

# 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> (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<sub>2</sub> 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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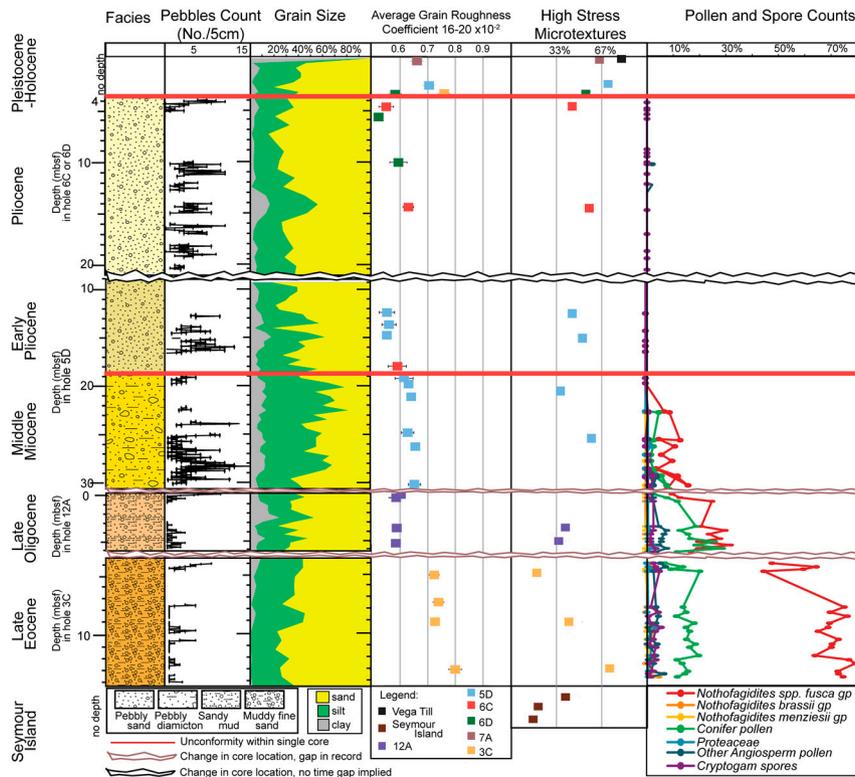
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**Fig. 3.** Summary of main sedimentological proxies used to reconstruct the climatic evolution of the northernmost Antarctic Peninsula and associated changes in vegetation in the Cenozoic. The palynomorph relative abundance diagram displays changes 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. 24). 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. 24), 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 (diamiction) 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



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<sub>2</sub> 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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