

Drilling Reveals Climatic Consequences of Tasmanian Gateway Opening

PAGES 253, 258-259

One of the great stories of geoscience is how Gondwana broke up and the other southern continents drifted northward from Antarctica, which led to major changes in global climate.

The recent drilling of Ocean Drilling Project (ODP) Leg 189 addressed in detail what happened as Australia drifted away from Antarctica and the Tasmanian Gateway opened. The drifting contributed to the change in global climate, from relatively warm early Cenozoic "greenhouse" conditions to late Cenozoic "ice-house" conditions. It isolated Antarctica from warm gyral surface currents from the north and provided the critical deepwater conduits that eventually led to ocean conveyor circulation between the Atlantic and Pacific Oceans.

Leg 189 continuously cored sediments on foundered continental blocks (Figure 1) between Australia and Antarctica. The cores cover the early slow separation of Australia and Antarctica (70-43 Ma), the later fast separation while a land bridge still existed (43-37 Ma), the initial current breakthrough south of the South Tasman Rise (37-33.5 Ma), and Australia's independent fast movement northward thereafter.

Early Deep Sea Drilling Project (DSDP) drilling of the Tasmanian Gateway provided a basic framework of paleoenvironmental changes associated with the opening. Kennett et al. [1975] proposed that climatic cooling and an Antarctic ice sheet developed as the Antarctic Circumpolar Current (ACC) progressively isolated Antarctica thermally. Its onset coincided with the onset of global cooling near the Eocene-Oligocene boundary at ~33.5 Ma [Kennett, 1977; Miller et al., 1987].

Leg 189 cores reflect the evolution of a tightly integrated and dynamically-evolving system that involves lithosphere, hydrosphere, atmosphere, cryosphere, and biosphere. The relatively shallow water depths throughout the Cenozoic make this one of the few places where almost complete marine sequences, containing well-preserved skeletons of calcareous plankton, could be cored in the Southern Ocean. Dating of the cores depends largely on

calcareous and siliceous plankton and dinocysts. Environmental interpretation depends on such plankton, benthic foraminifers, dinocysts, spores and pollen, and the

sediments in which they are entombed. Exon et al. [2001] fully document the early results and the conclusions drawn from them.

Drilling

The drill sites were at 65-70°S until 33.5 Ma, and are on continental blocks that formed the Tasmanian land bridge until then. The bridge essentially closed the eastern end of the widening Australo-Antarctic Gulf (AAG). Later, the sites drifted northward with Australia to their present latitudes of 42-48°S. The

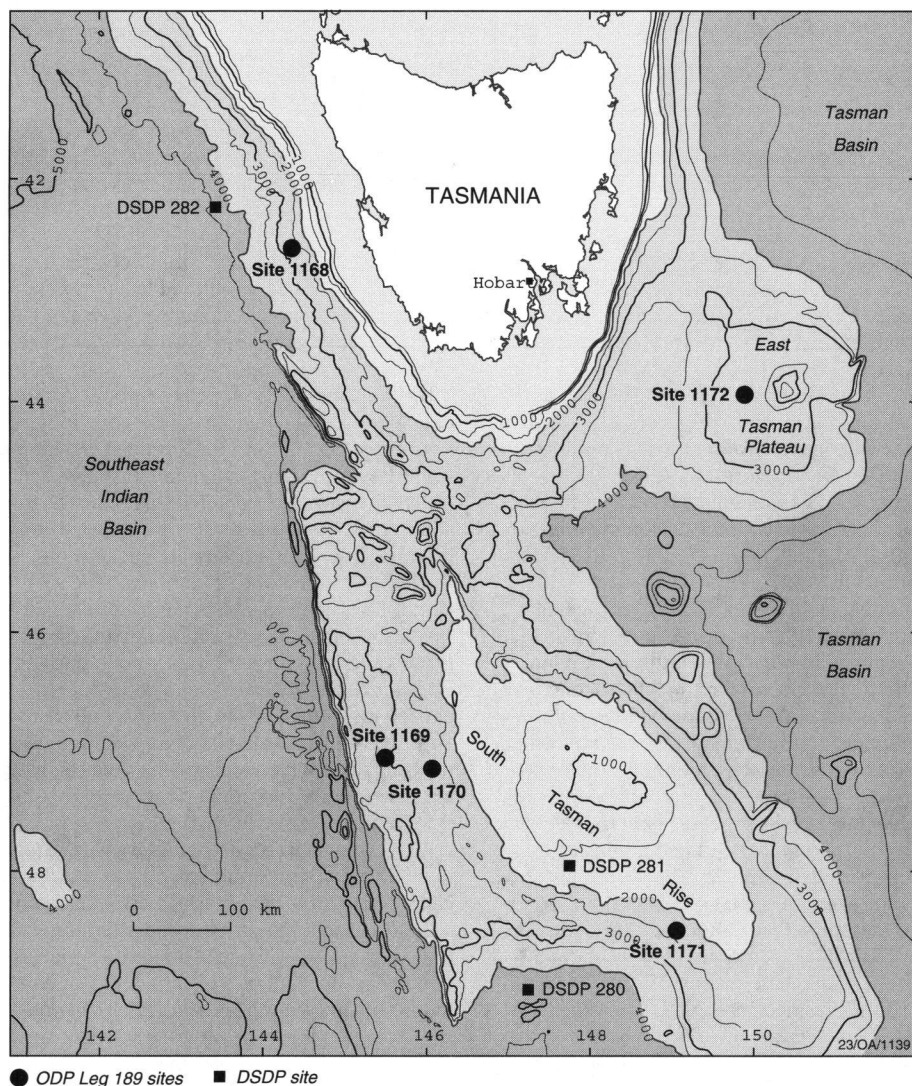


Fig. 1. Extensive swath-bathymetry was used to map the region offshore Tasmania. Leg 189 sites are solid circles and Deep Sea Drilling Project sites are solid squares. Contours are in meters.

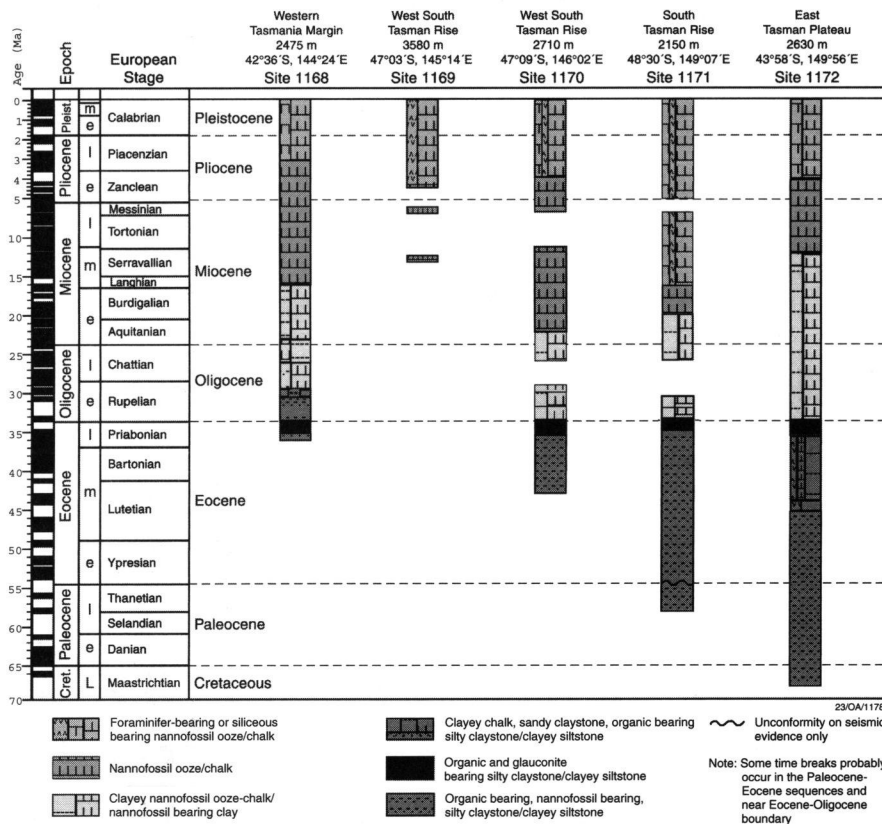


Fig. 2. This summary describes sediments deposited through time for all sites drilled during Leg 189, arranged from west (left) to east (right). Original color image appears at the back of this volume.

sedimentary sequence is entirely marine, with major terrigenous siliciclastic input until the earliest Oligocene (Figure 2), and it contains a wealth of micro-fossil assemblages that record conditions from the Late Cretaceous (70 Ma) until now. Drilling recovered 4539 m of core at five drill sites in water depths of 2475–3579 m, and core recovery was generally good despite Southern Ocean storms.

The broad geological history of all five sites was comparable, with deposition of terrigenous muds in shallow marine deltas until 37 Ma, glauconitic terrigenous silts on a subsiding continental shelf until 33.5 Ma, and pelagic calcareous clays and oozes in deep water thereafter (Figure 2). When the Tasmanian Gateway first opened in the late Eocene, easterly flowing currents winnowed the bottom sediments on the shallow blocks and formed condensed sequences. Although sedimentation was continuous for long periods, appreciable time breaks probably exist in the deltaic and shelf sediments and certainly exist in the deepwater sediments at most sites.

Three sites were west of the Tasmanian land bridge until the latest Eocene, and hence in the AAG: Site 1168 on the west Tasmanian margin, and Sites 1169 and 1170 on the western South Tasman Rise (STR). The other two sites were always in the Pacific Ocean and were separated from the AAG by the Tasmanian land bridge until the Oligocene. In Site 1171 on the southernmost STR, time breaks in the Oligocene and the late Miocene can be

related to the ACC, which broke through nearby. Site 1172, on the East Tasman Plateau (ETP) and farther from the ACC, recovered an almost-complete stratigraphic section from the Late Cretaceous onward.

Two transitional sequences of global significance were fully cored, the Cretaceous-Tertiary boundary (65 Ma) and the Eocene-Oligocene boundary (33.5 Ma); and detailed study is underway. Site 1172 contains ODP's most southerly Cretaceous-Tertiary boundary. The boundary lies immediately above a 60-cm-thick sandy mudstone of high magnetic susceptibility in a thick, massive gray mudstone of latest Cretaceous age. The sandy mudstone is presumed to represent debris related to the Yucatan Peninsula asteroid impact, which caused the demise of the dinosaurs and many other creatures. About 40 cm above the magnetically susceptible sequence, the core changes to brown, highly bioturbated mudstone of earliest Cenozoic age.

The Eocene-Oligocene boundary was cored in all four deep sites and has no paleontologically recognizable time break across it, although a depositional break may well exist in the three eastern sites. There is an upward transition over a few meters from gray late Eocene mudstones to greenish latest Eocene glauconitic siltstones, and finally to white early Oligocene chalks. The Eocene terrigenous sediments were laid down in water depths increasing from 100 m to 500 m, and under strengthening easterly flowing currents, as the Tasmanian

land bridge separated from Antarctica. Oligocene chalks were deposited in rapidly deepening water as the region subsided to water depths exceeding 1000 m and was cut off from terrigenous sediment sources.

Tectonics Drove the Changes

The tectonic separation of the Tasmanian region from Antarctica after 33.5 Ma, and its drift northward to its present latitude, allowed the ACC to form. This isolated Antarctica from warm northern water, and an ice cap formed.

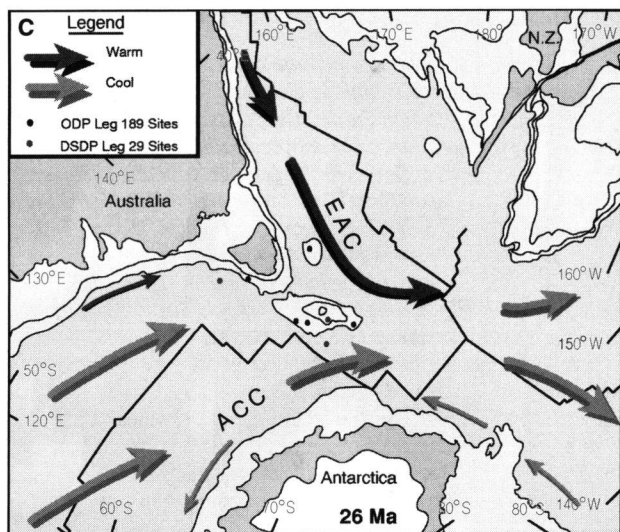
Three important Cenozoic tectonic events can now be identified by combining Leg 189 results with other geophysical and geological data: Paleocene strike-slip movement on the southeast STR, which was ended at 55 Ma by seafloor spreading to the south; Eocene continental strike-slip movement along the western boundary between STR and Antarctica, which terminated in the latest Eocene around 34 Ma; and early Oligocene collapse of the continental margin around Tasmania after 33.5 Ma. Early Oligocene subsidence and collapse also occurred in the Victoria Land Basin east of the rising Transantarctic Mountains [*Cape Roberts Science Team*, 2000] and along the coast of southeast Australia.

Sedimentation rates depended on local tectonics, which helped control distance from on-land sources, and also on sedimentation, patterns, bypassing, and current erosion. Apatite fission track dating [O'Sullivan and Kohn, 1997] suggests tectonic uplift and erosion in west and east Tasmania during the late Paleocene to early Eocene. On the west Tasmanian margin, Site 1168 received sediment continuously from Tasmania, and sedimentation rates were moderate and fairly constant, with little change as terrigenous sedimentation gave way to dominantly carbonate sedimentation at 33.5 Ma. On STR, Sites 1170 and 1171 were part of the tectonically-active borderland between Antarctica and Australia in the Paleocene and Eocene, but they were isolated from major land masses thereafter, with the local hinterland sinking and diminishing in size. Thus, sedimentation was relatively fast during terrigenous deposition in the late Eocene and slow thereafter. On the isolated ETP, sedimentation at Site 1172 was generally slow from the Maastrichtian onward for both terrigenous and carbonate sedimentation, suggesting that the terrigenous source was always relatively small or distant.

The onset of fast spreading at 43 Ma led to increased subsidence, and by the late Eocene all the sites were swept by the developing ACC and sedimentation rates were low. Final separation of the STR and Antarctica was associated with more rapid subsidence, full current flow of the ACC, and slow pelagic carbonate deposition.

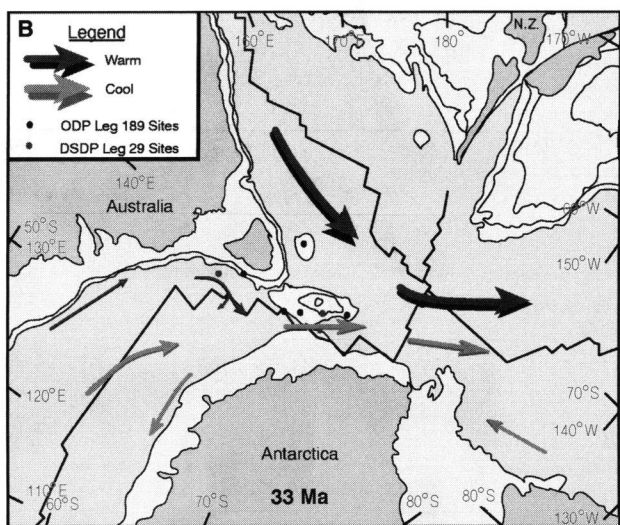
Paleoenvironments before the Gateway Opened (70–37 Ma)

From the latest Cretaceous until the late Eocene, as illustrated in Figure 3a, Australia was joined to Antarctica with the long, narrow,



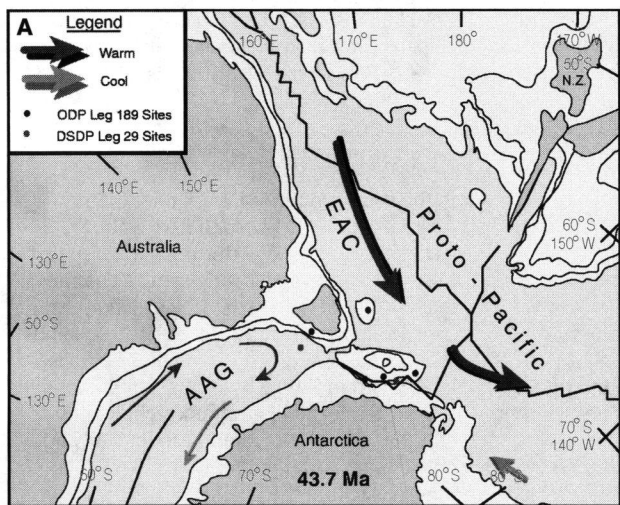
Drifting

- Fast spreading continues
- TLB subsiding rapidly
- Pelagic carbonates on TLB
- AAG not restricted
- Southern Ocean developing
- Deep AAG-PP connection
- EAC not to Antarctica
- ACC in full flow
- TOC in existence
- Antarctic glaciation



Separation

- Fast spreading continues
- TLB subsiding rapidly
- Glaucinitic silts on TLB
- AAG restricted
- Shallow AAP-PP connection
- EAC not to Antarctica
- ACC develops soon after
- Global cooling soon after
- TOC soon after
- Onset of Antarctic glaciation



Rifting

- Fast spreading starts
- TLB in place
- Shallow marine muds on TLB
- AAG very restricted
- No AAG-PP connection
- EAC warms Antarctic
- No TOC

23/OA/1262

Fig. 3. As Australia and Antarctica separated, changes through time led to Antarctic glaciation and thermohaline oceanic circulation. AAG = Australo-Antarctic Gulf; ACC = Antarctic Circumpolar Current; EAC = Eastern Australian Current; PP = Proto-Pacific Ocean; TLB = Tasmanian Land Bridge; and TOC = thermohaline oceanic circulation. Original color image appears at the back of this volume.

and shallow AAG separated from the proto-Pacific Ocean by a land bridge. A warm current bathed eastern Australia and Antarctica,

and a weak, warm current circulated in the AAG. Marine siliciclastic sediments, largely silty clays, were deposited in a warm sea on

broad, shallow, tranquil shelves. Sediment supply to deltas kept up with the rapid subsidence related to rifting, with average depositional rates of 5–10 cm/ky.

Marine calcareous and siliceous microfossils were preserved only sporadically in the generally poorly-oxygenated sediments, but dinocysts, spores, and pollen were always preserved. The spores and pollen show that this part of Antarctica was relatively warm with little ice throughout this time, and it supported temperate rain forests with southern beeches and ferns—part of the “greenhouse” world. Differences in the mudstones indicate that the eastern AAG was more poorly ventilated than the gradually widening Tasman Sea with its western boundary current, the East Australian Current (EAC). There were also differences from north to south related to distance from the opening gateway and from major land masses.

Paleoenvironments as the Gateway Opened (37–33.5 Ma)

In the late Eocene (37–33.5 Ma), as illustrated in Figure 3b, fast sea-floor spreading was moving Australia rapidly northward away from Antarctica. The AAG was widening and deepening, and the Tasmanian land bridge and its broad shelves started to subside. Warm, shallow currents no longer reached the Antarctic margin, and cool shallow currents penetrated the newly-formed Tasmanian Gateway from the west and started to circulate around Antarctica, providing positive feedback for further cooling. These currents swept the still-shallow offshore areas so that clays were no longer deposited, and glauconitic silts were deposited very slowly as condensed sequences (<1 cm/ky). Palynological and other evidence suggests that considerable fluctuations in temperature were superimposed on general cooling, and the amount of upwelling also fluctuated. Calcareous microfossils are rare, but diatoms and foraminifers indicate that there was minor deepening in the latest Eocene at some sites.

The most conspicuous changes of the entire 70-million-year history of this region occurred over the Eocene-Oligocene transition, when Australia and Antarctica finally separated. The changes were from warm to cool climate; from shallow to deep water deposition; from poorly-ventilated basins to well-ventilated open sea; from dark siliciclastic to light pelagic carbonate deposition; from micro-fossil assemblages dominated by dinoflagellates to those dominated by calcareous pelagic microfossils; and from organic-rich to organic-poor sedimentation.

Paleoenvironments after Separation (33.5 Ma Onwards)

From the early Oligocene onwards, everything changed. As illustrated in Figure 3c, Australia was separating rapidly from Antarctica, with open ocean between. Warm currents from the tropics were completely cut off from some parts of Antarctica by the developing ACC,

now with both shallow and deep circulation, leading to global cooling and some formation of ice sheets. However, the warm EAC, and warm waters flowing down the western Australian margin and into the Southern Ocean, kept the Tasmanian region relatively warm, resulting in carbonate deposition rather than the deposition of siliceous diatoms that marks much of the Antarctic margin.

In the cores from the offshore Tasmanian region, and even in the Cape Adare region on the conjugate Antarctic margin [Hayes *et al.*, 1975], there is no sign of early Oligocene glaciation despite the presence of mountain glaciers on Tasmania. Although the cores contain no evidence of land vegetation, plant material may have been deposited and then oxidized. Despite the northward movement of the Tasmanian region, the micro-fossils and clay minerals indicate that the Oligocene and Neogene were cooler than the Eocene. Much of the land bridge had subsided beneath the ocean, so there was a smaller hinterland to supply sediment. Furthermore, the colder ocean provided less moisture, decreasing precipitation and erosion. As a result, far less siliciclastic sediment was eroded and transported from the land, and generally slow deposition of deep-water pelagic sediments (~1 cm/ky) set in on the starved Antarctic and Tasmanian margins.

The Tasmanian Gateway continued to open, strengthening and widening the ACC, and further isolating Antarctica from warm water. Ice sheets like the present sheets covered East Antarctica from about 15 Ma [Kennett, 1977]. This intensified global cooling and thermohaline circulation, and the "icehouse" world had arrived. However, temperatures and current activity fluctuated, and dissolution and erosion varied over time. The movement of the Tasmanian region northward kept it north of the oceanic Polar Front, and pelagic carbonate continued to accumulate slowly in deep waters. In the late Neogene, Australia was progressively moving into the drier mid-latitudes. Along with global climate change

associated with ice sheet expansion in high latitudes, this led to massive aridity on Australia, and in some Leg 189 sequences there is a concomitant increase in dust blown from Australia after 5 Ma.

Future Studies

Work is continuing apace on the material from Leg 189 to build on the early results recorded in Exon *et al.* [2001]. Comparisons with sequences drilled elsewhere on the Antarctic margin—for example, ODP Leg 188 in Prydz Bay [O'Brien *et al.*, 2001; Cape Roberts Science Team, 2000]—will further improve our understanding of momentous changes in the Earth's history and some of the constraints on modern climates. Post-cruise studies and comparisons will better define and explain regional similarities and differences in tectonism, sedimentation, and climate. Initial studies of physical properties, wireline logs, and micro-fossils all show that climatic cycles of varying length are present throughout the entire sequence, and the ongoing studies will better define Milankovitch and other cycles. In the Neogene pelagic carbonates, the excellent preservation and high depositional rates will allow detailed isotope studies to determine surface and bottom water temperatures through time. We can now build unique Southern Ocean correlations between various micro-fossil groups: calcareous nannofossils, planktonic foraminifers, diatoms and radiolarians, and dinocysts, spores, and pollen.

Acknowledgments

This research used samples and data provided by the Ocean Drilling Program, which is sponsored by the U.S. National Science Foundation (NSF) and participating countries under the management of Joint Oceanographic Institutions (JOI) Incorporated. Funding for this research was provided by U.S. and international agencies.

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Combined Technologies Allow Rapid Analysis of Glacier Changes

PAGES 253, 260–261

Monitoring of glacier changes plays an important role within the Global Climate Observing System (GCOS) [Haerberli *et al.*, 2000], and Landsat imagery has proven to be a useful tool for monitoring glacier changes over large and remote areas [Aniya *et al.*, 1996; Li *et al.*, 1998]. An accurate glacier map can be obtained by simple segmentation of a ratio image from Thematic Mapper (TM) channels 4 and 5 [Bayr *et al.*, 1994; Jacobs *et al.*, 1997; Paul, 2002]. Individual glaciers were recently derived within a Geographic Information System (GIS) using a vector layer with glacier basin boundaries.

Glacier changes were calculated and visualized by processing sequential images within a fully automated work flow.

This method was originally developed for the new Swiss Glacier Inventory 2000 (SGI 2000), which used a high-resolution digital elevation model (DEM) for ortho-rectification and retrieval of glacier parameters, and a digitized glacier inventory from 1973 for delineation of glacier basins [Paul *et al.*, in press, 2002]. In many glacierized regions of the world that lack information about glacier extent or changes, neither a high-resolution DEM nor a digitized glacier inventory is accessible. This study presents the possibilities of glacier change documentation

in the southern part of the Tyrolean Alps, Austria, without using such information.

Digital overlay of TM-derived glacier maps from 1985 and 1999 clearly exhibit changes that could not be revealed by in-situ measurements of length changes at the glacier terminus. While small glaciers often suffer a decrease in area around the whole perimeter, glaciers larger than 5 km² also shrank significantly after becoming separated from formerly adjacent streams or an increasing area of rock outcrops within the glacier.

Image Selection

With the TM4/TM5 ratio image method, all debris-free glacier ice, as well as snow, is classified as "glacier" and, as a consequence, snow fields adjacent to a glacier would hide the real glacier perimeter. Thus, the most important task for glacier studies with Landsat TM and other optical sensors is to find a

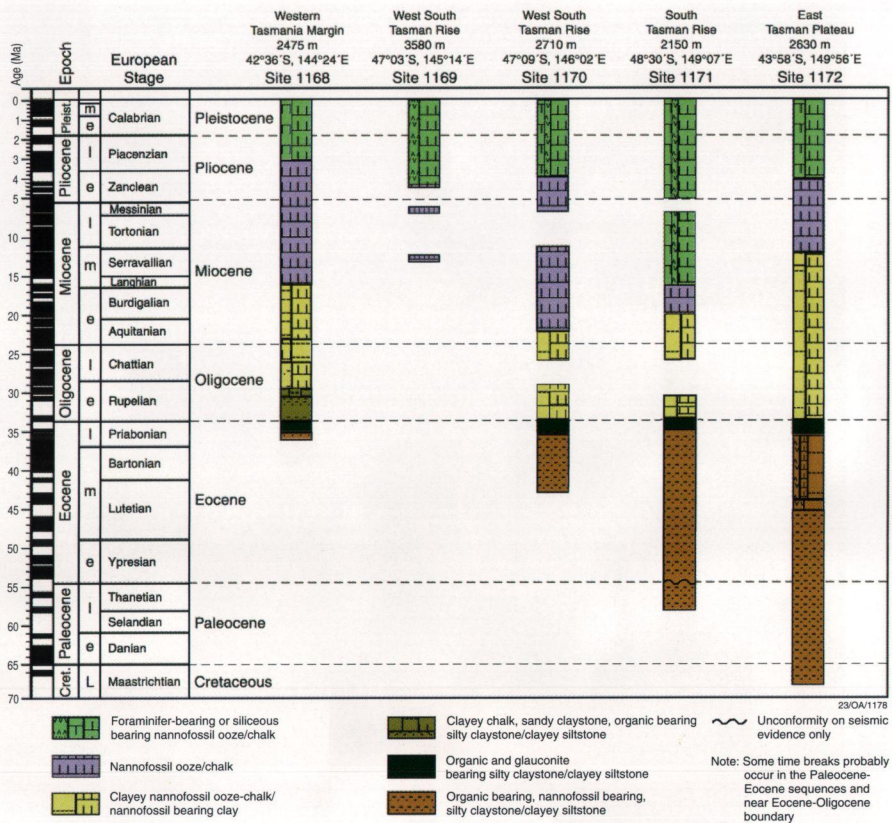
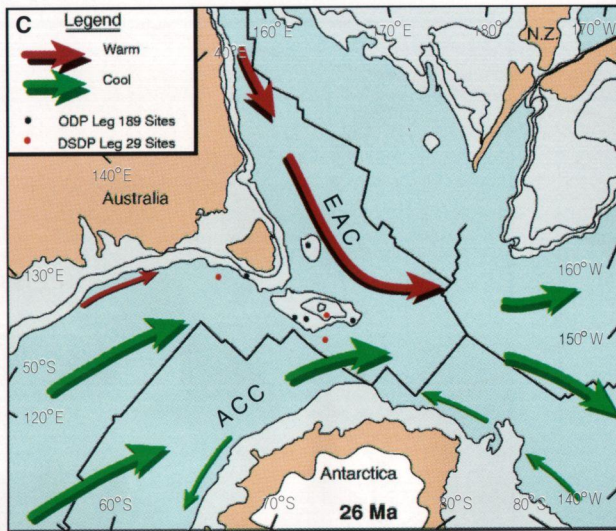
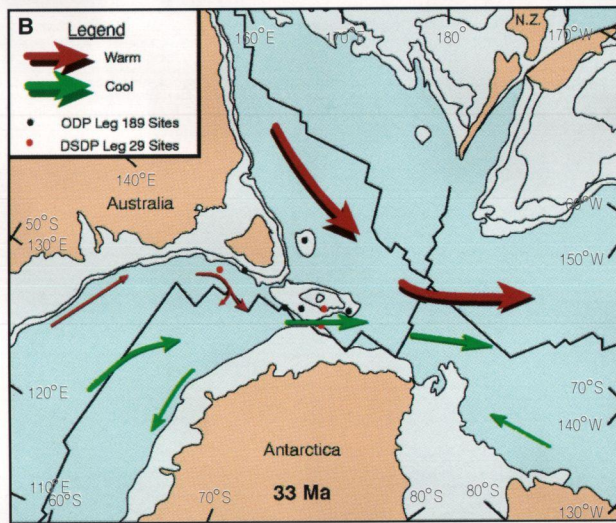


Fig. 2. This summary describes sediments deposited through time for all sites drilled during Leg 189, arranged from west (left) to east (right).



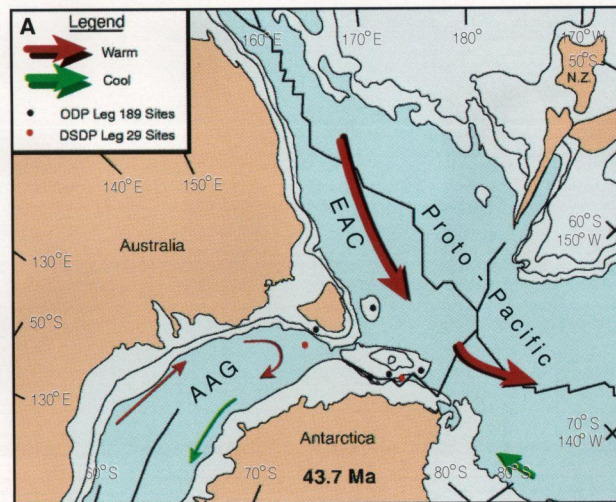
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- TLB subsiding rapidly
- Pelagic carbonates on TLB
- AAG not restricted
- Southern Ocean developing
- Deep AAG-PP connection
- EAC not to Antarctica
- ACC in full flow
- TOC in existence
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