Progressive Cenozoic cooling and the demise of Antarctica's last refugium

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The Antarctic Peninsula is considered to be the last region of Antarctica to have been fully glaciated as a result of Cenozoic climatic cooling. As such, it was likely the last refugium for plants and animals that had inhabited the continent since it separated from the Gondwana supercontinent. Drill cores and seismic data acquired during two cruises (SHALDRIL I and II) in the northernmost Peninsula region yield a record that, when combined with existing data, indicates progressive cooling and associated changes in terrestrial vegetation over the course of the past 37 million years. Mountain glaciation began in the latest Eocene (approximately 37–34 Ma), contemporaneous with glaciation elsewhere on the continent and a reduction in atmospheric CO_2 concentrations. This climate cooling was accompanied by a decrease in diversity of the angiosperm-dominated vegetation that inhabited the northern peninsula during the Eocene. A mosaic of southern beech and conifer-dominated woodlands and tundra continued to occupy the region during the Oligocene (approximately 34–23 Ma). By the middle Miocene (approximately 16–11.6 Ma), localized pockets of limited tundra still existed at least until 12.8 Ma. The transition from temperate, alpine glaciation to a dynamic, polythermal ice sheet took place during the middle Miocene. The northernmost Peninsula was overridden by an ice sheet in the early Pliocene (approximately 5.3–3.6 Ma). The long cooling history of the peninsula is consistent with the extended timescales of tectonic evolution of the Antarctic margin, involving the opening of ocean passageways and associated establishment of circumpolar circulation.

cryosphere | paleoclimate | plant evolution | polar biota | climate change

The marine oxygen isotopic record suggests abrupt cooling and growth of a large Antarctic ice sheet in the latest Eocene (*ca.* 34 Ma) (1), coincident with an abrupt decrease in atmospheric CO_2 concentrations across the Eocene–Oligocene transition (2, 3). Onshore and offshore geological data indicate that development and expansion of a West Antarctic ice sheet occurred mainly in the Miocene (4), after CO_2 concentrations reached approximately their current levels (3). Since the late Miocene, the Antarctic ice sheets have repeatedly advanced beyond their current limits onto the continental shelf, the frequency of ice sheet advance and retreat having increased during the Pliocene and Pleistocene (5, 6).

The cause of the progressive development of the Antarctic cryosphere through the Cenozoic is a matter of vigorous debate (7). Both thermal isolation of the continent (8) and a decline in atmospheric CO_2 (9) are viable mechanisms for inducing long-term cooling in the Antarctic region. Testing these hypotheses, however, requires detailed knowledge of Antarctic climate history, in combination with well-dated constraints on both the tectonic evolution of the Southern Ocean and CO_2 variation. At the present time, the record of Antarctic climate change through the Cenozoic remains highly fragmented. The Antarctic Peninsula (AP) region, in particular, lacks continuous sedimentary sequences of latest Eocene and younger age, which has masked the record of climate cooling, as well as the associated record of plant and animal evolution. Here we report results of a seismic stratigraphic investigation and drill core analyses resulting from the Shallow Drilling on the Antarctic Continental Shelf (SHALDRIL) project in the northernmost AP (Fig. 1) and address the following questions. What was the timing of climate deterioration in the AP and when did the region become fully glaciated? How did the demise of the climate impact vegetation on the continent? What does the paleoclimate record tell us about the factors that controlled climate change in the past?

The concept behind SHALDRIL was to sample ancient marine strata in areas where sea ice and icebergs might otherwise prevent extended drilling operations. This includes most of the Antarctic continental shelf where ship-based drilling operations are typically restricted to a few days at best. Selection of drill sites was based on detailed seismic stratigraphic analyses to determine where dipping strata of targeted ages come to the surface and within reach of shallow drilling. Condensed stratigraphic intervals, which represent periods of reduced sedimentation, were targeted because they yield the longest geological records within the thinnest core intervals and because they are most likely to yield microfossils for biostratigraphic and paleoenvironmental analyses.

Seismic data collected during four separate cruises were used to select drilling targets within the sedimentary strata that occur on the northwestern continental shelf of the Weddell Sea and on the southern flank of the Joinville Plateau (Figs. 1 and 2). Although the drill cores acquired during SHALDRIL recovered only segments of the stratigraphic section, they sampled condensed stratigraphic intervals representing important time windows in the record, including the late Eocene, late Oligocene, middle Miocene, early Pliocene and Pleistocene, with age constraints based mainly on diatom biostratigraphy (Fig. S1 and Table S1). Sedimentological analyses of these cores included lithologic descriptions, multisensor core logging, grain-size ana-

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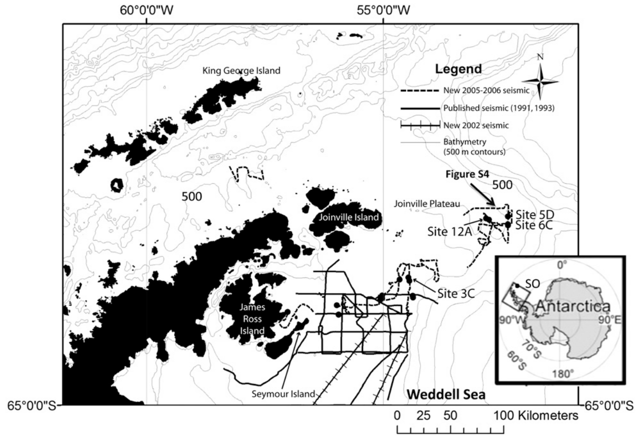


Fig. 1. Northern Antarctic Peninsula showing seismic lines used for selection of SHALDRIL sites and drilling locations (dots), excluding fjord sites that targeted Holocene deposits. Drill sites with hole numbers sampled pre-Pleistocene strata. Inset shows location of map. Depth contour interval is 500 meters. SO = South Orkney Islands.

lysis, pebble count and fabric analysis, clay mineralogy, grain shape analysis, and scanning electron microscopic analysis of sand grain surface textures (Figs. S2 and S3 and Tables S2 and S3). Given the depth of the cores and their distance from land, we assume that sand size material is transported to the sites by icebergs. This is supported by grain-size data, which shows little evidence for sorting (Fig. 3). Therefore, changes in grain shape (roughness) and the relative abundance of glacial (high stress) microtextures are assumed to reflect changes in degree of glaciation.

Both terrestrial and marine palynomorphs were analyzed (Table S4). An absence of calcareous foraminifera in the Oligocene and younger part of the section precluded isotopic analyses. The combined seismic stratigraphic and drillcore data resulting from the SHALDRIL project provide a record of climate change, glacial history, and associated changes in continental and marine flora.

The oldest strata targeted during SHALDRIL are located at Site 3 in the northwestern Weddell Sea (Fig. 1). They are composed of a condensed stratigraphic section associated with a prominent unconformity that extends along the entire northwestern rim of the basin (6) (Fig. 2*B*). Earlier seismic stratigraphic work showed that strata sampled at Site 3 rest above this surface and postdate the Eocene deposits of the La Meseta Formation on Seymour Island (10). Sediments of late Eocene age were sampled in Hole 3C, based on diatom biostratigraphy (approximately 37–34 Ma; Fig. S1).

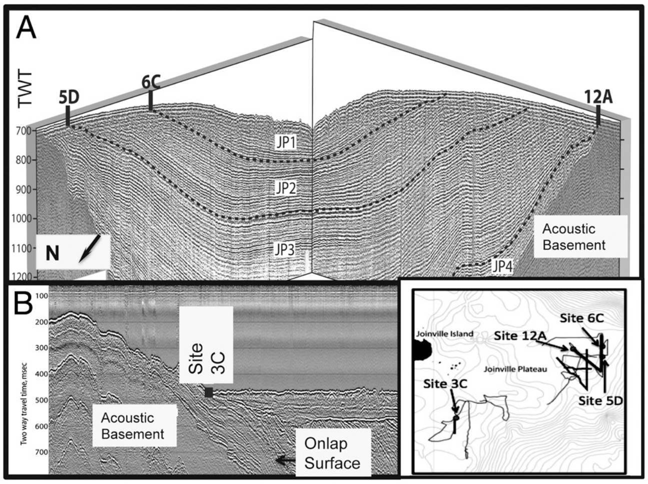


Fig. 2. (*A*) Seismic sections across the Joinville platform and slope showing main stratigraphic units (JP1, JP2, JP3, and JP4) and stratigraphic intervals sampled by SHALDRIL sites 5D, 6C, and 12A. (*B*) Seismic profile showing location of SHALDRIL Site 3C. Insert map shows seismic line and drill site locations.

The sediments recovered in Hole 3C are composed of very dark, greenish gray, muddy fine sand with some burrowing (Fig. S2). The clay mineral assemblage has lower illite and higher kaolinite concentrations than the assemblages in cores from the other sites where younger strata were sampled (Table S2). The kaolinite is most likely reworked from older sedimentary strata in the area, such as those cropping out on Seymour Island (11). The increase in chlorite concentrations from 10–20% within the upper part of Hole 3C may indicate an intensification of physical weathering caused by cooling. Rare iceberg transported pebbles, primarily well-cemented sandstones, reflect limited ice rafting from localized sources. This is consistent with high grain angularity and glacial surface features on individual sand grains and contrasts with a lack of ice-rafted pebbles and lower occurence of glacial surface textures in sediments of the slightly older uppermost La Meseta Formation on Seymour Island (Figs. 1 and 3 and Fig. S3).

The marine palynomorph assemblage from Hole 3C is dominated by one species of dinoflagellate cyst, *Vozzhennikovia apertura*, indicating cooler, less hospitable sea-surface temperatures than those that prevailed during the deposition of the La Meseta Formation. Yet, periods of ice-free surface water were necessary to allow this planktonic algae to bloom. The terrestrial palynomorphs indicate that the adjacent landmass was dominated by species of southern beech in the late Eocene, including up to ten different species of the *Nothofagidites fusca* group. The second most abundant group is composed of various podocarp conifer pollen, plus Araucariaceae. (Fig. 3 and Table S4). There are also rare Proteaceae and other angiosperm pollen, such as Liliaciaceae (or similar types), Restionaceae, Poaceae, Caryophyllaceae, and Chenopodiaceae. This flora indicates cooler conditions than those recorded by pollen from the older Middle Eocene part of La Meseta Formation on Seymour Island. The Seymour Island assemblages are more diverse and include plants such as Sapindaceae, Olacaceae, members of the *Nothofagidites brassii*-group, as well as more diverse Proteaceae and ferns (12), a relatively "warm" climate association indicating at least frost-free zones in sheltered areas. Analysis of fossil leaf assemblages suggests a markedly seasonal climate on Seymour Island during the Middle Eocene, with a mean annual temperature of $10.8 \pm 1.1\,^{\circ}\mathrm{C}$, a warm month mean of $24 \pm 2.7\,^{\circ}\mathrm{C}$, a cold month mean of $-1.17 \pm 2.7\,^{\circ}\mathrm{C}$, and 1,534 mm annual rainfall (13). In contrast, the late Eocene pollen assemblages from Hole 3C indicate that the local vegetation grew in harsher conditions, similar to those in colder forested parts below the tree line in modern southern Chile and southwestern New Zealand today.

The combined results from Hole 3C imply the presence of alpine and even tidewater glaciers in the AP during the late Eocene. This interpretation may be supported by the occurrence of middle Eocene (alpine?) glacial deposits on King George Island in the South Shetland Islands (14), although equivalent age deposits on Seymour Island show no evidence for glaciation at that time (15).

The other SHALDRIL sites used in this investigation were drilled on the flanks of the Joinville Plateau, located at the northernmost tip of the AP (Fig. 1). The seismic records from the area show an acoustically laminated, seaward dipping sedimentary succession (Fig. 2*A*). The section is subdivided into four seismic units (JP4—JP1), based on angular relationships between these units or with acoustic basement and where three or more reflections converge toward the edge of the basin (condensed sections). Overall, there is little change in acoustic facies and unit thickness, which is indicative of sedimentation in a ramp setting influenced by contour currents. This interpretation is consistent with prior studies from the northwestern Weddell Sea region that have

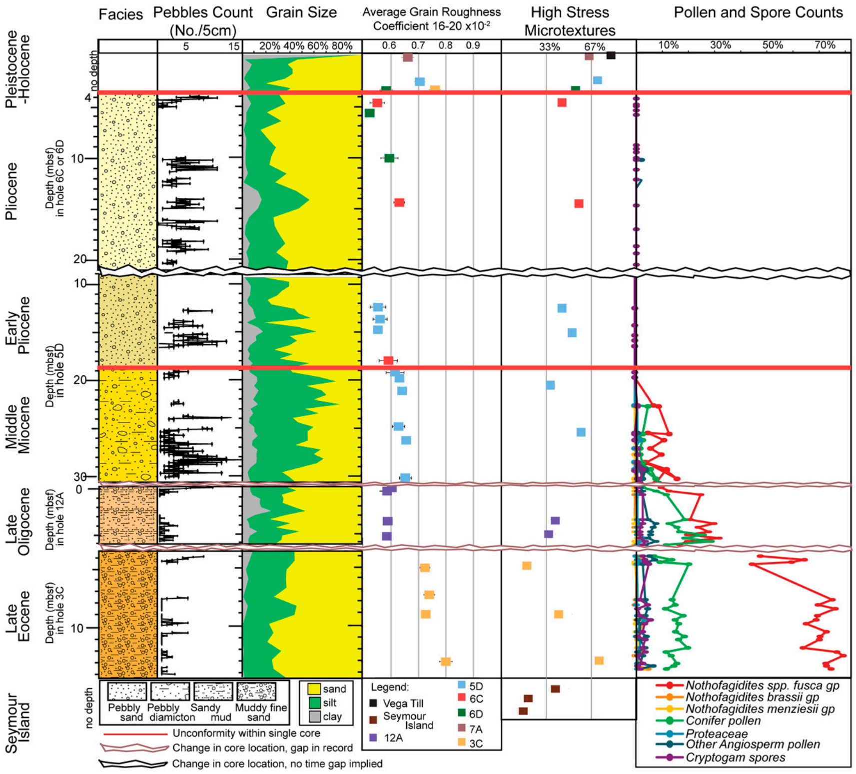


Fig. 3. Summary of main sedimentological proxies used to reconstruct the climatic evolution of the northernmost Antarctic Peninsula and associated changes in vegetation in the Cenozoic. The palynomorph relative abundance diagram displays changes in composition and abundances of the main groups of terrestrial palynomorphs. In the Palynomorph Counts column, everything to the right of the listed pollen and spore curves is reworked pollen and spores. The grain surface texture column is an average occurrence of glacially transported grains on a relative scale of zero abundance (0%), low abundance (<33%), medium abundance (33–67%) and high abundance (67–100%), which is based on actual counts of features normalized to 100%. See *SI Appendix* for methods used to measure and display grain size, grain roughness, and grain microtextures.

argued for sedimentological influence by contour currents associated with the cyclonic motion of the Weddell Gyre (16, 17).

The lower part of the Joinville Plateau section (Seismic Unit JP4) was targeted at Site 12, which is characterized by strong overlap of reflections with acoustic basement (Fig. 2*A*). Hole 12A was dated as late Oligocene in age (between 28.4 and 23.3 Ma) by diatom and calcareous nannofossil biostratigraphy and strontium isotope dating (Fig. S1 and Table S1). The sediments recovered at this site consist of dark gray sandy mud with some clay lenses and many burrows, likely representing a shallow marine setting (Fig. S2). High concentrations of illite and chlorite within the clay fraction indicate intense physical weathering in the source area, probably under a colder climatic regime than that of the Eocene section recovered at Site 3 (Table S2). There is marked increase in ice-rafted sand grains relative to Core 3C, but a marked decrease in grain roughness and slight decrease in glacial surface textures on individual sand grains. This implies combined influence of glacial and nonglacial sediment transport (Fig. 3).

The terrestrial palynomorph assemblage from Hole 12A, which is dominated by recycled specimens, is of lower diversity than the late Eocene assemblage sampled in Hole 3C (Fig. 3 and Table S4). It is mainly composed of species of beech (*Nothofagidites* spp., *fusca* group) and podocarpaceous conifer pollen, with rare Proteaceae and other angiosperms, plus mosses. Overall, this flora suggests a colder climate than the Eocene assemblage in Hole 3C, yet with temperatures higher than the alpine tree line limit (approximately 10 °C warm month mean). In situ organic-walled marine algae recovered from this interval are very sparse and their signal is diluted by recycled specimens. The in situ flora, however, is predominantly composed of leiospheres and acanthomorph acritarchs and clearly indicates a colder marine environment than that of the late Eocene. The prominence in leiospheres, in particular, may indicate the presence of sea ice, because these forms are typical of assemblages found today at the limit between seasonal and pack ice in the Arctic (18). Thus, both terrestrial and marine palynomorph assemblages indicate that the Oligocene was a time of significant climate deterioration in the AP region relative to the late Eocene. The sedimentological data indicate occurrence of glaciers, but continued sediment transport by nonglacial processes.

The results from Hole 12A are largely consistent with those from Ocean Drilling Program Leg 113, which drilled sites in the Weddell Sea and on the flanks of the South Orkney Plateau. Those sites record a significant transition from relatively warm conditions of the late Eocene to colder conditions during the Oligocene (19). They are also consistent with results from a study of fossil plant remains on King George Island in the South Shetland Islands, which indicate progressive cooling during the Oligocene (20). Oligocene glacial deposits occur in the South Shetland Islands (21) and possibly on Seymour Island (22), although the age of the Seymour Island deposits has been questioned (23). Seismic data show no evidence of glacial expansion onto the AP continental shelf during the Oligocene (4, 6).

The condensed interval separating seismic units JP3 and JP2 on the Joinville Plateau was targeted at SHALDRIL Site 5 (Fig. 2*A*), and the sediments recovered in the lower section of Hole 5D are interpreted as middle Miocene in age based on diatom biostratigraphy (approximately 12.8–11.7 Ma; Fig. S1 and Table S1). The middle Miocene sediments from this site include a gray unsorted mixture of clay, silt, sand and gravel (diamicton) with no burrowing (Fig. 3 and Fig. S2). The overall concentration and diversity of pebbles suggest ice rafting from distant sources. The clay mineral assemblage of Hole 5D shows no major difference to that of Hole 12A (Table S2). However, further cooling would not have resulted in a different clay mineral composition as long as physical weathering conditions prevailed in the source area. There is an increase in silt, grain roughness and glacial surface textures in the middle section of Hole 5D relative to the Oligocene deposits recovered in Hole 12A (Fig. 3). Together, these data indicate more severe glacial conditions relative to the Oligocene.

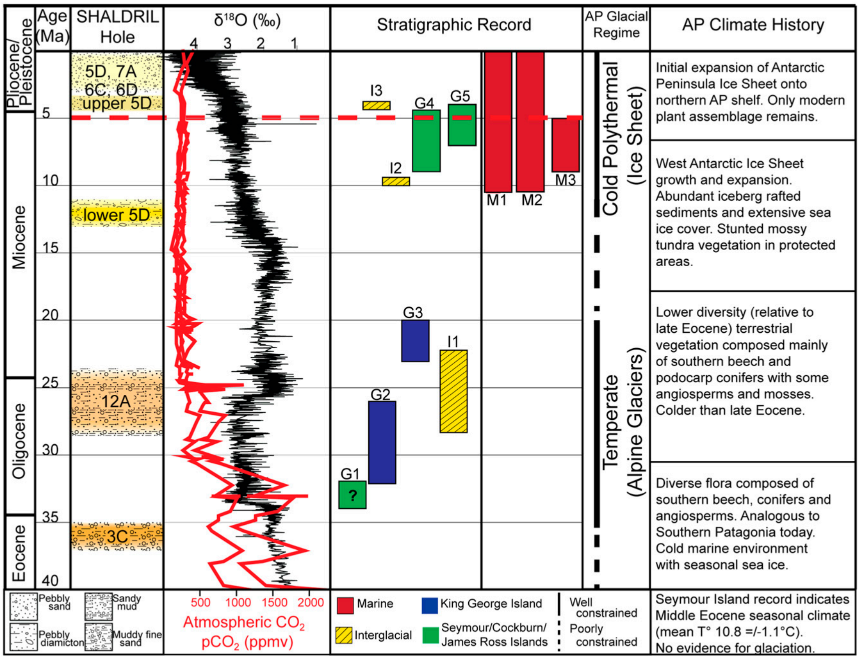
Sediments from the middle Miocene section of Hole 5D contain a mixture of terrestrial palynomorphs, mainly recycled, with a sparse penecontemporaneous assemblage of *Nothofagidites* spp. (*fusca* gp.) and a few podocarpaceous conifer pollen, along with tundra taxa (identified as such in Ross Sea assemblages) (24, 25, 26), such as Caryophyllaceae (*Colobanthus*-type) and Poaceae (grasses), plants that grow today on the Antarctic Peninsula, plus moss species (Fig. 3 and Table S4). The concentrations of *Nothofagidites* and *Podocarpidites* pollen are not nearly as high as those recovered during the Mid Miocene Climatic Optimum (approximately 15.7 Ma) recorded in the Ross Sea (26), but the similarities in assemblage indicate that the climate must have included intervals of warmer austral summer temperatures (10 °C warm month mean) in protected areas to allow flowering of these alpine species. Radiometric ages of volcanic tephra associated with pristinely preserved plant remains from the Dry Valleys (Transantarctic Mountains, East Antarctica) show the last vestiges of tundra life in that region disappeared earlier, prior to 13.85 Ma (25). Hence, the last areas of tundra on Antarctica existed in the peninsula region. It is likely that these plants mostly had a low shrubby to ground-hugging habit in these more extreme conditions. Marine palynomorphs in Hole 5D mostly show predominance in sea-ice-indicative species such as sphaeromorph and acanthomorph acritarchs (Table S4).

The combined sedimentological and palynological results from SHALDRIL Holes 12A and 5D indicate a major climatic deterioration of the AP region between the late Oligocene and late middle Miocene, with a much greater degree of glacial influence indicated by proxy evidence from Hole 5D. Site 5 is located in an area known as "iceberg alley" where abundant icebergs calved from the Ronne-Filchner Ice Shelf, which drains the West Antarctic Ice Sheet, drift northward in their journey out of the Weddell Sea. The presence of exotic pebbles in the middle Miocene sediments of Hole 5D provides supporting evidence for the expansion of the West Antarctic Ice Sheet onto the continental shelf of the southern Weddell Sea at this time (6).

Strata of late Miocene age were not sampled as part of the SHALDRIL project; however, late Miocene glacial deposits do occur on Seymour Island (23) and on James Ross Island (27–29). The extent of these glaciations has remained uncertain, but seismic records from the continental shelves on the western and eastern sides of the AP imaged glacial unconformities that are interpreted to be of late Miocene age (6, 30, 31).

Seismic data acquired during SHALDRIL imaged a prominent unconformity that extends across the Joinville Plateau, where it cuts deeply into the stratigraphic section (Fig. S4). The unconformity was penetrated at SHALDRIL Hole 5D (Fig. 2*A*), where early Pliocene deposits overly middle Miocene deposits. The early Pliocene section sampled in Holes 5D and 6C consists of dark greenish gray sandy units with only minor clay and abundant ice-rafted pebbles of variable lithology (Fig. S2). Holes 6C and 6D sampled deposits with large concentrations of smectite relative to older sediments from the area, indicating a higher proportion of volcanic rocks in the source area of the sediments (Table S2). These sediments are marked by a medium abundance of grains with glacial surface textures and by low grain roughness indicating mixed transport modes (Fig. 3). These sediments are interpreted to represent a current-influenced deposit with abundant iceberg-rafted material from distant sources. These results are consistent with those from a well-dated ($^{87}Sr/^{86}Sr$ and $^{40}Ar/^{39}Ar$) succession of interbedded volcanic and glacial deposits on James Ross Island that has yielded a record of glacial-interglacial oscillations since approximately 6.2 Ma (27–29).

Sand grains from Pleistocene sediments in the upper part of Hole 5D exhibit more abundant glacial surface textures relative to older strata and there is a marked increase in grain roughness (Fig. 3). Samples from all Pliocene and Pleistocene sections were



Initial expansion of Antarctic Peninsula Ice Sheet onto northern AP shelf. Only modern plant assemblage remains.

West Antarctic Ice Sheet growth and expansion. Abundant iceberg rafted sediments and extensive sea ice cover. Stunted mossy tundra vegetation in protected areas.

Lower diversity (relative to late Eocene) terrestrial vegetation composed mainly of southern beech and podocarp conifers with some angiosperms and mosses. Colder than late Eocene.

Diverse flora composed of southern beech, conifers and angiosperms. Analogous to Southern Patagonia today. Cold marine environment with seasonal sea ice.

Seymour Island record indicates Middle Eocene seasonal climate (mean T° 10.8 =/-1.1°C). No evidence for glaciation.

Fig. 4. Summary of climate evolution in the Antarctic Peninsula from prior work and results from this study. Oxygen isotope record from Zachos et al. (1) and pCO_2 compilation from Zachos et al. (33). The areas between the two red lines shows the range of uncertainty for the alkenone and boron proxies used to measure pCO_2. Other sources as follows: Glaciations—G1? (22), G2 (21), G3 (15, 21, 32), G4 (15, 23), G5 (27–29); Interglacials—I1 (15), I2 (23), I3 (27–29); Marine ice sheet advance and retreat—M1 (30, 31), M2 (6), M3 (5). See text for discussion. Bold dashed red line indicates initial grounding of the Antarctic Peninsula Ice Sheet on the Joinville Plateau.

found to be barren of penecontemporaneous palynomorphs, except for the occurrence of a few specimens of Chenopodiaceae (goosefoot family, probably low weedy forms) that may be in situ (Table S4). Nevertheless, this evidence indicates an absence of any significant land vegetation during the Pliocene and Pleistocene.

Given the limited sampling of the thick stratigraphic successions that exist in the study area, short-term oscillations in climate are not captured by the SHALDRIL records, so it is not possible to determine how these events affected the Antarctic Peninsula. However, the six stratigraphic intervals sampled during SHALDRIL, when combined with existing data from the region, indicate progressive cooling and cryosphere evolution since the late Eocene (Fig. 4). Sea-surface cooling in the late Eocene, evidenced by a nearly monospecific dinoflagellate cyst assemblage, coincides with a dramatic change in the land vegetation that had inhabited the Peninsula prior to approximately 37 Ma (13). By the late Oligocene, continued cooling resulted in a significant reduction in plant species and the onset of a tundra landscape, with limited woodland vegetation. The middle Miocene was a time of widespread glaciation and existence of sea ice during winter months, but no marine ice sheet was present in the northernmost part of the peninsula. The last remnant of vegetation on Antarctica existed in the peninsula region; a tundra landscape persisted until at least 12.8 Ma and was extinguished no later than 5.3 Ma. The late Miocene was not sampled, but is known to have been a time of growth and expansion of the Antarctic Peninsula Ice Sheet (5, 6, 23, 27–31) (Fig. 4). The culminating step in the AP climate demise was the initial advance of the ice sheet onto the northernmost continental shelf in the early Pliocene.

Whereas changing atmospheric CO_2 concentrations undoubtedly contributed to the abrupt cooling that occurred across the Eocene/Oligocene transition (2, 33), continued cooling and glacial expansion in the AP region is best explained by gradual development of ocean passages, extended isolation of the continent, and development and expansion of the Circum Antarctic Current. The formation of a complete circum-Antarctic passage has been a continuous process spanning the past 50 million years (Table S5).

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