciers dynamically responding to climate change (Levy et al., 2019) would have led to sediment delivery from the continent interior to the shelf edge, leading to the formation of turbidity flows down to the slope and rise area. This statement is supported by the findings from Gulick et al. (2017), based upon which Oligocene−Miocene sequences record 11 glacial advances and retreats from the Aurora Subglacial Basin. A remarkable change in the depositional style above unconformity WL7 is represented by a steep prograding wedge on the continental shelf and slope, produced during maximum advances of the ice sheet (Donda et al., 2007 and references therein). Based on a tentative slope-to-rise correlation, WL7 would correspond to the boundary between the Ms-II and Ms-III megasequences of Gulick et al. (2017), the latter being considered the expression of an expanded polar ice sheet that has occupied the Sabrina Coast continental shelf since the late Miocene. Mass-wasting deposits on the continental rise are interpreted to represent the distal record of glacial advance and collapse and slope failures, suggesting the occurrence of a dynamic ice sheet with a well-organised subglacial drainage system. Recurrent outburst flooding events may have occurred here even under polar conditions (Donda et al., 2020 and references therein).

Seismic surveys of the Sabrina Coast shelf were collected by the United States Antarctic Program cruise NBP14-02 (2014) and from the continental slope and rise by the international collaborative project IN2017-V01 (led by Australia, and involving the United States, Italy, Spain; 2017). Other regional seismic profiles collected in previous cruises include Russian, Australian and Japanese multichannel seismic profiles, available through the SDLS.

The Sabrina Coast shelf sequences are proposed as a future IODP drilling target (Proposal 931-Pre) that aims to investigate high-latitude greenhouse warmth, the timing of initial EAIS development, and its subsequent history and sensitivity to past climatic and oceanographic boundary conditions. Drilling targets are anticipated to enable scientists to date the arrival of the first ice to the shelf, constrain the timing of 10 unconformities present in Ms-II, as well as to refine the dating of the regional unconformity. The scientific rationale of proposed future drilling in this frontier region are broad ranging and include:

Investigate how Antarctic terrestrial and proximal marine environments contributed and/or responded to Cretaceous Paleogene greenhouse climate. Eocene strata will provide comparison with other sectors of East Antarctica already obtained for this time period (c.f. Contreras et al., 2014; Pross et al., 2012), but may also capture new records of hyperthermal events, such as the Paleocene/Eocene Thermal Maximum (PETM), which are proposed to have resulted from high-latitude melting of permafrost (DeConto et al., 2012).

Identify the nature of pre-Eocene glaciation. This region is ideally suited to obtain Cretaceous to Paleogene coastal plain sediment derived from the catchment of East Antarctica's Gamburtsev Mountains. This is the region where East Antarctica's ice caps were first thought to nucleate and flow towards the coast, eventually coalescing as continental-scale ice sheets (Bo et al., 2009; DeConto and Pollard, 2003), but the timing of initial terrestrial alpine glaciation remains unknown (Miller et al., 2005, 2020).

Characterise the Paleogene greenhouse to Neogene icehouse transition in East Antarctica. A key objective of future drilling would be to constrain the timing of the first regional marine-terminating glaciers and subsequent ice advance across the shelf (Gulick et al., 2017). Such data, when combined with modelling experiments, can help elucidate if the first marine ice advances out of the ASB were synchronous to, or pre/post-dated, similar advances in the other sectors of Antarctica.

Constrain the frequency and style of Oligocene to late Miocene marine ice sheet and climate variability. This would focus on dating the 10 imaged unconformities in Ms-II to assess their relationship with isotopic or sea level excursions noted in far-field geologic records. Drilling of these sequences would enable assessment of how regional glacial systems responded during warmer-than-present Eocene to Miocene climates (e.g., Middle Eocene Climate Optimum, MECO). Drilling would also help constrain the paleoenvironmental conditions during Miocene shelf progradation, and how this relates to similar shifts in sedimentation around the continental margin (e.g., Prydz Bay and the Ross Sea; Cooper and O'Brien, 2004; Hambrey and McKelvey, 2000; McKay et al., 2009, 2019). This interval is of interest as seismic lines indicate large meltwater drainage systems existed, helping to identify thresholds for surface melt processes around the EAIS margin (Levy et al., 2019; Lewis et al., 2006; Liebrand et al., 2016; Shevenell et al., 2008).

Characterise the Aurora Subglacial Basin (ASB) catchment response to Pliocene warmth. This would complement significantly the records of substantial glacial retreat that occurred in the Wilkes Basin, Lambert and Ross Sea catchments during the warm Pliocene. Notably, the ASB is potentially the last marine-based catchment to deglaciate under scenarios of oceanic warming (Golledge et al., 2017). Therefore geologic evidence for past regional retreat will help identify climatic and oceanic thresholds for marine-based ice sustainability.

Seismic surveys of the Sabrina Coast slope and rise (Fig. 3.20) highlight the potential to obtain Miocene to Pleistocene geologic records to assess oceanic drivers and responses to EAIS variability (Donda et al., 2020; Leitchenkov et al., 2015; O'Brien et al., 2020; Post et al., 2020). Levee deposits on the banks of large channel systems offshore of the Sabrina Coast are proposed as drilling targets. These types of settings were demonstrated during both IODP Expeditions 318 (Escutia et al., 2011a; see Wilkes Land margin discussion in this chapter) and 374 (McKay et al., 2019) to provide high-resolution archives of glacially-influenced sedimentation (McKay et al., 2019; O'Brien et al., 2020; Post et al., 2020) (Fig. 3.20). IODP pre-proposal 1002 was submitted in 2021 to drill sites on the continental rise in this sector, based on a recent Australian RV Investigator cruise which collected piston cores, entitled 'Totten Glacier Climate Vulnerability under varying Neogene climate conditions: lessons for East Antarctica Ice Sheet climate sensitivity' (Table 3.1).

While drilling on the continental shelf requires a mission-specific style drilling platform to capture the critically important direct record of ice sheet variability in this sector of the EAIS, a standalone, but complimentary proposal would use a ship-based drilling system, such as the JOIDES resolution to obtain records from the continental slope/rise. The integration of data from these two continental shelf and slope to rise drilling proposals is essential to fully capture the range of complex ocean-ice-biogeochemical processes that operated in this climatically sensitive region of East Antarctica over the past 66 million years (Adusumilli et al., 2020; Gulick et al., 2017; Rintoul et al., 2016).

3.4.7.4 Wilkes Land margin and Georges V Land

The termini of large Antarctic outlet glaciers draining the Wilkes Subglacial Basin are located along the George V Land and the eastern sector of the Wilkes Land coasts, including Adélie Land (Fig. 3.21). Topographic

TABLE 3.1 List of past drilling projects on the Antarctic continental margin (excluding expeditions to the north of the Antarctic polar front), and proposed expeditions discussed by PRAMSO under various stages of development.

Drilling project	Region	Sites	Year(s) drilled	Age range of primary targets	Initial results reference
Dry Valley Drilling Project (DVDP)	Ross Sea	DVDP 1–15	1972–1975	Late Miocene-Quaternary	McGinnis (1981)
DSDP Leg 28	Ross Sea/Wilkes Land	DSDP 264–274	1973	Oligocene-Quaternary	Hayes et al. (1975)
DSDP Leg 35	Bellinghausen/ Amundsen Sea	DSDP 322–325	1974	Late Oligocene-Quaternary (thin Cretaceous)	Hollister et al. (1976)
MSSTS	Ross Sea	MSSTS-1	1979	Late Oligocene to Early Miocene	Barrett (1986)
CIROS	Ross Sea	CIROS-1,2	1984–1986	Eocene to Quaternary	Barrett (1989)
ODP 113	Weddell Sea	ODP 689–697	1987	Cretaceous to Quaternary	Barker and Kennett (1988)
ODP119	Prydz Bay	ODP 736–746	1987–1988	Cretaceous to Quaternary	Barron and Larsen (1989)
Cape Roberts Project	Ross Sea	CRP-1, CRP-2/2A, CRP-3	1997–1999	Eocene to Miocene, (thin Quaternary)	Barrett et al. (1998, 2000), Fielding et al. (1999)
ODP 178	Bellingshausen Sea/Antarctic Peninsula	1095–1103	1998	Late Miocene-Quaternary (including high-res. Holocene)	Barker et al. (1999)
ODP 188	Prydz Bay	ODP 1165–1167	2000	Late Eocene-Quaternary (snapshot Cretaceous)	O'Brien et al. (2001)

(*Continued*)

TABLE 3.1 (Continued)

Drilling project	Region	Sites	Year(s) drilled	Age range of primary targets	Initial results reference
ANDRILL	Ross Sea	AND-1, AND-2	2006–2007	Early Miocene to Quaternary	Naish et al. (2007), Florindo et al. (2008)
SHALDRIL	Weddell Sea, Antarctic Peninsula	NBP0602A-01 to NBP0602A-12	2005–2006	Late Eocene to Holocene (including high-res. Holocene)	Anderson (2006)
IODP Expedition 318	Wilkes Land	IODP U1355-U1361	2010	Middle Eocene to Holocene (including high-res. Holocene)	Escutia et al. (2011a)
PS104/MeBo	Amundsen Sea	PS104-006, -009, -020, -021, -024, -038, -040, -041, -042	2017	Cretaceous to Holocene	Gohl et al. (2017)
IODP Expedition 374	Ross Sea	IODP U1521–U1525	2018	Early Miocene-Quaternary	McKay et al. (2019)
IODP Expedition 379	Amundsen Sea	IODP U1532–U1533	2019	Late Miocene-Quaternary	Gohl et al. (2021)
IODP Expedition 382	Scotia Sea	IODP U1534–U1538	2019	Late Miocene-Quaternary	Weber et al. (2019)

PROPOSED EXPEDITIONS	Region	Sites	Proposal status	Age Range	Lead proponent(s)
IODP Proposal 732 Full	Bellinghausen Sea/Antarctic Peninsula	Eight primary piston core sites (PEN1–5, BEL1–3)	Approved by IODP – awaiting scheduling	Miocene-Pleistocene	James Channell, Rob Larter
IODP 813 Full (Expedition 373)	Wilkes Land	Sixteen sites (seabed drill) to 80 m penetration	Approved by IODP – awaiting scheduling	Eocene to Pliocene	Trevor Williams, Carlota Escutia
IODP 931-Pre (EAIS evolution)	Sabrina Coast	Six sites (mission-specific platform) to 80 m penetration	Assessed by IODP Science Evaluation Panel – invited to submit full proposal	Paleocene to Quaternary	Amelia Shevenell, Sean Gulick
IODP 1002-Pre-(Totten Glacier Climate Vulnerability)	Sabrina Coast	Five sites using standard ship-based	Submitted to IODP – April 2021	Miocene-Pleistocene	Bradley Opdyke, Federica Donda
IODP Proposal 953-Pre	Australian-Antarctic Rift-Drift	Four sites using standard ship-based	Assessed by IODP Science Evaluation Panel – invited to submit full proposal	Cretaceous to Quaternary	Peter Bijl, Isabel Sauermilch
IODP 998-pre (Ross Sea)	Ross Sea	Four sites using standard ship-based	Submitted to IODP – October 2020	Cretaceous to Early Miocene	Robert Mckay, Laura De Santis
SWAIS-2C	Ross Sea (Siple Coast)	2(+) Sites using custom-designed sub-ice shelf drill	Approved – to be drilled 2021/22	Pliocene to Quaternary	Richard Levy, Molly Patterson
Ekström Ice Shelf	Dronning Maud Land/Weddell Sea	3(+) sites using custom-designed sub-ice shelf drill	Proposal in development	Cretaceous to Early Miocene	Gerhard Kuhn

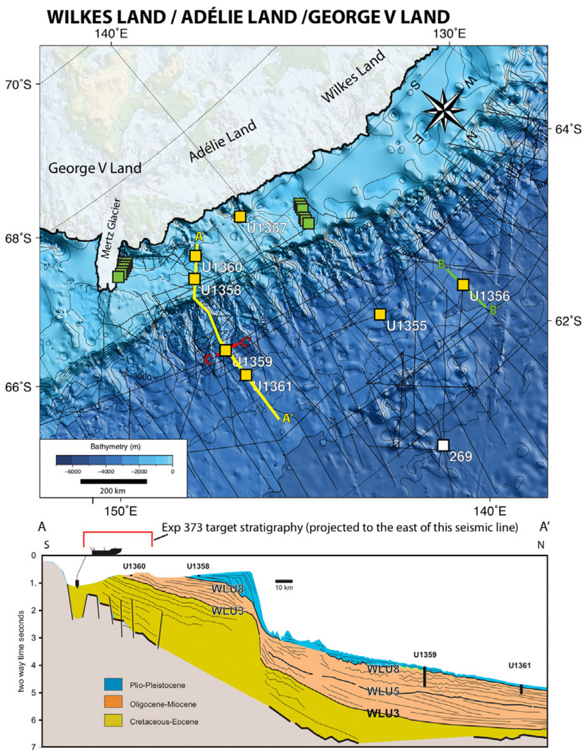

FIGURE 3.21 Overview map of Eastern Wilkes Land sector with existing seismic lines (white lines), drill sites and topographic features mentioned in text.Bathymetry is from Bathymetric Chart of the Southern Ocean (Arndt et al., 2013) and subglacial topography from BedMachine Antarctica dataset (Morlighem et al., 2020). DSDP Leg 28 sites are shown as white squares (site 269), and IODP Expedition 318 sites as yellow squares (sites U1355 to U1361). Future sites (IODP Proposal Full-813/Exp 373) system (discussed in text) are shown as green squares (unlabelled site numbers). These future sites are proposed to be collected via a seafloor drilling system with shallow (~80 m) penetration, and a transect of sites is intended to recover key snapshots of this stratigraphic framework. Seismic tracks are from the SCAR Antarctic Seismic Data Library System (SDLS) and additional survey information. Track lines of the seismic profiles shown in bottom panel and Fig. 3.22 are marked with bold yellow (A−A′), green (B−B′) and red (C−C′) lines, respectively. (Bottom) Wilkes Land seismic stratigraphy showing major unconformities (WLU3−WLU8) and associated shifts in the geometry of sedimentary packages on the continental shelf, location of key IODP Exp 318 sites. Line profile in shown in upper panel, and constructed from seismic lines ATC82-107, GA2904 and GA4201 presented by Escutia et al. (2011a).

reconstructions in this region using satellite radar altimetry and airborne radio-echo sounding surveys show fast flowing glaciers within the Wilkes Subglacial Basin are located at the mouth of deep submarine basins (Ferraccioli et al., 2009; Fretwell et al., 2013; Morlighem et al., 2020; Paxman et al., 2019, 2018) (Fig. 3.2). In these basins, the bed from the periphery of the ice sheet is inland-sloping (Fretwell et al., 2013; Morlighem et al., 2020) suggesting their susceptibility to MISI if warmer Circumpolar Deep Water access the base of the glaciers. Moreover, ice sheet dynamic simulations show the existence of a small ice plug on a ridge at the margin of the Wilkes Subglacial Basin (Mengel and Levermann, 2014). If the ice plug was removed by melting it would contribute less than 80 mm of global sea-level rise but most importantly, it could destabilise the regional ice flow leading to a self-sustained discharge of the entire basin and a global sea-level rise of 3−4 m (Mengel and Levermann, 2014). However, a recent ice sheet model sensitivity test investigating EAIS ice drainage basin responses to atmospheric and oceanic warming, show the Wilkes Land sector is likely to be more sensitive to atmospheric warming than other EAIS basins, and relatively insensitive to ocean warming alone (Golledge et al., 2017). Consequently, determining the past response of this sector to both atmospheric and oceanic change is critical to ground-truth these models and help project the future response of the Wilkes Subglacial Basin drainage basin to future change.

Until 2010, our understanding of past EAIS dynamics in this sector of East Antarctica was based on a regional seismic stratigraphic framework based on the available network of seismic reflection profiles in the area (e.g., see Cooper et al., 2008, and references therein for a review). The Deep Sea Drilling Project (DSDP) Leg 28, intermittently cored Site 269 (4285 m water depth) to a depth of 958 m below sea floor (mbsf) and obtained sediments spanning the Oligocene to recent (Hayes et al., 1975). The cores documented extensive Antarctic glaciation beginning at least by Oligocene to early Miocene times and indicated that water temperatures were cool to temperate in the late Oligocene and early Miocene and then cooled during the Neogene, presumably as glaciation intensified (Hayes et al., 1975). Unfortunately, spot-coring, low recoveries (42%), poor age control and basement highs surrounding the basin where Site 269 lies, causing thinning and/or onlapping of the seismic units, prevented confidently extending the results from coring regionally. It was not until 2010, when IODP Expedition 318 drilled seven sites in a latitudinal transect from the continental shelf to the lower continental rise providing the first robust geological constrains for Cenozoic strata offshore the Wilkes Subglacial Basin (Escutia et al., 2011a). Continental shelf sites targeted strata across seismic unconformities interpreted to contain the record of the transition to a glaciated EAIS, and the grounding line advances and retreats across the continental shelf that followed (e.g., De Santis et al., 2003; Eittreim et al., 1995; Escutia et al., 2005; Tanahashi et al., 1994; Wannesson et al., 1985), in addition to the oceanographic conditions that prevailed with each ice configuration. Continental rise sites targeted levee systems developed on the flank of deep-sea channels, which serve as conduits for turbidity flows and for cascading Adélie Land Bottom Waters, respectively (Bindoff et al., 2000; Close, 2010; Eittreim et al., 1972; Escutia et al., 2000; Fukamachi et al., 2000). Furthermore, along-slope bottom currents had been reported to interact with gravity flows forming contourite ridges or mixed turbidite-contourite levee deposits (e.g., Caburlotto et al., 2010, 2006; Close et al., 2009; Donda et al., 2003; Escutia et al., 2003, 2002). Thus, these levee deposits are ideal targets for high-resolution archives of distal ice sheet dynamics and oceanographic change.

To provide for an account of the stratigraphic control achieved by Expedition 318, we adopt the nomenclature of unconformities and seismic units in the region of drilling by De Santis et al. (2003) and Escutia et al. (2005), with eight major regional unconformities (WL-U1-WL-U8) bounding seismic units WL-S2 to WL-S9 (Fig. 3.22). IODP data were also used for improvement of regional seismic stratigraphy (Leitchenkov et al., 2015). In addition, we refer the reader to previous papers that provide for a detailed description of seismic attributes of the seismic sequences, the processes

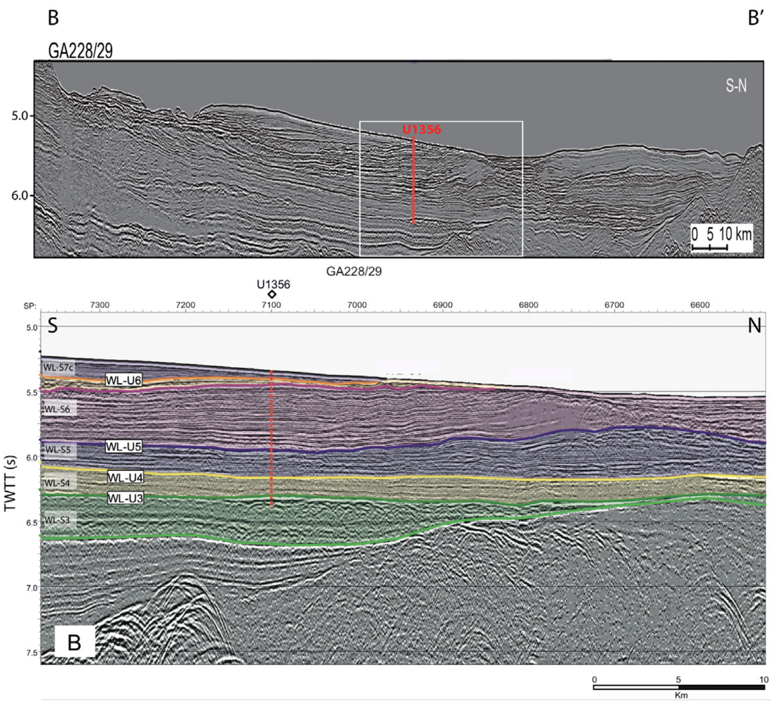

FIGURE 3.22 (Top panel) Uninterpreted seismic profile of line GA228/29 showing the location and the depth reached during drilling of Site U1356. White box shows a detailed seismic line in (Bottom panel) Interpreted seismic profile showing unconformities and seismic units defined in the region of the eastern Wilkes Land and Georges V margins. Seismic line locations are shown in Fig. 3.21. *(B) Modified from Escutia, C., Brinkhuis, H., Klaus, A., 2011a. Cenozoic East Antarctic ice sheet evolution from Wilkes Land margin sediments. Proceedings of the Integrated Ocean Drilling Program 318.*

involved in their development and the inferred record of glaciation before Expedition 318 drilling (e.g., Close et al., 2009; De Santis et al., 2003; Donda et al., 2003; Eittreim et al., 1995; Escutia et al., 2005, 2002, 2000; Tanahashi et al., 1994; Wannesson et al., 1985). Furthermore, a recent paper by Sauermilch et al. (2019) provides a regional comparison between horizons and sedimentary units, with inferred and assigned ages ranging from the Cretaceous to the Miocene, along the whole Wilkes Land and Australian margins.

The oldest sediments drilled during Expedition 318 were recovered from Site U1356 located in the lowermost continental rise (3992 m water depth). The site drilled on the flank of a levee deposit to a depth of 1006.4 mbsf, and recovered sediments below and above unconformity WL-U3 that was reached at 895 mbsf (Escutia et al., 2011a; Tauxe et al., 2012) (Figs. 3.21 and 3.22). Sediments below 1006 mbsf, and their bonding unconformities remain unsampled to date, although drilling at U1356 suggests a late Cretaceous-Paleocene age for much of these strata (Escutia et al., 2014; Leitchenkov et al., 2015). Sauermilch et al. (2019) provide a summary of previous interpretations for these units and, based on correlations between the Antarctic and the Australian margins, infer ages spanning from 83 to 65 Ma in the eastern Wilkes Land and George V Land margins.

The ~100 m of sediments below unconformity WL-U3 recovered from Site U1356 were dated early to middle Eocene (54–46 Ma), providing age and paleoenvironmental constrains for the upper part of seismic unit WL-S3 (Escutia et al., 2011a; Tauxe et al., 2012) (Fig. 3.22). Paleotopographic reconstructions show the Wilkes Subglacial Basin at that time to be occupied by low-lying lands (Paxman et al., 2019, 2018; Wilson and Luyendyk, 2009; Wilson et al., 2012), which based on palynomorph data from Site U1356 were covered by diverse near-tropical forests at least from 54 to 51.9 Ma (Contreras et al., 2014, 2013; Pross et al., 2012). SSTs are estimated to have ranged between 31°C (±2.5°C) and 24°C (±4.0°C), depending on whether a TEX^{H}_{86} or TEX^{L}_{86} calibration is used, respectively (Kim et al., 2010; Schouten et al., 2013). Continental temperatures indicate mean summer air temperatures in the Antarctic coastal regions to be 20°C–23°C (±5.0°C) (Contreras et al., 2013; Peterse et al., 2012; Pross et al., 2012). This record is interrupted by a hiatus spanning from ~52 to 51 Ma (Bijl et al., 2013; Tauxe et al., 2012). Middle Eocene sediments overlying the hiatus record the dominance of a temperate rainforest biome extending into the coastal regions and a decline of around 2°C–4°C in temperature since the early Eocene (Contreras et al., 2013; Pross et al., 2012). This cooling has been attributed to the onset of westward throughflow of the Antarctic Counter Current from the southwest Pacific Ocean into the southern Australo-Antarctic Gulf at ~49–50 Ma, based on the appearance of dominant endemic Antarctic dinocysts on the Wilkes Land Margin from 50 Ma onwards (Bijl et al., 2013). It has been suggested that this throughflow could have been favoured by a gradual drowning of continental blocks in the southern part of the Tasmanian Gateway that resulted in accelerated rifting during the early-to-middle Eocene transition (52–48 Ma) (Bijl et al., 2013; Close et al., 2009; Stagg et al., 2004).

The upper middle Eocene and the late Eocene are conspicuously missing at Site U1356 in a hiatus spanning from ~46 to 33.6 Ma, which is associated with unconformity WL-U3, (Escutia et al., 2011a; Tauxe et al., 2012). Unconformity WL-U3 was previously interpreted as an erosional surface based on reflector truncation and downlap surfaces on the continental shelf (De Santis et al., 2003; Eittreim et al., 1995). The erosion was inferred to be related to the development of the first continental ice sheet at ~34 Ma (e.g., De Santis et al., 2003; Escutia et al., 2005), at ~40 Ma (Eittreim et al., 1995), or to erosion by strong bottom currents related to an increase in seafloor spreading rates and margin subsidence at ~45 Ma (Close et al., 2007). More recently, non-deposition rather than erosion has been proposed as the dominant driver for the formation of WL-U3 based on stratigraphic similarities between the Antarctic and Australian conjugate slopes (Sauermilch et al., 2019).

Despite the distal setting of Site U1356, earliest Oligocene (33.6 Ma) sediments within seismic unit WL-S4 immediately above unconformity WL-U3 unequivocally reflect icehouse environments (Escutia et al., 2011a; Escutia and Brinkhuis, 2014). Among the evidence, the presence of dropstones (up to boulder-sized) in early Oligocene sediments indicates iceberg activity on the margin. A regime shift in zooplankton–phytoplankton interactions and community structure is interpreted as the appearance of eutrophic and seasonally productive environments on the Antarctic margin (Houben et al., 2013). In addition, sediments record a distinct shift from to smectite- and kaolinite-dominated clays below WL-U3, suggestive of chemical weathering under warm and humid climates to illite- and chlorite-dominated assemblages above the unconformity pointing to much colder/drier physical weathering regimes (Escutia et al., 2011a; Passchier et al., 2013). Coeval earliest Oligocene sediments were also recovered from Site U1360, drilled on the continental shelf to a total depth of 70 mbsf (Escutia et al., 2011a; Houben et al., 2013). Although recovery was poor, partly a function of the shallow penetration depth that prevented sufficient weight being placed on the drill bit, sediments recovered from Site U1360 were interpreted as ice-proximal to ice-distal glaciomarine deposits, similar to those from the Oligocene and Miocene strata of the Ross Sea (Kulhanek et al., 2019; Naish et al., 2001; Powell and Cooper, 2002).

These results point to processes related with ice sheet growth, including crustal deformation (i.e., glacial isostatic adjustment, GIA) and gravitational perturbations in addition to tectonic subsidence resulting in a complex spatial pattern of relative sea-level change around the Antarctic margin, as the principal mechanisms in the development of unconformity WL-U3 (Escutia and Brinkhuis, 2014; Stocchi et al., 2013). The continuous presence of reworked middle-late Eocene dinocyst species in the overlying Oligocene sediments (Bijl et al., 2018, 2013; Houben et al., 2013) suggests unabated submarine erosion of the Antarctic shelf as reported by Eittreim et al. (1995), rather than non-deposition (Sauermilch et al., 2019). Eocene material in dredge samples offshore of the Mertz Glacier (Truswell, 1982) support this interpretation.

Sediments recovered from seismic units WL-S4 and WL-S5 are dated to the Oligocene and earliest Miocene (Escutia et al., 2011a; Tauxe et al., 2012) (Fig. 3.22). Dinoflagellate cyst records from Sites U1356 and U1360, combined with those from other locations across the Antarctic margin, suggest an abrupt shift to high seasonal primary productivity associated with the development of seasonal sea ice at Oi-1 times (33.6 Ma, Houben et al., 2013). This is in agreement with numerical climate models simulations indicating that sea-ice formation along Antarctic margins may have followed full-scale Antarctic glaciation (DeConto et al., 2007). However, sea ice−related dinocyst species suggest the occurrence of sea ice near-site U1356 only during the first 1.5 million years (33.6−32.1 Ma) of the Oligocene (Bijl et al., 2013). For the remainder of the Oligocene dinocyst assemblages resemble present-day open-ocean north of the sea-ice edge, with episodic dominance of temperate species similar to those found in the present-day subtropical front (Bijl et al., 2013). The prevalence of oligotrophic and temperate surface waters over the site notably during interglacial times is supported by the presence of carbonate-rich intervals at Site U1356 and Site 269, along with sedimentological and geochemical evidence for considerable latitudinal frontal migrations over the course of Oligocene glacial-interglacial cycles (Bijl et al., 2013; Evangelinos et al., 2020; Salabarnada et al., 2018) that at least during the late Oligocene (within WL-S5) are paced by obliquity (Salabarnada et al., 2018). The oligotrophic, temperate dinocysts and nannofossil remains suggest fundamentally warmer surface water conditions than today. This is supported by SST reconstructions at Site U1356 averaging 17°C albeit highly variable and with estimated temperature differences of 1.5°C−3.1°C between glacials and interglacials cycles (Hartman et al., 2018). The records show a long-term temperature increase towards 30.5 Ma, followed by a minimum around 27 Ma and an optimum around 25 Ma (Hartman et al., 2018).

A thick succession of Mass Transport Deposits (MTDs) with interbedded calcareous, bioturbated and laminated claystones characterise the latest late Oligocene record (24.76−23.23 Ma) at Site U1356 (Escutia et al., 2011a,b). The stacked MTDs succession has been interpreted to record repeated ice sheet advances across the continental shelf during the cooling trend leading to the Mi-1 event glaciation (Escutia and Brinkhuis, 2014; Escutia et al., 2011a). In situ deposits interbedded between the U1356 MTDs indeed record a cooling trend in SST towards the end of the Oligocene, following the climatic optimum at 25 Ma (Hartman et al., 2018). DSDP Site 269 sediments between ~24 and 23.6 Ma provide a window to oceanic conditions at this time characterised by upwelling, high-nutrient waters and TEX_{86}-derived SST between 9°C and 13.5°C (Evangelinos et al., 2020). In addition, two expansions of proto-Circumpolar Deep Water closer to the Wilkes Land margin at ~23.6 and ~23.23 Ma are recorded by higher Ca XRF values, better preservation of calcareous microfossils, higher Br/Ti ratios, high amounts of dinocyst that characterise temperate and oligotrophic waters, and high SSTs (from 11.5°C to 12.9°C) (Evangelinos et al., 2020).

Site U1356 sediments recovered above unconformity WL-U5 and within seismic unit WL-S6 record three important events in the evolution of Earth climates: the Oligocene-Miocene transition at 23.03 Ma, the MCO (17−15 Ma) and the MMCT (14.2−13.8 Ma) (Fig. 3.3). Early Miocene deposits record similar conditions to those described for the end of the Oligocene characterised by a relative lack of ice rafted debris, and temperate pollen assemblages indicative of mean summer on-land temperatures of >10°C (Sangiorgi et al., 2018). The MCO is characterised by inland retreat of the ice sheet and temperate vegetation (Sangiorgi et al., 2018). SST records show that waters were warm (i.e., 11.2°C−16.6°C ±2.8°C calibration error), lacked a strong sea ice component and were relatively low in nutrients compared to today (Sangiorgi et al., 2018). Specifically, dinocyst assemblages resemble those found today in the Pacific sector of the Southern Ocean at around or north of the Subtropical Fronts, where sea-surface

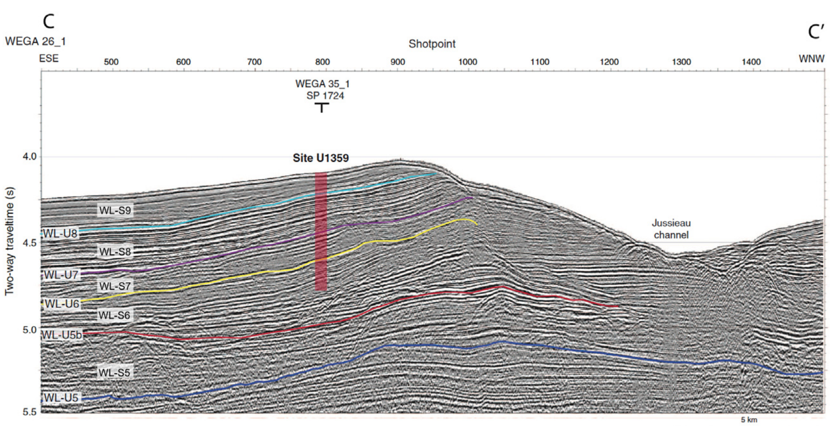

FIGURE 3.23 Seismic line WEGA 26_1 across IODP Site U1359 showing regional unconformities and seismic units defined in the region of the eastern Wilkes Land and Georges V margins. Seismic line locations are shown in Fig. 3.21. *Modified from Escutia, C., Brinkhuis, H., Klaus, A., 2011a. Cenozoic East Antarctic ice sheet evolution from Wilkes Land margin sediments. Proceedings of the Integrated Ocean Drilling Program 318.*

temperatures vary between 8°C and 17°C (Prebble et al., 2013). After the MCO, the MMCT expansion of marine-based ice sheets occurred, recorded by an interval of increased gravel and pebble-sized ice rafted debris after 14.0 to 13.8 Ma (Escutia et al., 2011a; Pierce et al., 2017; Sangiorgi et al., 2018), and dinocyst taxa (i.e., Selenopemphix Antarctica) exclusively known from the present-day seasonal sea ice zone south of the Antarctic Polar Front (Prebble et al., 2013).

Sediments from seismic unit WL-S9 are dated latest-late Miocene to recent (Escutia et al., 2011a; Tauxe et al., 2012) (Fig. 3.23), encompassing the Pliocene and the Pleistocene epochs when the Earth transitioned from having only ice sheets in Antarctica to having ice sheets occupying both polar regions. Sediments recovered from the continental rise at Sites U1359 and U1361 contain a distal record of ice sheet dynamics during Pliocene-Pleistocene glacial and interglacial cycles (Escutia and Brinkhuis, 2014; Escutia et al., 2011a). Iceberg debris accumulation in sediments from Sites U1359 and 1361 provide a record of ice sheet growth and decay that is orbitally paced (Hansen et al., 2015; Patterson et al., 2014). High fidelity spectral analyses in sediments from Site U1361 show that during the warm Pliocene period (4.3 to 3.5 Ma), glacial-interglacial cycles occur with a periodicity of about 40,000 years (i.e., paced by obliquity) with maximum iceberg debris accumulation associated with enhanced calving of icebergs during ice-sheet margin retreat (Patterson et al., 2014). Evidence for repeated retreat of the marine-based EAIS into the Wilkes Subglacial Basin between 5 and 3 Ma is provided by the geochemical provenance of fine-grained detrital material recovered from this deep-water site (Bertram et al., 2018; Cook et al., 2013). Shifts in sediment provenance were paralleled by increases in marine productivity, while the onset of such changes was marked by peaks in ice-rafted debris mass accumulation rates (Bertram et al., 2018). This argues against a switch in sediment delivery between ice streams and instead suggests that deglacial warming triggered increased rates of iceberg calving, followed by inland retreat of the ice margin (Bertram et al., 2018). Early Pliocene ice sheet retreats from the outer continental shelf are also recorded in coeval sediments recovered from Site U1358, indicating repeated times of grounding line migration across the outer continental shelf during past glacials, with interglacial times characterised by open marine conditions with reduced summer sea ice (Orejola and Passchier, 2014; Reinardy et al., 2015).

After 3.3 Ma, the pacing of the glacial-interglacial cycles is in the 100,000-year and 20,000-year frequencies (i.e., eccentricity and precession, respectively) (Patterson et al., 2014). These authors suggest that the Southern Ocean cooled after 3.5 Ma, which is supported by a shift in surface water productivity recorded by a decrease in biogenic opal content at Site U1359 after 3.7 Ma (Khim et al., 2017). As cooling progressed, the development of a perennial sea-ice field limited the oceanic forcing of the EAIS driven by obliquity, leaving atmospheric forcing driven by precession to regulate both sea ice and ice sheet dynamics in this region (Patterson et al., 2014). Despite this shift in orbital pacing, the marine margin of EAIS of Wilkes Land retreated inland from its present-day margin throughout Late Pliocene and Pleistocene interglacials. For example, a temporary southward migration of the Antarctic Polar Front is recorded by the presence of subantarctic diatoms at Site U1361 during marine isotope stage KM3 (3.17–3.15 Ma) (Taylor-Silva and Riesselman, 2018). In addition, marine sedimentological and geochemical records from Site U1361 provide evidence for ice margin retreat in the vicinity of the Wilkes Subglacial Basin Basin during MIS 5 (130–82 ka), MIS 9 (337 ka) and MIS 11 (424 ka) (Jimenez-Espejo et al., 2020; Wilson et al., 2018). At Site U1359, sediments sourced from the east Antarctic Craton and the Ross Orogen are interpreted as an indication for retreats of the East Antarctic ice sheet into the Wilkes Subglacial Basin (Pant et al., 2013). Furthermore, based on studies on the accumulation of ^{234}U in carbonates from inland glacial erratics, Blackburn et al. (2020) suggest that during the warmer and longer MIS11 interglacial, the EAIS grounding line may have retreated about 700 km into the Wilkes Subglacial Basin from the current coastline, which assuming current ice volumes would have contributed about 3–4 m to global sea levels from the Wilkes Subglacial Basin alone. However, inferred higher-than-modern temperatures during the shorter MIS5 and MIS9 interglacial periods did not result in a comparable retreat.

Despite the wealth of information resulting from IODP Expedition 318, it did not recover the 12-Myr interval between 46 Ma, when temperate rainforests covered the coastal areas of Wilkes Land, and 34 Ma, the start of major Antarctic glaciation at the Eocene-Oligocene boundary (e.g., Escutia et al., 2019), an interval when CO_2 fell from approx. 1000 to 600 ppm (Fig. 3.3). The evolution of environments and vegetation during the intervening 12 million years is unknown for mainland Antarctica. This interval is likely to be present in strata on the continental shelf, accessible at shallow drilling depths in tilted and truncated strata, based on the presence of reworked late Eocene sediments at Site U1356, of middle and late Eocene dinocysts in dredged sedimentary rocks from the continental shelf, seismic stratigraphy and lowermost Oligocene sediments cored at Site U1360 (Escutia and Brinkhuis, 2014). Therefore, IODP Expedition 373 (Proposal 813) aims to investigate the development of Antarctic climate over the Eocene, using shallow marine sediment cores from the George V Land shelf. Currently, the most southerly Antarctic Eocene record is from Seymour Island at the northern end of the Antarctic Peninsula; while Eocene data from the Ross Sea are extremely limited (e.g., Galeotti et al., 2016). This mission-specific platform expedition is awaiting rescheduling after initially being planned for early 2018 and intends to use seafloor drill system to obtain a series of shallow drill cores (~80 m deep) (Table 3.1, Fig. 3.21).

IODP Expedition 373 aims to sample a wide range of Antarctic climates, vegetation and paleoceanography between the sub-tropical and glaciated extremes to provide tests for climate models and a better understanding of how greenhouse climates operate (e.g., Baatsen et al., 2020). High-latitude paleotemperatures are warmer than the current generation of climate models can reproduce, implying that models are missing a key mechanism that enhances climate sensitivity and polar amplification across a range of geographies and greenhouse gas concentrations (Huber and Caballero, 2011). In addition to investigating the basic operation of high-latitude greenhouse climates, the proposed drill sites will allow us to examine the following four questions:

1. *What is the relation of Antarctic climate to tectonic opening of the Drake and Tasman ocean gateways?* The possible dates for full Drake passage opening range from 49 Ma to as young as 12 Ma (Dalziel et al., 2013; Scher and Martin, 2006), and Tasman opening has been proposed to be between 50 Ma (Bijl et al., 2013) and 30 Ma (Scher et al., 2015), or close to the E/O boundary itself, 34 Ma.
2. *Were there short-lived glaciations in the late Eocene prior to the main initiation of continent-wide glaciation* (e.g., Scher et al., 2014)? So far, no direct evidence has been found. Such insights are needed to understand the ocean—atmosphere—cryosphere interactions that set the stability threshold for ice on Antarctica.
3. *Do early Eocene sediments hold evidence for the polar permafrost hypothesis for Eocene hyperthermal events* (DeConto et al., 2012), *where vast amounts of carbon are proposed to have been released from Antarctic permafrost?*
4. *What is the nature of the E/O boundary on the George V Land shelf?* Depending on whether or not the sites were situated in a foreland basin caused by glacio-isostatic adjustment, the boundary may be erosive or there may be continuous sediment accumulation. This provides a test of glacio-isostatic adjustment models (e.g., Stocchi et al., 2013) that are critical to understanding solid earth—ice sheet interactions and therefore the potential contribution to sea level change (Whitehouse et al., 2019).

Another high priority for this region is to obtain direct records of early Oligocene to the Pleistocene ice sheet dynamics, paleoclimate and palaeoceanography from the continental shelf region and on-land (i.e., subglacial drilling, cosmogenic nuclide dating of exposed strata). Some sites in Expedition 373 also target Oligocene ice sheet—proximal sediments to understand past ice sheet extent and climate during this time. They can be integrated into coupled ice sheet-climate models for improved projections of sea level change. Alternate sites target younger strata. Younger Neogene records are also critical to relate ice behaviour and ice-proximal ocean configuration to open ocean and paleoclimate conditions recorded in IODP Expedition 318 sediments and other Southern Ocean and lower latitude records. In terms of deeper water sites across the Australian-Antarctic basin, IODP Proposal Pre-953 (Table 3.1) targets the Australian-Antarctic rift-drift transition and development of the ACC. While this pre-proposal aims to reconstruct the early Cenozoic history of the ACC onset and the tectonic separation of Australia and Antarctica, and is therefore largely outside the scope of this chapter on continental margin stratigraphy, one site is proposed on the Antarctic continental rise. This site is intended to reveal the subsidence history conjugate to the Australian margin and will provide a record of sea surface temperature gradients, polar front migrations, and the glacial and terrestrial history of the Wilkes Land margin over the Oligocene to Neogene.

3.5 Summary, future directions and challenges

Since the first edition of this book (Florindo and Siegert, 2008), the SCAR *Past Antarctic Ice Sheet Dynamics* (PAIS) research programme and its two key subcommittees: *Paleoclimate Records from the Antarctic Margin and Southern Ocean* (PRAMSO) and *Palaeotopographic-Palaeobathymetric Reconstructions* have made significant advances in constraining the Antarctic margin stratigraphy and obtaining new paleoclimatic records in order to better understand Antarctica's role in the Earth system since the Cretaceous. Highlights include a total of four completed IODP expeditions (Expeditions 318, 374, 379 and 382) that were explicitly designed to capture direct records of past ice sheet dynamics and ice sheet–ocean interactions. In addition, the scientific results from DSDP, ODP, IODP, MeBo, ANDRILL and SHALDRIL projects published over the past 15 years have revolutionised our understanding of the sensitivity of Antarctica's ice sheets to the warming events and have provided critical benchmarks against which models used to project the future response of the AIS to anthropogenic forcing have been tested (DeConto and Pollard, 2016; Golledge et al., 2015, 2019; Pollard and DeConto, 2009). Three of these IODP expeditions had the explicit aim to extensively sample continental shelf strata, which would have significantly advanced our ability to understand if major shifts in offshore depositional patterns observed in seismic survey data were directly related to continent wide climatic shifts and ice sheet behaviour, or whether these shifts were diachronous and related to regional tectonic and erosional events.

Drilling successes since the initiation of the PRAMSO initiative in 2009 have been abundant, even in the face of difficulties associated with riserless ship-based drilling on Antarctica's continental shelves, which can result in variable core recovery. These difficulties include: (1) poor recovery of rotary coring of unconsolidated Plio-Pleistocene sediments; (2) poor recovery in the upper 50 to 100 m of each hole, until weight on the bit stabilises drilling; and (3) adverse weather and ice conditions resulting in ship heave and site abandonment in the upper 100 mbsf. These three challenges are often associated with each other, as experience from drilling the past 12 years has indicated the greatest challenge relates to weather and ice, which in turn significantly shortens drilling windows and restricts the ability to penetrate to enough depth to drill past into consolidated strata and place sufficient weight on the drill-bit to improve recovery. While IODP Expedition 318 to Wilkes Land drilled three sites on the shelf, recovery was low in the cores targeting sequences to date Cenozoic variability of the ice sheet (although valuable snapshot of the early Oligocene and late Miocene-early Pliocene were recovered in addition to a ~180 m thick Holocene diatom ooze section), due to narrow drilling windows between regular poor weather excursions and ice conditions. More recently IODP Expedition 379 planned to drill numerous sites on the continental shelf, but a poor sea ice season restricted access to this region and only drifts on the lowermost continental rise were cored. However, there remains a need to return to these regions for drilling and, while similar risks will exist in the future, these areas remain high priorities to understand the sensitivity of Antarctica's marine ice sheet in warmer than present climate. Some of these challenges could be overcome by the use of riser drilling (e.g., Mission Specific Platforms), as well as continued development of novel drilling seafloor and sub-ice sheet drilling systems (Escutia et al., 2019; Kennicutt et al., 2016; Mckay et al., 2016). More success was obtained with ship-based drilling in the Ross Sea with IODP Expedition 374, where regular open water conditions and predictable ice conditions allowed for high recovery of Late Miocene and older continental shelf strata. Although diamict lithologies are commonly perceived as the largest issue for drilling recovery in Antarctic, experience from DSDP Leg 28, ODP Leg 119 and IODP Expedition 374 demonstrate this is incorrect. While IODP Expedition 374 indicates that unconsolidated diamict remains difficult to recover (e.g., Plio-Pleistocene strata) from ship-based drill systems, drilling lithified glacial diamicts with a hard mud matrix is much easier as it is homogenous and cohesive, and recovery rates from rotary drilling actually exceed those of many other regions globally.

The challenges of continental shelf drilling of Plio-Pleistocene strata are also offset by the ability to piston core sequences on the continental rise and abyssal plain. In this depositional setting, IODP expeditions 318, 374, 379 and 382, following the pioneering ODP 178 and 188 expeditions, all obtained high-recovery sequences of orbital scale to millennial scale variability of Plio-Pleistocene ice sheet dynamics and oceanic change adjacent to the Antarctica margin. Even in scenarios of low recovery rates, 'snapshot' records from shallow and deep coring the Wilkes Land, Amundsen Sea and Sabrina Coast have provided unique glimpses into Cretaceous to early Cenozoic Antarctic environment from the Antarctic margin.

This review highlights the complexities of tectonic vs climate controls on the climate, ice sheet evolution and stratigraphic architecture of the Antarctic margin. Each sector of Antarctica discussed in the chapter has fundamentally different tectonic histories, including rifting on the Gondwana margin during the Mesozoic in East Antarctica and the Weddell Sea; through to rifting associated with the break-up of Gondwana during the Early Cenozoic in the Amundsen and Ross Sea; and continued rifting into the Miocene and Quaternary persisting in several focussed regions along the Pacific margin of West Antarctica. Despite these differences, first-order similarities in the stratigraphic architecture of the continental shelf are evident, with basin/rift-fill strata (of variable ages) overlain by Early Cenozoic strata that are predominately aggradational, resulting from run-off of fluvial systems into the marine margin that capture depositional records of inland temperate to subtropical coastal climates. By latest Eocene to Early Miocene times, an increased glacial influence is apparent in many offshore records, through the presence of iceberg rafted debris. This glacial influence resulted in a shift towards progradational strata becoming more predominant by the early Miocene in most of the basins around the margin, and is suggested to be the consequence of glacial expansions of highly-erosive polythermal glacial systems characterised by large volumes of turbid meltwater and glaciofluvial discharge.

By the middle to late Miocene times, a shift in glacial thermal regime led to reduced sediment supply from turbid meltwater input and glaciofluvial run-off, but erosion of basin fill sediments continued due to expansion of marine-based ice sheets leading to overdeepening of the continental shelf in many sectors. This resulted in an aggradational deposition pattern on the inner- to middle-continental shelf around much of the margin, accompanied by the development of large prograding fan systems on the continental slope and rise, fed by ice stream sediment transport and deposition processes. During periods of ice sheet retreat, thick hemipelagic drapes on the continental shelf provide unique archives of continental margin climate and oceanographic changes, most notably in the form of Pliocene and Miocene diatom oozes and diatom rich muds from ANDRILL and IODP cores.

New sub-ice shelf drilling campaigns, similar to that used by ANDRILL, are being planned near the modern-day grounding line in the Siple Coast region to assess if complete collapse of the marine-based WAIS occurred during Late Pleistocene interglacials. It is also capable of drilling semicontinuous stratigraphic marine archives of Early Pleistocene, Pliocene (and older climates) from the highest latitudes yet obtained in Antarctica. This will use the next generation of light weight drill systems capable of being deployed in the deep field. The use of rapid-access ice drills to recover shallow cores from beneath grounded ice sheets will likely also be utilised more widely in the future, since airborne geophysical surveys have highlighted several spots where to penetrate thick sediment basins near the Antarctic coast. These sub-ice shelf/ice sheet drill records to constrain past marine-based ice sheet collapse in Plio-Pleistocene signature should be complemented by further drilling of sediment drifts growing on the continental slope/rise near the main route for mass wasting discharge and sediment delivery from the inner shelf to the ocean.

Further offshore, continental rise to abyssal plain record continue to provide continuous records of dynamic ice sheet behaviour through the development of iceberg rafted debris and provenance proxies, while geochemical, sedimentological and palaeontological proxies also provide indications of oceanographic and biological system shifts in the Southern Ocean. These offshore records also provide age control for the continental shelf stratigraphy discussed above, whereby dated shifts in the continental slope/rise stratigraphic architecture and offshore depositional systems (e.g., levee/drift building, channel incision) are tied to changes in the seismic facies and continental shelf stratigraphic architecture. There are still large areas of the continental slope and rise that remain unexplored despite the discovery of the potential high resolution and relatively continuous records that can be obtained from drilling sedimentary mounds accumulating on the continental slope and rise, allowing ice sheet dynamics to be linked with Southern Ocean circulation and global changes. The huge and comprehensive work done by the PAIS Paleo-sea bed and paleotopographic subcommittee represents a milestone in understanding the changes affecting the pan-Antarctic continent across past climatic thresholds. However, this work needs to be refined with further seismic surveys to provide a better constrained and detailed picture of processes, causes and feedbacks, and estimates on the rates of change. Even though grids of seismic data were collected locally (and successfully drilled), most of the WAIS margin has been surveyed only with a few long, seismic profiles, connecting different regions, and some regions of East Antarctica are completely unexplored. It is therefore only indirectly possible in most cases to chronstratigraphically correlate sedimentary sequences and compare processes acting in the different sectors of the Antarctic margin. In addition, only a few seismic transects go across the continental shelf edge to the deep ocean, both in West and East Antarctica. We understand that trough-mouth fans were built in front of major ice streams, but only some of these have been partially surveyed. Slope canyons are rare in Antarctica, but they are the main transfer conduits for Antarctic dense water to the global thermohaline circulation. However, despite their significance, we still know very little about the formation and evolution of these canyons. Moreover, an improved understanding of how water masses are exchanged between the Southern Ocean and the continental shelf is fundamental to assessing the processes the lead to increases in southward ocean heat flux, which may have triggered past ice sheet collapses and warming of terrestrial climates. Therefore, more data are needed to fully understand the processes acting near the shelf edge, to help constrain past changes in ocean–ice sheet interactions.

Most of the East Antarctic continental shelf is still unexplored due to severe sea ice coverage and long distance from scientific stations. A large effort in collecting geophysical and geomorphological data is key to identifying high-resolution paleoclimate and paleoceanographic records that, in turn, will provide valuable boundary conditions and benchmarks for testing climate and ice sheet models used to project future change. As highlighted in the recent 30-year framework for the future of scientific ocean drilling (Koppers and Coggon, 2020), there remains a need to continue drilling on the Antarctic margin in order to ground-truth future climate change in the polar regions, and to fully succeed in this vision we need to continue to improve seismic coverage and drilling from sectors of the ice sheet margin that are understudied. At the same time, improvement of existing, and development of new, technologies for seabed and sub-ice shelf/sheet drilling in remote regions remains an imperative for the community (Kennicutt et al., 2016; Mckay et al., 2016).

The international coordination and multidisciplinary approaches nurtured by the SCAR PAIS program and PRAMSO/Palaeotopographic-Palaeobathymetric Reconstructions subcommittees over the last 10 years has led to a wealth of new data and environmental proxies, allowing a fundamental shift in our understanding of the functioning of natural mechanisms affecting the Antarctic's climate and ice sheets over the Cenozoic. Most of the results collected during completed expeditions, especially the recent deep drilling campaigns in 2018 and 2019, will be published in the next ten years and will be integrated with increasingly more sophisticated and complex modelling experiments. In turn, these will lead to new hypotheses that can tested by future drilling and geological studies on the margin. The success of the coordinated PRAMSO community approach will continue in the frame of the new SCAR program INStabilities and Thresholds in ANTarctica (INSTANT). There are still gaps to be filled in the least accessible sectors of the West and East Antarctic margin, as well as in previously drilled regions of the Ross Sea, Amundsen, Wilkes Land and Antarctic Peninsula. The regional differences in the tectonic, ice sheet and climate histories discussed in this chapter highlight that wide spatial and temporal coverage will to be key to understanding the full complexity of past ice sheet dynamics and their relevance for estimates of future rates of change driven by anthropogenic climate change. The collection of these new geomorphological, seismic and drilling data will be challenging and will require innovative approaches but will open a new and exciting phase of Antarctic research.

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