

The Opening of the Tasmanian Gateway Drove Global Cenozoic Paleoclimatic and Paleoceanographic Changes: Results of Leg 189

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The major ice sheets of the Cenozoic Era are unusual in geological history. Progressive cooling at high latitudes during the Cenozoic eventually formed major ice sheets, initially on Antarctica and later in the Northern Hemisphere. In the early 1970s it was proposed that climate cooled and an Antarctic ice sheet (cryosphere) developed as the Antarctic Circumpolar Current (ACC) progressively isolated Antarctica thermally (Kennett et al., 1975). This current resulted initially from the opening of the Tasmanian Gateway, and the history of this opening was the main focus of ODP Leg 189. Early ocean drilling in the Tasmanian Gateway between Australia and Antarctica (Deep Sea Drilling Project Leg 29; Kennett, Houtz et al., 1975) provided a basic framework of paleoenvironmental changes associated with the opening, but was of insufficient quality and resolution to fully test the potential interrelationships of plate tectonics, circum-polar circulation and global climate. Until now, the timing of events has remained inadequately constrained.

The opening of the Tasmanian Gateway in the latest Eocene and the only other important ACC constriction, the Drake Passage, in the earliest Neogene (Fig. 1), had enormous consequences for

global climate. These consequences came by isolating Antarctica from warm gyral surface circulation of the Southern Hemisphere oceans, and also by providing the conduits that eventually led to ocean conveyor circulation between the Atlantic and Pacific Oceans. Both factors, in conjunction with positive feedbacks and other changes in the global system, have been crucial in the development of the polar cryosphere, initially in Antarc-

tica in the Paleogene and early Neogene, and later in the Northern Hemisphere in the late Neogene (Shackleton and Opdyke, 1977; Ruddiman et al., 1989). Furthermore, the continued expansion of the Southern Ocean during the Cenozoic because of the northward flight of Australia from Antarctica, has clearly led to further evolution of the Earth's environmental system and of oceanic biogeographic patterns.

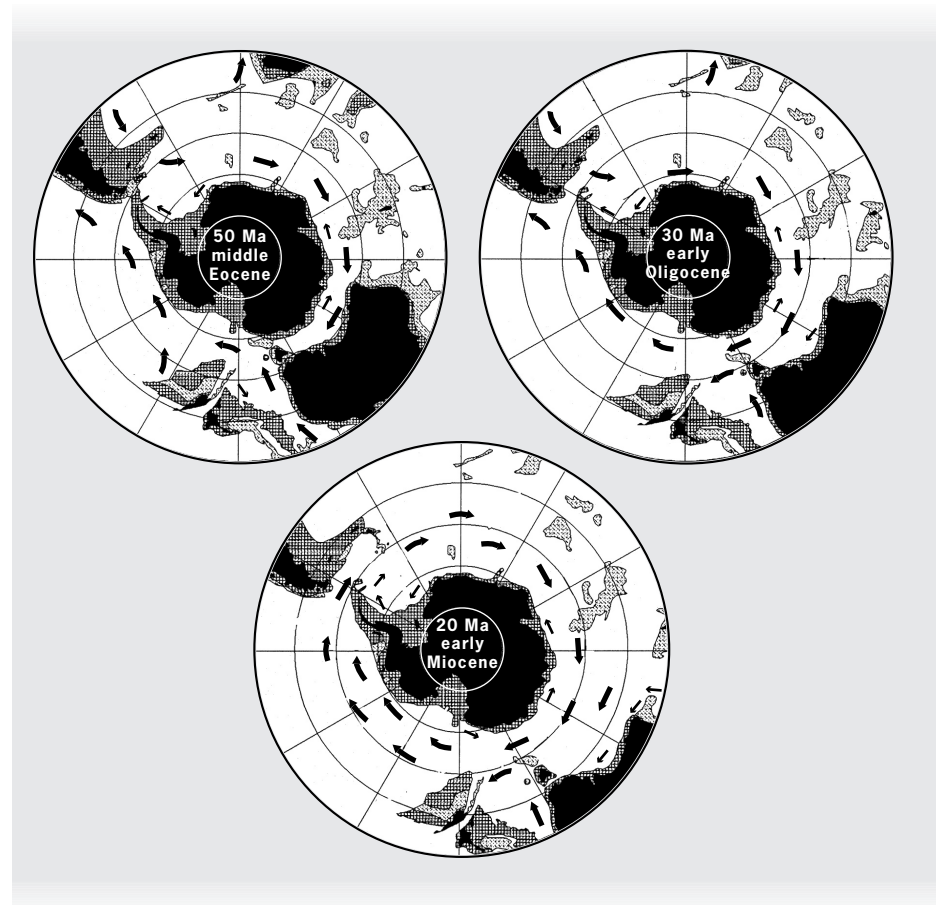


FIGURE 1 Antarctica and surrounding continents in middle Eocene, early Oligocene and early Miocene times, showing the change from meridional to circum-Antarctic current circulation that brought about the thermal isolation of Antarctica (after Lawver et al., 1992; Shipboard Scientific Party, 1999). Leg 189 was in the plateau areas around Tasmania.

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The five Leg 189 drill sites, in water depths of 2475 to 3579 m (Fig. 2), tested the above hypothesis and refined and extended it, greatly improving understanding of Southern Ocean evolution and its relation with Antarctic climatic development. The focus of the expedition was to better document the climatic and oceanographic consequences of the opening of the gateway during the transition from warm Eocene climates to cool Oligocene climates. The relatively shallow region off Tasmania (Exon and Crawford, 1997) is one of the few places where well-preserved and almost complete marine

Cenozoic carbonate-rich sequences can be drilled in present-day latitudes of 40–50°S, and paleolatitudes of up to 70°S. The broad geological history of all the sites was comparable. However, the Paleocene-Eocene separation of the three Indian Ocean sites from the two Pacific Ocean sites by the Tasmanian land bridge led to important differences. Depositional conditions in the restricted Australo-Antarctica Gulf (AAG), west of the land bridge, contrasted with those in the more open Pacific Ocean. There are also differences from north to south related to

proximity to the opening gateway and to major land masses.

In all, 4539 m of core was recovered (overall recovery 89% despite some real Southern Ocean weather), with the deepest core taken 960 m beneath the seafloor. The sedimentary sequence cored is entirely marine, and contains a wealth of microfossil assemblages that record marine conditions from the Late Cretaceous (Maastrichtian) to the late Quaternary, with major terrestrial input until the earliest Oligocene. The drill sites are on submerged continental blocks, which were at polar latitudes in the Late Cretaceous when Australia and Antarctica were still united, although rifts had developed as slow separation and northward movement of Australia commenced. The cores indicate that the Tasmanian land bridge completely blocked the eastern end of the widening AAG until the late Eocene, during both slow and fast (from 43 Ma) spreading phases.

THE SEQUENCES DRILLED

The stratigraphic results of the expedition are summarised in Figure 3. In general, terrigenous sedimentation in a shallow marine deltaic setting dominated until the late Eocene, and pelagic carbonate deposition in deep waters thereafter. Distance from the ACC strongly affected the nature of sedimentation in the late Eocene.

Three sites were west of the Tasmanian land bridge, and hence in the AAG until the Oligocene. Site 1168 on the west Tasmanian margin cored to 883 metres below the sea floor (mbsf). This site recovered an almost complete sequence of Oligocene to Recent chalk and ooze, and some late Eocene shelf mudstone. Site 1169 on the western South Tasman Rise cored to 249 mbsf and recovered only chalk and ooze, with an expanded early Pliocene to Recent sequence, and small parts of the late and middle Mio-

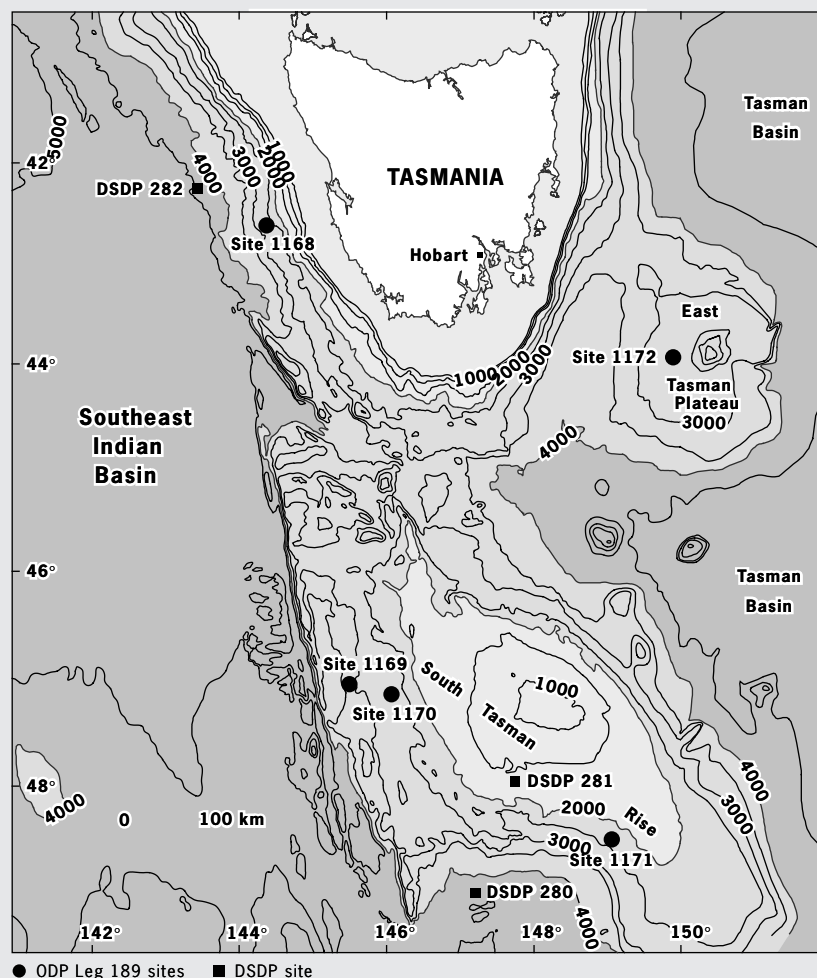


FIGURE 2 Bathymetry of the offshore Tasmanian region, making use of extensive swath-bathymetry (Hill et al., 1997). Leg 189 sites are solid circles, and DSDP sites are squares. Contours in meters.

cene. Site 1170, 40 km east of Site 1169, cored to 780 mbsf and recovered early Oligocene to Recent chalk and ooze, and middle to late Eocene shelf mudstone. This site lay close to the developing ACC, which caused erosion or non-deposition of most of the mid-Oligocene and the late Miocene.

Two sites were always in the Pacific Ocean (in the initially narrow Tasman

Sea) and east of the Tasmanian land bridge until the Oligocene. Site 1171, on the southernmost South Tasman Rise, cored 959 mbsf and recovered an almost-complete late Oligocene to Recent chalk and ooze sequence, and much of a late Paleocene to late Eocene shelf mudstone sequence. Several time breaks in the Eocene and Oligocene, and the late Miocene, can be related to the nearby ACC.

Site 1172, on the East Tasman Plateau, was also on the Pacific side of the land bridge, but further from the Antarctic Circumpolar Current. It recovered almost-complete sequences of Oligocene to Recent chalk and ooze, and Late Cretaceous to late Eocene shelf mudstones. Short time breaks were identified in the earliest Paleocene, early middle Eocene and earliest Oligocene.

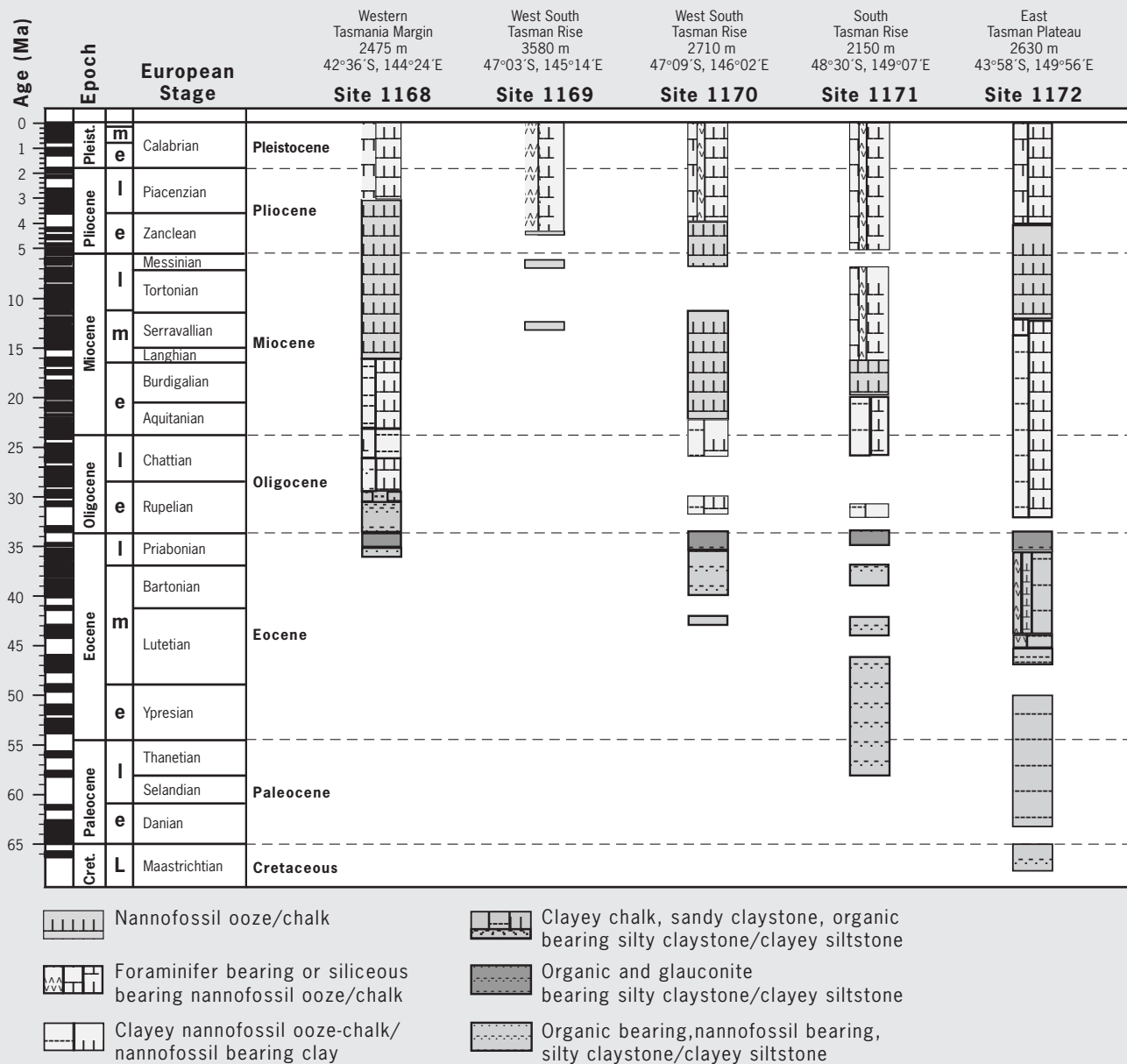


FIGURE 3 Summary stratigraphy and sediment facies for all sites drilled during Leg 189 arranged against time, from west to east.

HIGHLIGHTS

Sedimentation rates depended on local tectonics, distance from source, sedimentation patterns, and by-passing and current erosion, and vary among the sites (Fig. 4). Apatite fission track dating indicates that west and east Tasmania were subject to regional cooling in the late Paleocene to early Eocene, indicating tectonic uplift and erosion (O'Sullivan and Kohn, 1997). West of Tasmania, Site 1168 continuously received sediment from Tasmania, and sedimentation rates were moderate and fairly constant from the late Eocene onward (3–5 cm/ky), with little change as terrigenous sedimentation gave way to carbonate sedimentation. On the South Tasman Rise, Sites 1170 and

1171 were part of the tectonically active borderland between Antarctica and Australia in the Paleocene and Eocene, but were isolated from major landmasses thereafter, with the local hinterland sinking and diminishing. Thus sedimentation rates were relatively high (5–10 cm/ky) during terrigenous deposition in the early and middle Eocene, and generally low thereafter. Sedimentation rates were low in the late Eocene (1–2 cm/ky) as the sites were current-swept by the developing ACC, and later during pelagic carbonate deposition. On the East Tasman Plateau, sedimentation rates at Site 1172 were generally low from the Maastriichtian onward (1–2 cm/ky) for both terrigenous and carbonate sedimentation,

suggesting that the terrigenous source was relatively limited until it vanished in the Oligocene.

Four key observations come from the geochemistry (Fig. 5). First, in Sites 1170, 1171 and 1172, Paleogene sediments are generally carbonate-poor, and Neogene sediments carbonate-rich. Second, the transition from carbonate-poor to carbonate-rich sediments is quite abrupt, except at Site 1168. Third, carbonate and total organic carbon contents are antithetic: Paleogene sediments usually contain greater than 0.5 % TOC, whereas Neogene sediments contain little TOC. Fourth, organic matter type (primarily Rock Eval pyrolysis), and paleosalinity characterizations (C/S ratios), identify geochemical facies. The facies show distinct changes at the Paleocene-Eocene boundary, in the middle Eocene, and near the Eocene-Oligocene boundary. Fifth, at Sites 1168, 1170 and 1171, methane content from headspace gas measurements increases abruptly downward into the organic carbon-containing Paleogene sediments, which contain thin, almost-mature hydrocarbon source rocks.

Prior to the late Eocene, marine siliciclastic sediments, largely silty claystone, were deposited in a relatively warm sea on broad, shallow tranquil shelves. Sediment supply was rapid and despite the rifting, drifting, and compaction, deltaic deposition kept up with subsidence. Calcareous and siliceous microfossils are sporadically present, and dinocysts, spores and pollen are always present. The spores and pollen show that, throughout this time, this part of Antarctica was relatively warm with little ice, and supported temperate rain forests with southern beeches and ferns – part of the “Greenhouse” world. Differences in the claystones indicate that the eastern AAG was more poorly ventilated than the gradually widening Pacific Ocean with its western boundary current, the East Australian

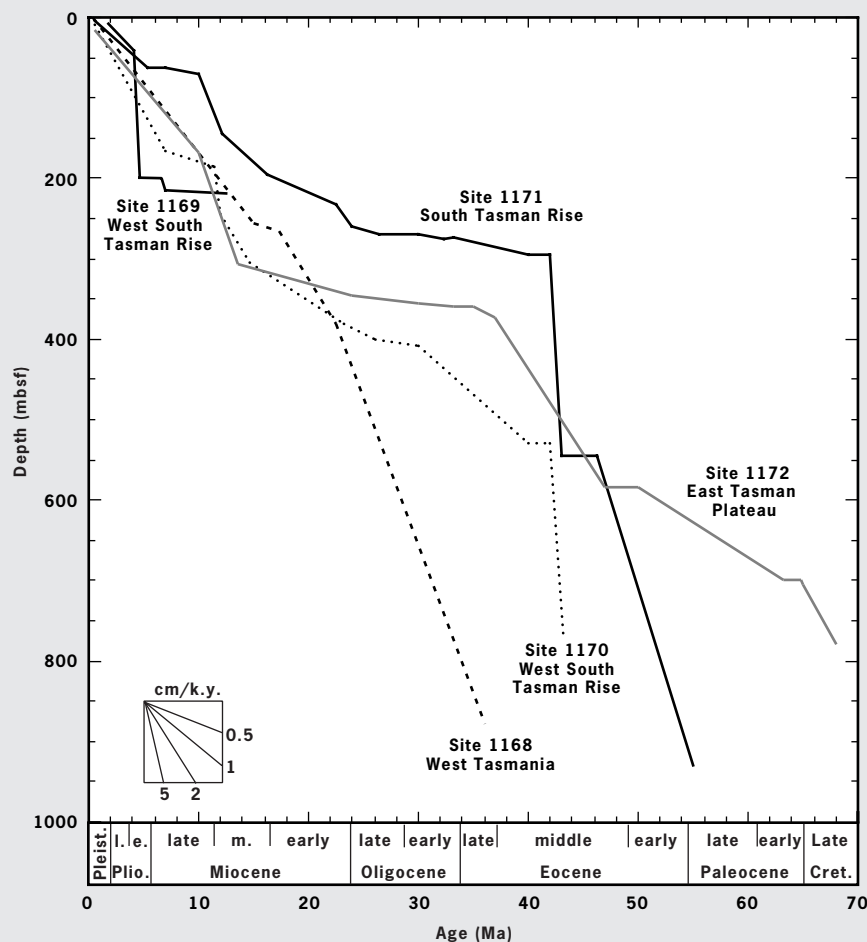


FIGURE 4 Sedimentation rate summary curves for all sites drilled during Leg 189.

Current. However, currents from low latitudes warmed both sides of the land bridge.

In the late Eocene (37–33.5 Ma), the Tasmanian land bridge separated from Antarctica, the bridge and its broad shelves began to subside, and cool surface currents started to circulate around Antarctica from the west. These swept the still-shallow offshore areas, and glauconitic siltstones were deposited very slowly, as condensed sequences. Palynological and other evidence suggests that there were considerable fluctuations in tempe-

rature superimposed on a general cooling, and the amount of upwelling also fluctuated in response to changing oceanic circulation. Calcareous microfossils are rare, but diatoms and foraminifers indicate that there was minor deepening in the latest Eocene (33.5 Ma) at some sites.

The most conspicuous change of the entire 70 million year sequence in this region occurred over the Eocene-Oligocene transition, when Australia and Antarctica finally separated: shallow to deep, warm to cold, dark siliciclastic to light pelagic carbonate deposition, palyno-

morph dominated to pelagic microfossil dominated, poorly to well ventilated, organic-rich to organic-poor.

By the early Oligocene (Fig. 6), warm currents from the tropics were 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. In the Tasmanian offshore region, conditions were significantly cooler and there is no positive evidence of land vegetation, although plant material would have been oxidised in well-ventilated waters.

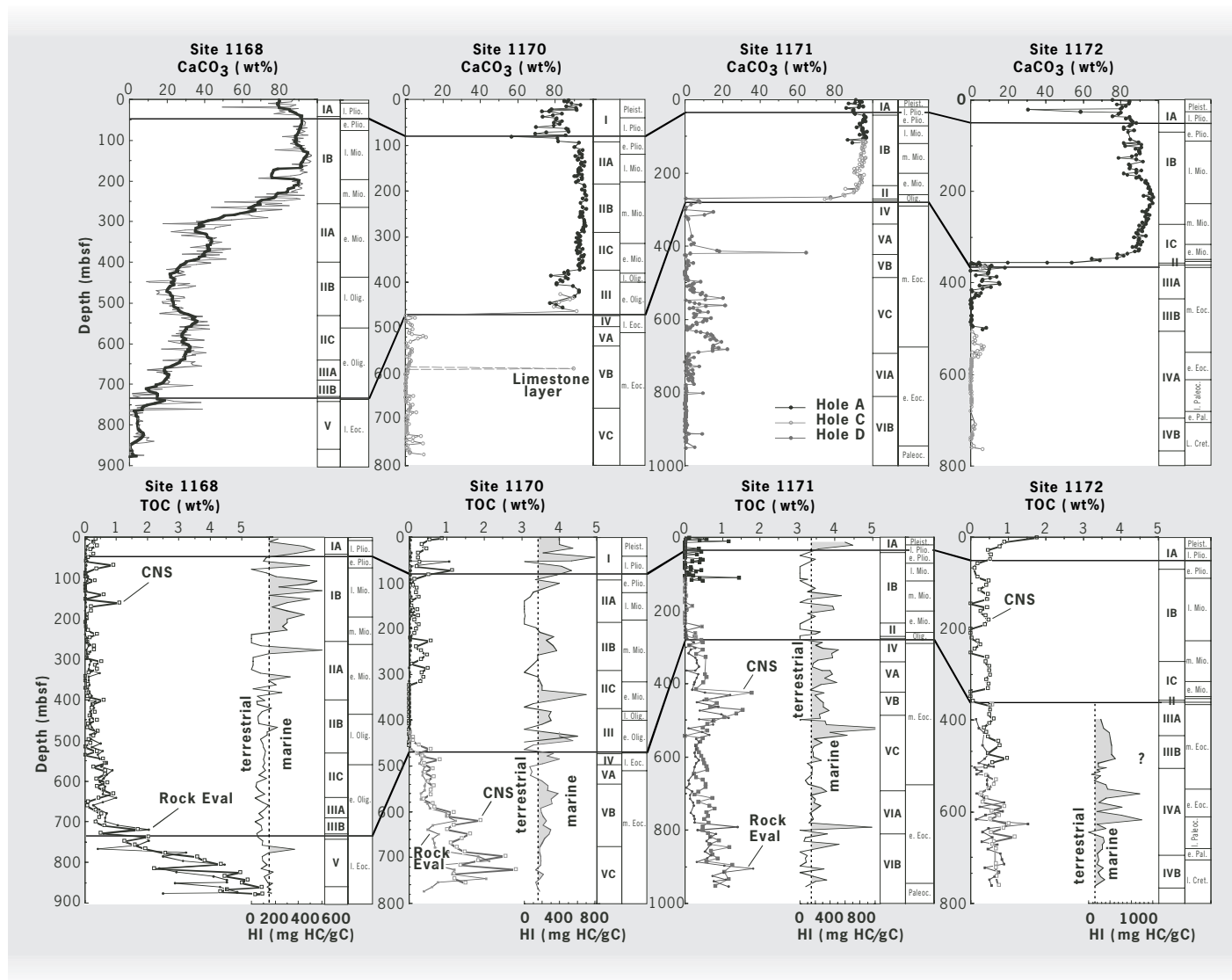


FIGURE 5 Summary of organic geochemistry results. The upper panel shows carbonate content (weight percent CaCO_3), whereas the lower panel shows total organic matter content and hydrogen indices. Also shown are regional correlations and approximate location of lithostratigraphic units and age.

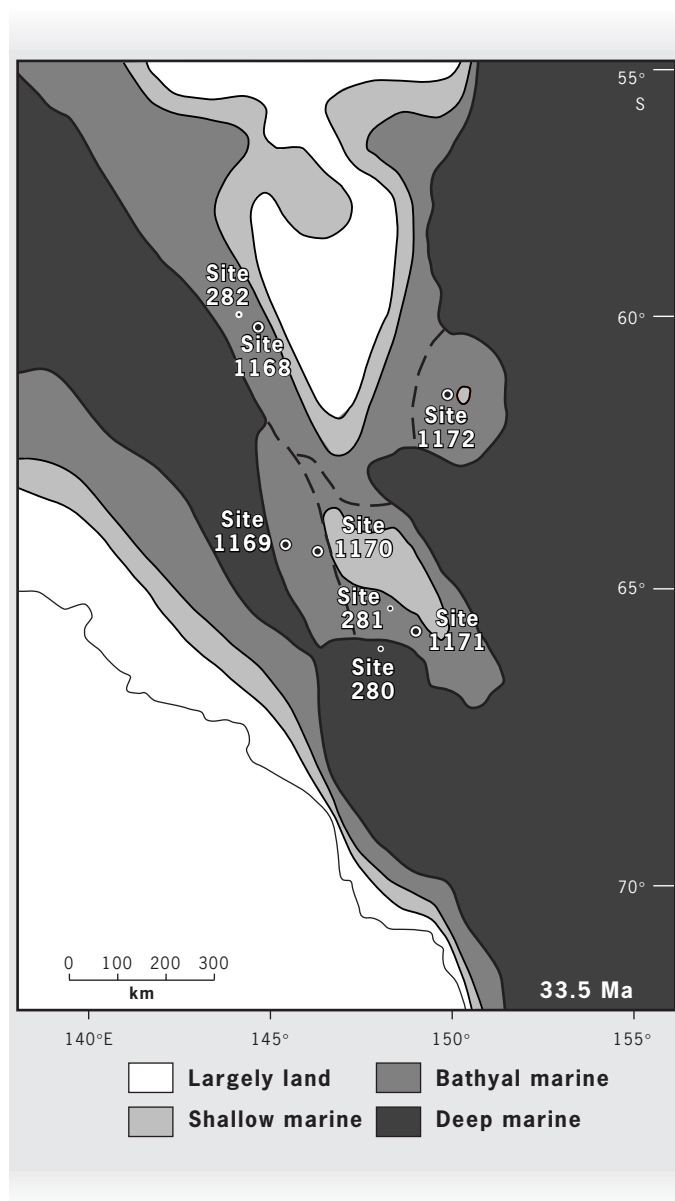


FIGURE 6 Paleogeographic map of the Tasmanian and South Tasman Rise region in the earliest Oligocene (33.5 Ma), based partly on Royer and Rollet (1997, Fig. 8) and on Leg 29 and Leg 189 results. A deep-water connection had just been established south of South Tasman Rise, between the restricted Australo-Antarctic Gulf to the west and the Pacific Ocean, allowing the onset of deep circum-Antarctic circulation. Most of the continental margin was covered with bathyal seas, and most oceanic crust with deep water. Dots = DSDP Leg 29 Sites. Open circles with dots = Leg 189 Sites.

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 moi-

sture, decreasing precipitation and erosion. Altogether, far less siliciclastic sediment was transported from the land, and generally slow deposition of deep-water pelagic sediments set in on the starved Antarctic and Tasmanian margins. However, the East Australian Current and currents flowing down the western Australian margin kept the Tasmanian region relatively warm, resulting in carbonate deposition rather than the siliceous biogenic deposition that

marks much of the Antarctic margin. In the offshore Tasmanian region, and even in the Cape Adare region on the conjugate Antarctic margin (Piper and Brisco, 1975), there is no sign of glaciation in the early Oligocene. However, mountain glaciers existed on Tasmania in the earliest Oligocene (Macphail et al., 1993).

Drake Passage opened fully early in the Neogene (Lawver et al., 1992), and the Tasmanian Gateway continued to open, strengthening and widening the ACC, and strongly isolating

Antarctica from warm water influences from lower latitudes. The east Antarctic cryosphere evolved into ice sheets comparable to the present ones at about 15 Ma (Shackleton and Kennett, 1975; Kennett, 1977). This intensified global cooling and thermohaline circulation: the “Ice House” world had arrived. However, temperatures and current activity fluctuated, and dissolution and erosion varied over time. The Tasmanian region had been moving steadily northward so its sediments were never south of the Polar Front, and pelagic carbonate continued to accumulate in deep waters at average rates of 1–2 cm/ky. The late Neogene sequences contain windblown dust from Australia, which was progressively moving northward into the drier mid-latitudes. Along with global climate change associated with high latitude ice sheet expansion, this led to massive aridity on Australia, and an increase in dust abundance in some Leg 189 sequences after 5 Ma.

Comparisons with sequences drilled elsewhere on the Antarctic margin (e.g. Prydz Bay ODP Leg 188: O’Brien, et al., 2000) will further improve our understanding of these momentous changes in the Earth’s history, and some of the constraints on modern climates. If Australia had not broken away from Antarctica and moved northward, global climate may well have remained warm. We can now document in some detail the changes related to that tectonic movement. Our results identify three important Cenozoic tectonic events: Paleocene strike-slip movement on the southeast South Tasman Rise (STR) terminated at 55 Ma by seafloor spreading to the south; Eocene strike-slip movement along the western boundary between STR and Antarctica, terminating in the latest Eocene around 34 Ma; and early Oligocene subsidence and collapse of the continental margin around Tasmania. The 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 Otway coast on mainland Australia, northwest of Tasmania (Heggie et al., 1988).

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 microfossils all show that climatic cycles of varying length are present throughout the entire sequence, and present 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. There is a unique opportunity to build Southern Ocean correlations between various microfossil groups – calcareous nannofossils, planktonic foraminifers, diatoms and radiolarians, and dinocysts, spores and pollen.

CONCLUSIONS

Leg 189 results essentially encapsulate the Cenozoic evolution of the Antarctic system from “Greenhouse” to “Ice House”. The changes recorded in the cores reflect the evolution of a tightly integrated, and at times dynamically evolving, system involving the lithosphere, hydrosphere, atmosphere, cryosphere, and biosphere. Major successes included establishing differences for most of the Cenozoic between the Indian and Pacific Oceans, and also from north to south, by recovering relatively complete sequences, which will allow us to establish an unprecedented integrated biostratigraphic framework for the region. We expected to penetrate only to the middle Eocene, but in fact drilled Paleocene sediments in the southernmost site, which greatly im-

proved our understanding of South Tasman Rise tectonic history, and Paleocene and Cretaceous sediments in the eastern site, revolutionising our understanding of the geological history of the East Tasman Plateau.

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Deformation and Fluid Flow Processes in the Nankai Trough Accretionary Prism: ODP Leg 190

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The Nankai Trough accretionary prism represents an “end-member” prism accreting a thick terrigenous sediment section in a setting with structural simplicity and unparalleled resolution by seismic and other geophysical techniques (Aoki et al., 1982; Moore et al., 1990, 1991). It therefore represents a superb setting to address ODP's Long Range Plan objectives for accretionary prism coring, *in situ* monitoring, and refinement of mechanical and hydrological models. Additional interest has recently been focused on this portion of the Nankai Trough because it has experienced major, catastrophic earthquakes along its seismogenic zone (Ando, 1975; Hyndman et al., 1995; Park et al., 2000; Kodaira et al., 2000).

Our approach for drilling at the Nankai margin includes sites for coring, *in situ* observation, and long-term monitoring to (1) constrain prism hydrology, mechanical properties, and deformational styles and (2) test existing models for prism evolution. Leg 190, the first of a two-leg program, concentrated on coring and sampling two transects of sites across the prism. Leg 196, planned for 2001, will use logging-while-drilling technology to collect *in situ* physical properties data and will also install advanced CORKs (Davis

et al., 1992) for long-term *in situ* monitoring of prism processes including pressure, temperature, fluid geochemistry, and strain.

The Nankai Trough (Fig. 1) is the subducting plate boundary between the Shikoku Basin and the southwest Japan arc (Eurasian plate). The Shikoku Basin is part of the Philippine Sea plate, which is subducting to the northwest under southwest Japan at a rate of 2–4 cm/yr (Karig and Angevine, 1986; Seno, 1977), slightly oblique to the plate margin.

The goals of Legs 190/196 are to: (1) understand the structural and hydrologic evolution of the décollement zone; (2) delineate chemical gradients and fluid flow paths; (3) contrast the stratigraphic and deformational framework along strike; and (4) document the Miocene to Recent evolution of the accretionary prism.

DRILLING RESULTS

During Leg 190, we successfully cored six sites (Figs. 1 and 2), meeting most of the leg objectives and also revealing some surprising new findings.

CHANGES IN PHYSICAL PROPERTIES

Lithostratigraphy and sediment diagenesis vary markedly in three dimensions throughout the Nankai-Shikoku Basin system. These variations in turn exert considerable influence on physical properties, hydrology, fluid-sediment geochemistry, and microbial activity. Discontinuities in porosity, P-wave velocity, electrical conductivity, and grain density generally correspond to lithologic and diagenetic boundaries.

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