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# 1. Leg 189 Synthesis: Cretaceous–Holocene History of the Tasmanian Gateway[1]

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## ABSTRACT

During Ocean Drilling Program (ODP) Leg 189, five sites were drilled in bathyal depths on submerged continental blocks in the Tasmanian Gateway to help refine the hypothesis that its opening near the Eocene/Oligocene boundary led to formation of the Antarctic Circumpolar Current (ACC), progressive thermal isolation of Antarctica, climatic cooling, and development of an Antarctic ice sheet. A total of 4539 m of largely continuous upper Maastrichtian–Holocene marine sediments were recovered with a recovery rate of 89%. The sedimentary sequence broadly consists of shallow-marine mudstones until the late Eocene, glauconitic siltstones during that time, and pelagic carbonates thereafter. The microfossils in the mudstones and siltstones are largely palynomorphs and diatoms, and those in the carbonates are largely nannofossils and foraminifers.

During the Late Cretaceous, northward movement of Australia away from Antarctica commenced, forming the Australo-Antarctic Gulf (AAG). However, a Tasmanian land bridge at 70°–65°S almost completely blocked the eastern end of the widening AAG until the late Eocene; there is no evidence of extensive current circulation across the ridge until the earliest Oligocene. Prior to the Oligocene, muddy marine siliciclastic sediments were deposited in temperate seas. During the late Eocene, the northeastern AAG was warmer and less ventilated than the gradually widening southwest sector of the Pacific Ocean, which was affected by a cool northwesterly flowing boundary current—a difference that may have existed since the Maastrichtian. In the late Eocene (~37 Ma), the Tasmanian land bridge and its broad shelves began to subside,

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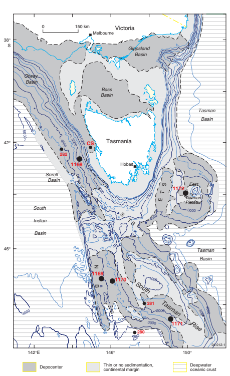
currents swept the still-shallow offshore areas, and condensed glauconitic siltstones were deposited. Palynological and diatom evidence suggest a general cooling. The southwestern South Tasman Rise finally separated from Antarctica at the time of the Eocene/Oligocene boundary (~33.5 Ma), the rise subsided, and the continental margin of Tasmania collapsed. The Tasmanian Gateway opened to deep water, disrupting oceanic circulation at high southern latitudes and leading to one of the major climatic shifts of the Cenozoic. Thereafter, a marked reduction in siliciclastic supply, as well as the flow of warm currents from northern latitudes, favored deposition of carbonate. At the eastern sites, deposition of Oligocene bathyal carbonates directly followed an unconformity caused by the onset of the ACC, but change was more gradual in the west. In contrast, siliceous biogenic sediments typified the Antarctic margin, now isolated from warm water by the ACC. Steady northward movement kept the Tasmanian region north of the Polar Front throughout the Neogene, and pelagic carbonates accumulated.

# INTRODUCTION

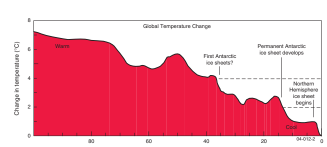
Kennett, Houtz, et al. (1975) proposed that the climate cooled and an Antarctic ice sheet (cryosphere) developed in late Eocene to early Oligocene time as the Antarctic Circumpolar Current (ACC) progressively isolated Antarctica thermally. Australia's movement north from Antarctica formed the Tasmanian Gateway and was considered to have triggered ACC formation and the global cooling that started ice sheet formation, initially on Antarctica and later in the Northern Hemisphere. While Paleogene rifting slowly opened the Australo-Antarctic Gulf (AAG) between the two continents, the Indian and Pacific Oceans remained separated by the almost continuous Tasmanian "land bridge" until the late Eocene, so no ACC existed. Circulation of warm water from the tropics warmed Antarctica through a complex series of climatic feedback mechanisms. Early drilling (Deep Sea Drilling Project [DSDP] Leg 29) in the Tasmanian Gateway between Australia and Antarctica provided a basic framework of paleoenvironmental changes associated with gateway opening (Kennett, Houtz, et al., 1975). However, the cored sequences were of insufficient quality and resolution to more fully test the potential interrelationships of plate tectonics, circumpolar circulation, and global climate.

Ocean Drilling Program (ODP) Leg 189, carried out in early 2000, was designed to assist with better understanding of the nature and timing of changes associated with gateway opening (Fig. F1). We aim in this contribution to provide a summary of the Leg 189 results that includes some postcruise studies, with special emphasis on the papers written for this *Scientific Results* volume. We present new information about the nature of and processes involved in the Paleocene and Eocene warm episode, late Eocene transitional climate, and Oligocene and later cooling (Fig. F2). Also, a large group of papers based largely on Leg 189 drilling will appear in an American Geophysical Union Geophysical Monograph (Exon et al., in press a); these are only briefly mentioned here. Implications for petroleum prospectivity were presented by Exon et al. (2001) and are not considered here. A detailed comparison with data from other ODP and DSDP sites and other stratigraphic information is provided in Exon et al. (in press b). It shows that, in nonabyssal sequences off southern Australia and New Zealand, the transition from si-

**F1.** Cretaceous–Cenozoic sedimentary basins, p. 28.




**F2.** Global temperature changes, p. 29.



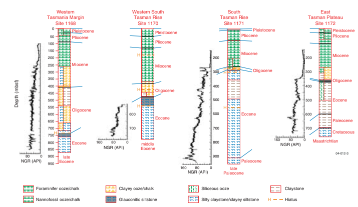
liciclastic to carbonate sedimentation generally occurred somewhere in the late Eocene or early Oligocene. In the Australian sector of the Antarctic margin, the Eocene–Oligocene transition is from nonmarine clastics to shallow glaciomarine siliciclastics and diatomaceous sediments.

## Overview of Drilling Results

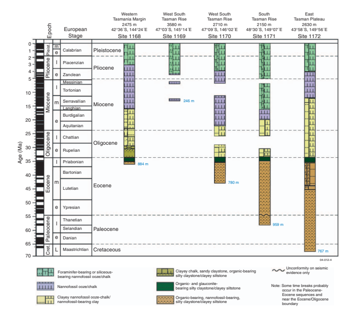
During Leg 189, 4539 m of nearly continuous sediment core was recovered from five deepwater sites off Tasmania (Table T1), ranging in age from Late Cretaceous (75 Ma) to present day. The general character of the drilled sequences is summarized in Figures F3 and F4. The Paleogene sediments vary considerably among sites (Fig. F3), reflecting their varied locations with respect to the pre-Oligocene Tasmanian land bridge between Australia and Antarctica, their meridional position, and their tectonic differences. At that time, all the sites were located in high southern latitudes of 60°–70°S, compared to their present latitudes of 42°–48°S. There are also differences in the carbonates of the post-separation Oligocene and younger sequences.

**T1.** Leg 189 sites, p. 36.

**F3.** Sequences drilled, p. 30.



**F4.** Time stratigraphy and sediment facies, p. 31.



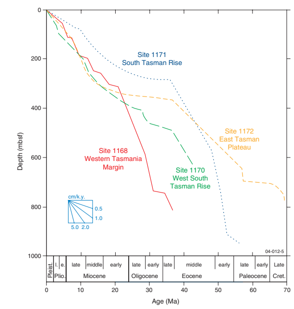
In the Paleogene, the western Site 1168 was located in the narrow and tranquil AAG, west of the land bridge and connected to the Indian Ocean. This sequence on the west Tasmanian margin (cored to 883 meters below seafloor [mbsf]) recovered upper Eocene shelf mudstone and an almost continuous sequence of Oligocene and younger chalk and ooze.

The other sites were located in the Pacific Ocean and east of the culmination of the Tasmanian land bridge. This sector of the southwest Pacific ocean was relatively narrow and constricted during the Paleogene. Site 1170 on the western South Tasman Rise (STR) (cored to 780 mbsf) contains middle to upper Eocene shelf mudstone and lower Oligocene and younger chalk and ooze. This site lay closer to the developing ACC than Site 1168, and the ACC caused erosion or nondeposition of much of the middle Oligocene. At nearby Site 1169 (cored to 264 mbsf), middle Miocene and younger ooze was recovered.

Site 1171 on the southernmost STR (cored to 959 mbsf) consists of an upper Paleocene to upper Eocene shelf mudstone sequence and an almost complete upper Oligocene and younger chalk and ooze sequence. Hiatuses of latest Eocene and Oligocene age reflect increased bottom water flow. The Neogene section is relatively continuous, apart from a late Miocene hiatus. Site 1172 on the East Tasman Plateau (ETP) was farther from the ACC. An Upper Cretaceous to upper Eocene shelf mudstone sequence was recovered, along with Oligocene and younger chalk and ooze. Hiatuses were identified in the lowermost Paleocene, middle Paleocene, lower middle Eocene, and lowermost Oligocene.

Figure F3 compares the four deepest penetrating sites. As usual in ODP drilling, recovery was poorest in the deepest section. Upper Maastrichtian mudstones were cored only at Site 1172. Paleocene mudstones were cored at Sites 1171 (upper Paleocene only) and 1172 (a 75-m sequence with a major hiatus between the Danian and late Paleocene). Complete sequences of Eocene mudstones were cored at Sites 1171 (~600 m) and 1172 (~200 m), the thin sequence on the ETP probably representing its remoteness from source areas. Middle and upper Eocene mudstones were cored at Site 1170, and upper Eocene mudstones were cored at Site 1168 west of Tasmania. The thick (~300 m), primarily Oligocene sequence at Site 1168 grades eastward into rapidly thinning deepwater Oligocene chalks. Miocene deepwater calcareous ooze is thickest at Site 1168 (~300 m) and thinnest at Site 1171 (~170 m). Pliocene oozes are remarkably consistent in thickness (~70 m) at all sites. Pleistocene oozes are thickest at the deepwater STR Site 1170 and thinnest at the shallower, current-swept STR Site 1171. As outlined in the Leg 189 *Initial Reports* volume (Exon, Kennett, Malone, et al., 2001) and a brief synthesis in *Eos* (Exon et al., 2002) drilling showed that in the Tasmanian-Antarctic region there were three phases of sedimentation, clearly related to plate tectonic configuration and its influence on changes in ocean circulation and global climate. Depositional rates at Leg 189 sites varied considerably during the three phases and from location to location (Fig. F5). Warm "greenhouse" conditions persisted during the Late Cretaceous, Paleocene, and Eocene and were associated with deposition of shelf mudstone, the depositional rate of which (~2–5 cm/k.y.) matched the rapid subsidence on the rifting continental margins. In the late Eocene (37–33.5 Ma), early separation occurred between Australia and Antarctica in shallow water and the currents began to flow in the Tasmanian Seaway. This led to a second phase of deposition, consisting of slow sedimentation (<1 cm/k.y.) of glauconitic siltstone, which failed to keep up with subsidence of the margin. Rapid subsidence at the eastern sites commenced in the latest Eocene. By the earliest Oligocene (33.5 Ma) the seaway had opened substantially, and the third phase of deposition commenced, with slow deposition (1–2 cm/k.y.) of deepwater pelagic carbonates as Australia moved northward. Water depths no longer significantly increased following the Oligocene because subsidence rates had fallen off. The third phase covered both intermediate "doubthouse" conditions (33.5–15 Ma) and "Icebox" conditions (15–0 Ma).

**F5.** Sedimentation rate curves, p. 32.




## OVERVIEW OF CONTRIBUTIONS TO THE *SCIENTIFIC RESULTS* VOLUME

Twelve papers appearing in this volume add significant knowledge to the Cenozoic paleoenvironmental development of the region. These contributions are briefly summarized as follows.

**Stickley et al.** (this volume) summarize the Late Cretaceous to Quaternary biostratigraphy and calibrate this with magnetostratigraphy. Their age models for Sites 1168, 1170, 1171, and 1172 (see Fig. F5) integrate information from calcareous, siliceous, and organic walled microfossils. These data provide the necessary chronologic foundation upon which all other research papers from Leg 189 depend. The study is a unique synthesis of latest Cretaceous to Quaternary biostratigraphy in the Australian-Antarctic region, using all key microfossil groups.

**Robert** (this volume) presents a data report on bulk and clay mineral assemblages for the entire sequences at all sites except Site 1169. He provides detailed data tables and informative graphs and background information for Robert (in press). Differences in clay mineral assemblages are related to source material, regional tectonics, weathering, and erosion. At the eastern sites (1170–1172) a threefold split in bulk sediment mineralogy matches lithologic changes: lower upper Eocene and older siliciclastics (terrigenous minerals), uppermost Eocene–Oligocene transition (terrigenous minerals plus some biogenic carbonate), and Oligocene and younger carbonates (biogenic carbonate minerals). At Site 1168 the terrigenous–carbonate transition is gradual, with terrigenous minerals common until the lower middle Miocene. The clay mineral assemblages do not differ from east to west as much as the bulk mineralogy. Smectite is mostly dominant, with variable subordinate proportions of kaolinite and illite. Chlorite is commonly present at Sites 1170–1172.

**Latimer and Filipelli** (this volume) provide a data report on Eocene to present sediment geochemical results from Site 1171. Fe, Al, and Ti concentrations and elemental ratios (carbonate free) were measured to identify changes in metal sources and terrigenous inputs. Export production was studied using P and Ba concentrations and P/metal and Ba/metal; higher values represent higher production. There are major changes at ~260–290 mbsf (Eocene–Oligocene transition), where siliciclastic sediments grade upward into pelagic carbonate sediments. P/Ti and Ba/Ti ratios indicate large export production increases, the ratios changing from negligible in the Eocene to ~6–10 g/g in the Oligocene. The ratios declined gradually to ~4 g/g in the Pliocene–Pleistocene.

**Williams et al.** (this volume) compare Southern Ocean and global dinoflagellate cyst index events for the Late Cretaceous to Neogene. They use Leg 189 sites for much of the Southern Ocean control, and these sites have the benefit of detailed independent age control, primarily from magnetostratigraphy and, to some extent, from planktonic foraminifers and calcareous nannofossils. Williams et al. carefully document stratigraphic ranges of the dinocysts with abundant line drawings of taxa and photomicrographs provided to assist with identification, a useful resource for the international community of dinocyst workers.

**Brinkhuis, Sengers, et al.** (this volume) describe latest Cretaceous to earliest Oligocene (and Quaternary) dinoflagellate cysts from Site 1172 on the East Tasman Plateau, providing a standard reference for dinocyst biostratigraphy for these latitudes during the latest Cretaceous through the Oligocene. The Maastrichtian to earliest Oligocene record is well represented, with the exception of much of the early and some of the late Paleocene. Dinocyst species are largely endemic and relatively cool water, representing the "Transantarctic Flora," or are bipolar types. Until the early late Eocene, the assemblages are indicative of shallow-marine to restricted-marine, prodeltaic conditions. By middle late Eocene times, slow glauconitic sedimentation became established, reflecting the deepening of the Tasmanian Gateway. An associated notable turnover in dinocyst associations reflects a change from marginal marine to more offshore conditions. Organic microfossils are virtually absent in the Oligocene and Neogene pelagic carbonates.

**Brinkhuis, Munsterman, et al.** (this volume) provide an important overview paper on late Eocene, Oligocene, Miocene, and Quaternary dinoflagellate cyst distributions at Site 1168 west of Tasmania and illustrate the main trends in palynomorph distribution. The dinocyst species are largely cosmopolitan with some low-latitude taxa and, unlike those at Site 1172 to the southeast, the assemblages do not contain endemic Eocene Antarctic taxa. The general palynomorph distributions suggest relatively warm waters, an initially restricted shallow-marine setting, and deepening and initiation of open-ocean conditions in the Oligocene.

**Sluijs et al.** (this volume) describe dinoflagellate cysts from the Eocene–Oligocene transition, particularly for Site 1172 on the East Tasman Plateau and Sites 1170–1171 on the South Tasman Rise, and compare the results with broader shipboard information from Site 1168 west of Tasmania. At Sites 1170–1172, three distinctive dinocyst assemblages indicate relatively rapid stepwise environmental changes, from a prodeltaic to a deeper marine pelagic setting. The Antarctic endemic assemblage was replaced by a more cosmopolitan offshore assemblage at ~35.5 Ma and by an even further offshore assemblage at ~34 Ma.

Wei et al. (this volume), in a brief data report on the Paleogene calcareous nannofossil biostratigraphy of Leg 189, list the distribution of nannofossils at the various sites and summarize the occurrence of nannofossil datums. The nannofossil assemblages are particularly important in establishing the biostratigraphy of Oligocene carbonate sequences. They also provide sporadic but valuable ages and environmental information for the pre-Oligocene siliciclastic sequences.

Pfuhl and McCave (this volume) built integrated age models for the early Oligocene to early Miocene (30–14 Ma) at four sites, comparing biostratigraphy, magnetostratigraphy, stable isotope records, carbonate content, and weight percent sand. They show that the Marshall Paraconformity (named in New Zealand) forms a hiatus (~33–30 Ma) at the eastern sites but is essentially absent at Site 1168. At the two easternmost sites (1171 and 1172), the Oligocene/Miocene boundary is marked by a condensed section or hiatus (~24–23 Ma). There is a problematic mismatch of the Mi-1 event (~24 Ma) at Sites 1168 and 1170.

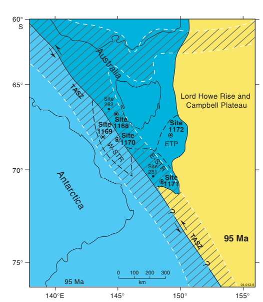
Ennyu and Arthur (this volume) provide a data report on oxygen and carbon stable isotope records of Miocene planktonic and benthic foraminifers and fine-fraction carbonate from Sites 1170 and 1172, as background for interpretations provided in Ennyu and Arthur (in press).

McGonigal and Wei (this volume) provide a data report on Miocene calcareous nannofossil biostratigraphy containing species range charts, a tabulation of key biohorizons, a summary of nannofossil zones and datums, and plates of photomicrographs. Although diversity and biostratigraphic resolution were greatest at Site 1168, a solid integrated biostratigraphy was constructed at all sites by incorporating the results from other microfossil groups and magnetostratigraphy.

Stant et al. (this volume) report on the Quaternary nannofossil biostratigraphy of four sites: two north and two south of the present-day Subtropical Front. Their study indicates that movement of the front in the Quaternary and late Pliocene influenced the distribution of warmth-loving *Discoaster* and large *Gephyrocapsa* species. In addition, discoasters survived longer (until 1.95 Ma) east of Tasmania at Site 1172 than west of Tasmania (until 2.51 Ma), suggesting that the East Australian Current warmed the eastern waters. An early Pleistocene hiatus encompasses the entire *Helicosphaera sellii* Zone, as it does at many other DSDP and ODP sites in the region.

# TECTONIC EVOLUTION

The Cretaceous through Eocene tectonic history of this region is similar to that of other margins of Antarctica. East-west rifts between Australia and Antarctica, a result of northwest–southeast oblique extension, may have formed as early as the latest Jurassic (Willcox and Stagg, 1990). In the Early Cretaceous, east Gondwana was still intact and the Tasmanian region lay deep within present-day Antarctica, southeast Australia, and the continental block of Lord Howe Rise, Campbell Plateau, and New Zealand (LCNZ) (Fig. F6). Ocean currents are inferred to have flowed west and north of Australia and east of the LCNZ continental block. Early in the Late Cretaceous, rifting caused marine transgression into the AAG from the west, and seafloor spreading commenced between ~95 Ma (Veevers, 1986) and ~83 Ma (Sayers et al., 2001). A




F6. Setting of the Tasmanian region during the Late Cretaceous, p. 33.

northwest–southeast, left lateral Tasmanian-Antarctic Shear Zone (TASZ) absorbed the relative motion of the two continents west of Tasmania, and AAG waters transgressed southward along the TASZ. Spreading propagated eastward, being fully under way west of Tasmania by the middle Eocene (Royer and Rollet, 1997), but the Tasmanian-Antarctic land bridge in the east allowed little to no water exchange between the AAG and the proto-southwest Pacific.

In the Late Cretaceous (~75 Ma), continental breakup and seafloor spreading began between Australia and the LCNZ (Cande and Stock, in press). Rifting propagated northward east of Australia, forming the Tasman Sea, and final breakup off northeastern Australia took place in the Paleocene (~60 Ma) (Gaina et al., 1999). Thereafter, major ocean currents could flow along the eastern coasts of Australia and Tasmania, the ETP and STR, and along the Antarctic margin to the south. However, the Tasmanian land bridge separating the AAG from the Pacific Ocean remained essentially intact until the latest Eocene. When a deepwater passageway developed between South America and Antarctica, to complete the Southern Ocean oceanographic circuit, remains disputed. Barker and Burrell (1977, 1982) argued that a deepwater pathway could not have developed in Drake Passage until close to the Oligocene/Miocene boundary. In contrast, Lawver and Gahagan (1998, 2003) suggested that the passageway opened somewhat later than the Tasmanian Gateway but no later than the early Oligocene, allowing the ACC to become established by then.

Leg 189 drill sites were located on four continental tectonic blocks: Site 1168 in the Sorell Basin on the west Tasmanian margin, Sites 1169 and 1170 in the Ninene Basin on the western STR block, Site 1171 in a small strike-slip basin on the central STR block, and Site 1172 on the ETP. The drill testing of seismic profiles has helped interpretation of the local tectonics (Hill and Exon, in press). According to Royer and Rollet (1997), the ETP rifted from Tasmania and the STR as part of Tasman Sea break-up in the Late Cretaceous (95 Ma), although Site 1172 subsided only slowly until the late Eocene.

Apatite fission track dating (O'Sullivan and Kohn, 1997) indicates a period of uplift and erosion near the Paleocene/Eocene boundary on the western and eastern margins of Tasmania. Between the eastern and central STR blocks near Site 1171, deformation ceased along the Balleny Fracture Zone at ~55 Ma, dating breakup between the southeastern STR and Antarctica. Northwest–southeast strike-slip movement along the west Tasmanian margin (Site 1168) ended in the middle Eocene (~43 Ma), when fast spreading between Australia and Antarctica transferred strike-slip movement to the north–south Tasman Fracture Zone on the west STR margin (Site 1170). Continent-continent movement ended only when Antarctica cleared the STR at the end of the Eocene (~34 Ma). However, the STR continued to move northward along the Tasman Fracture Zone relative to the western spreading center, finally clearing it in the early Miocene (~20 Ma). Heat from the passing spreading center caused uplift along the margin. At all Leg 189 sites the water started to deepen somewhat around the middle/late Eocene boundary (~37 Ma) (Hill and Exon, in press), but this may be attributable largely to a decrease in sedimentation rates rather than accelerated subsidence. A very rapid period of subsidence occurred near the Eocene/Oligocene boundary.

# CRETACEOUS–MIDDLE LATE EOCENE HISTORY: BEFORE GATEWAY OPENING

Before the Tasmanian Gateway opened, rifting and associated hinterland uplift and erosion allowed rapid deltaic sedimentation in the rifts. Evidence from seismic reflection profiles, drilling, and dredging indicates that as much as 4000 m of Cretaceous to Eocene, largely deltaic sediments were deposited in the offshore Tasmanian region (Exon et al., 1997; Hill et al., 1997, 2001; Hill and Exon, in press). For Leg 189 drill sites, late Maastrichtian through early late Eocene deposition (~75–36 Ma) was shallow-marine deltaic and siliciclastic. Moderately high depositional rates (~5–10 cm/k.y.) kept up with subsidence and compaction. Calcareous micropaleontological and palynological evidence indicates a cool to warm temperate climate through the late Maastrichtian to the late Eocene (**Brinkhuis, Sengers, et al.** and **Brinkhuis, Munsterman, et al.,** both this volume).

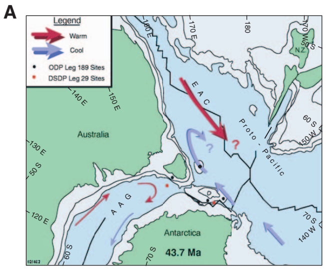
Cretaceous (Maastrichtian) sediments were recovered only at Site 1172 on the ETP, where they are 70 m thick. The microflora indicate a humid and seasonally cool climate. Smectite completely dominates the clays (Robert, in press), suggesting a warm climate and extreme chemical weathering in the source area. The lower, thicker facies is dark claystone and silty claystone, which is essentially noncalcareous and rarely bioturbated (Exon et al., in press b). Dinocysts, spores, pollen, and diatoms are common, and the environment is interpreted as generally highly restricted and paralic. Occasional more marine beds contain molluskan debris, planktonic foraminifers, and nannofossils. The upper, thinner facies comprises brown, paralic, sideritic sandstone and sandy mudstone that contain 20%–55% sand consisting largely of either siderite micronodules or quartz and glauconite. The Cretaceous/Tertiary boundary is not preserved, and an iridium anomaly is lacking (Schellenberg et al., in press).

By the Paleocene, areas of continental crust that had been thinned by Cretaceous rifting—the future Bass Strait, the South Tasman Saddle between Tasmania and the STR, parts of the TASZ between Antarctica and the STR, and the East Tasman Saddle between Tasmania and the ETP—had subsided and were near sea level. Thereafter, very limited interchange of shallow-marine waters could have occurred between the AAG and the Pacific Ocean. Although plate tectonic reconstructions such as those of Royer and Rollet (1997), Lawver and Gahagan (2003), and Cande and Stock (in press) suggest the presence of a shallow-marine connection by the middle Eocene (Fig. **F7A**), the sedimentary evidence from Leg 189 suggests that this connection must have been very limited. Even in the late Eocene, the contrast between the poorly oxygenated, relatively warm shallow-marine waters of the AAG (Site 1168) and the better oxygenated, relatively cool shallow-marine waters of the southwest Pacific Ocean (Sites 1170–1172) suggests a lack of significant interchange between southern Indian and Pacific Ocean waters even at the shallowest depths.

Throughout the Paleocene and Eocene, water circulation in the AAG was probably a sluggish clockwise gyre, with contributions of some warmer waters from lower latitudes in the Indian Ocean. In contrast, and modifying precruise assumptions, micropaleontological evidence (**Brinkhuis, Sengers, et al.,** this volume), with support from climate modeling, suggests that the eastern sites were influenced by cooler waters transported northwestward as a western boundary countercurrent.

**F7A.** Middle Eocene situation, p. 35.

A



Evidence for glaciation is completely lacking at Leg 189 sites, with both marine and terrestrial microfossils indicating temperate conditions. Relatively diverse late Eocene calcareous nannofossil assemblages indicate slightly warmer conditions in the Tasmanian Gateway sector of the Southern Ocean than at comparable latitudes elsewhere, although most of the sites lack warmth-loving discoasters. The nannofossil diversity and the dinocyst and diatom assemblages confirm the absence of seasonal sea ice over the shelf.

Paleocene and Eocene organic-rich mudstones were deposited on a highly restricted, moderately tranquil broad shelf near the rift opening between Antarctica and Australia. Benthic foraminiferal assemblages indicate deposition at shelf depths. The lack of sedimentary characteristics indicating turbulence suggests deposition below wave base (which may have been shallow in the prevailing equable climatic conditions) and largely free of appreciable current or tidal influences.

## Paleocene

The Paleocene was cored at Site 1172 on the ETP, and probably at Site 1171 on the STR. At Site 1172, a thin Danian (lowermost Paleocene) sequence is disconformably overlain by a thicker upper Paleocene sequence. The lowermost Danian (6 m thick) disconformably overlies the uppermost Maastrichtian and is brown noncalcareous muddy glauconitic quartz sandstone and sandy mudstone, deposited in paralic conditions. The disconformably overlying uppermost Paleocene (75 m thick) is dark glauconitic quartz-bearing mudstone; the water shoaled through time but remained paralic. Offshore dinocysts are much more common in the upper Paleocene than during the Danian. The microflora indicate a relatively warm and humid but weakly seasonal climate. Smectite continues to completely dominate the clays (Robert, in press), suggesting a warm climate and extreme chemical weathering.

At Site 1171, we follow Röhl et al. (in press a) in distinguishing a 44-m-thick upper Paleocene section that consists of laminated dark mudstone with almost no sand or carbonate. Sporomorphs are abundant, but other diagnostic fossils are rare; diverse pollen and spore assemblages indicate a strong terrigenous influence. The microflora and abundant smectite suggest a relatively warm, humid, but weakly seasonal climate. **Brinkhuis, Sengers, et al.** (this volume) and Röhl et al. (in press a) suggest that very shallow marine conditions prevailed. However, in the late Paleocene, Site 1171 had more restricted marine conditions than Site 1172.

## Early–Middle Eocene

The tectonic setting in the middle Eocene is shown in Figure **F7A.** Lower and middle Eocene siliciclastic sediments were cored at Sites 1170–1172:

1. Site 1172: lower Eocene = 70 m thick; middle Eocene = 180 m thick;
2. Site 1171: lower Eocene = 145 m thick; middle Eocene = 420 m thick; and
3. Site 1170: lower Eocene = 50 m thick; middle Eocene = 210 m thick.

At all sites in the early and middle Eocene, pervasive pollen and spore assemblages and abundant and continuous low-diversity assemblages of dinocysts indicative of eutrophic and brackish surface waters point to highly restricted nearshore conditions. Sporadic occurrences of well-preserved calcareous nannofossils suggest that their rarity is due to limited access to the restricted coastal setting and to high sedimentation rates, rather than to dissolution. Water mass ventilation was generally poor to limited, judging by the high organic carbon content, limited bioturbation, and benthic foraminiferal assemblages dominated by agglutinated forms and nodosariids.

Distinct cycles in physical properties, sediment type, and microfossil assemblages are well documented in middle and upper Eocene sediments at Site 1172 (Röhl et al., in press b) and are also evident at Sites 1170 and 1171. The cycles are between dark, poorly bioturbated, dinocyst-rich but nannofossil-poor sediments lacking glauconite and lighter, dinocyst-bearing, and more nannofossil-abundant, bioturbated sediments containing glauconite. Röhl et al. (in press b) conclude that the sediment cycles were produced under the influence of orbital perturbations of the Earth relative to the sun (Milankovitch cycles), which affected sea level and climate and, in turn, changed siliciclastic sediment supply, upwelling and nutrient supply, and associated bottom water ventilation. White (in press) argues that cycles observed in geochemical parameters in lower to middle Eocene sediments at all sites resulted from the influence of glacioeustasy in these very shallow marine environments.

At Site 1172, the plant microflora suggest a cool and uniformly humid climate in the hinterland, whereas abundant smectite suggests a warm climate and intense weathering. Exon et al. (in press b) showed that the lowermost Eocene (35 m) is dark, noncalcareous, variably glauconitic, quartz-rich shallow-marine mudstone with abundant siderite micronodules toward the top, suggesting paralic deposition. The overlying lower to middle Eocene dark, noncalcareous mudstone (83 m) is more fossiliferous and slightly more marine. The overlying middle Eocene is dark, noncalcareous diatomaceous mudstone (69 m), representing very different shelfal conditions in which siliceous organisms thrived and were preserved. The upper middle Eocene is somewhat calcareous, dark, diatom-bearing to diatomaceous mudstone (64 m) containing more sand. Deposition probably occurred on an open continental shelf. Overall, the Eocene trend was toward more open marine conditions as waters became slightly deeper, with less reducing conditions with time, as indicated by increasing carbonate and diatom components in the sediments in addition to changes in dinocyst assemblages (**Brinkhuis, Sengers, et al.,** this volume).

At Site 1171, marine mudstones contain dinocysts, indicating restricted, eutrophic, and neritic conditions throughout, with open marine taxa being relatively rare (Shipboard Scientific Party, 2001d). The microflora indicate a relatively warm, humid, but weakly seasonal early Eocene climate and a cooler and uniformly humid middle Eocene. The lower Eocene (45 m) consists of greenish noncalcareous and quartz-rich mudstone. The mixed clay mineral assemblage suggests intense erosion of steep relief areas (Robert, in press). The middle Eocene (142 m) is greenish gray mudstone with nannofossil and carbonate content moderate at the bottom, negligible in the middle, and moderate at the top. The return to dominance of smectite suggests a warm climate and decreasing erosion and intense weathering in the hinterland. At Site 1170, middle Eocene dark mudstones (241 m) contain abundant dinocysts that indicate somewhat restricted, euphotic, neritic conditions (Shipboard Scientific Party, 2001c). Some microfloral evidence suggests a relatively cool, humid climate, but smectite dominates the clays, suggesting warm climate and intense weathering in the hinterland. The nannofossil distribution suggests periods of somewhat more open marine, less restricted conditions.

In the Eocene, both the AAG and the southern Proto-Pacific Ocean were under the influence of temperate climate, but the currents were warmer in the AAG than in the proto-Pacific (Fig. F7A). Ventilation of the waters increased toward the developing seaway on the Pacific side of the Tasmanian land bridge. At Site 1170, laminations are periodically absent and there is some bioturbation. Farther east, the well-bioturbated shelf sediments at Site 1171 and other evidence indicate more ventilated conditions and the absence of an oxygen minimum zone. Within the open Pacific Ocean at Site 1172, the water mass was better ventilated than at either of the sites to the west.

# LATE EOCENE–OLIGOCENE HISTORY: THE GATEWAY OPENS

## Late Eocene

Site 1172 contains only 11 m of upper Eocene sediment deposited on the ETP shelf and small hiatuses (Stickley et al., submitted [N1]) caused by current action and nondeposition. As the water deepened from shelf to upper slope depths and current action increased, the sediment changed from diatomaceous mudstone to glauconitic siltstone. Smectite is the dominant clay. Site 1171 contains ~80 m of sediment laid down in a local basin on the southern STR, almost all being diatomaceous mudstone overlain by a few meters of glauconitic quartz-bearing sandstone. Smectite is the dominant clay at this site also. The water was deepening and current activity increasing on this part of the former land bridge and at Site 1170 in the Ninene Basin. Site 1170 contains ~50 m of upper Eocene sediments: marine mudstone overlain by glauconitic diatomaceous siltstone. Illite and smectite alternate as dominant clays; the illite content suggests proximity to an area of active tectonism (Robert, in press).

Site 1168 contains ~130 m of upper Eocene siliciclastic mudstone deposited in a restricted embayment on the broad west Tasmanian shelf in the AAG, which becomes increasingly more open marine upcore. Unlike the situation at other sites, spores are much more abundant than dinocysts, suggesting closer proximity to land during deposition. Also, the dinocyst taxa are largely cosmopolitan with some low-latitude forms, and (unlike those at Site 1172 to the southeast) the assemblages generally lack endemic high-latitude taxa, suggesting relatively warmer conditions (Brinkhuis, Munsterman, et al., this volume). The lowermost sequence consists of sandy mudstone, possibly largely nonmarine. Kaolinite dominates the clay assemblage, suggesting a source region marked by tectonic activity and intense chemical weathering (Robert, in press) or perhaps a change in source rocks. The bulk of the sediments are laminated, organic-rich, pyritic shallow-marine to paralic mudstone, indicating sluggish circulation and poor ventilation. Kaolinite decreases upcore and smectite increases, suggesting reducing tectonic activity but continuing chemical weathering (Robert, in press). Anoxic to dysoxic depositional environments extended up onto the continental shelf. Above this mudstone sequence are shallow-marine sandstones and mudstones containing quartz and sponge spicules derived from nearby beaches and banks (Exon et al., in press b).

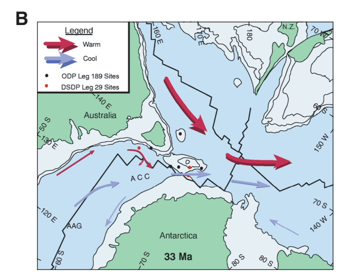
In the transitional upper Eocene interval, sedimentation changes uphole from more muddy to more sandy, with increased glauconite and quartz, reflecting an increase in bottom currents and winnowing. At Sites 1170, 1171, and 1172 the upward gradation is from mudstone into glauconitic siltstone. Despite evidence for general winnowing and the presence of hiatuses in the glauconitic siltstone, some levels containing angular quartz indicate episodes marked by little reworking. The glauconitic sediments are strongly bioturbated and were deposited in well-oxygenated bottom waters. Stepwise changes in dinocyst, pollen, and spore assemblages indicate environmental changes and deepening water (**Sluijs et al.,** this volume). Diatoms and benthic foraminifers indicate deepening from shallow to deeper neritic or possibly uppermost bathyal environments.

At Site 1172, dinocyst assemblages continue to be dominated by endemic forms (e.g., **Brinkhuis, Sengers, et al.,** this volume). Of course, Southern Ocean stable isotopic records generally indicate progressive cooling through the middle and late Eocene (Shackleton and Kennett, 1975; Stott et al., 1990; Kennett and Stott, 1990). During the late Eocene at Site 1171 and, especially, Site 1170, cooler continental conditions are indicated by increased illite relative to smectite, suggesting a reduction in continental chemical weathering. Pollen and spore records suggest diverse and cool temperate late Eocene plant communities in the hinterland. Floras were dominated by *Nothofagus* and podocarps with an understory of ferns, similar to a floral assemblage of similar age in the Weddell Sea sector of Antarctica (Mohr, 1990). Although the late Eocene pollen assemblages indicate cooling, they also show that the Tasmanian part of the Antarctic margin was still relatively warm compared to the distinctly cooler Oligocene. This contrasts with the Prydz Bay margin far to the west, where clear evidence exists for late Eocene glaciation close to sea level (Barron et al., 1991a, 1991b; Cooper and O'Brien, 2004). There is also convincing evidence for early Oligocene growth of a significant ice sheet on at least parts of East Antarctica (Zachos et al., 1996).

## Eocene–Oligocene Transition

Various lines of evidence suggest that Antarctica and the South Tasman Rise separated fully during the Eocene–Oligocene transition (Fig. **F7B**). All four deep sites contain a fairly continuous record over this interval until the earliest Oligocene, after which there are hiatuses at all sites except Site 1168 until ~30 Ma (**Pfuhl and McCave,** this volume; Fuller and Touchard, in press). In the early Oligocene, deposition at the Pacific sites changed to open-water pelagic carbonates. This lithologic change reflects the shift from siliciclastic to biogenic sedimentation, from a poorly to a well-oxygenated benthic environment, from tranquil to moderately dynamic environments, and from relatively warm to cool climatic conditions. This paleoenvironmental change in the oceans was the most profound of the entire Cenozoic (Kennett, 1977; Zachos et al., 1993). An early Oligocene cooling and dissolution episode is recorded widely in deep-sea carbonates and is associated with the well-known positive oxygen isotopic shift (Oi-1) at ~33 Ma (e.g., Shackleton and Kennett, 1975; Miller et al., 1991; Zachos et al., 1994).

**F7B.** Eocene/Oligocene boundary situation, p. 35.



In the earliest Oligocene, similar open-ocean conditions began to develop on both sides of the former Tasmanian land bridge. We argue that a shallow-water proto-ACC was established at the time of final separation and that the cool countercurrent that had reached Sites 1170–1172 from the southeast no longer did so (Fig. **F7B**). Currents continued to circulate clockwise in the AAG and westward along the Antarctic coast in the Pacific Ocean. By the late Oligocene, nearly all of the former land bridge south of Tasmania had submerged. The Tasmanian Gateway south of the STR was hundreds of kilometers wide and continuing to widen, and water depths were abyssal. The ACC, flowing from the west and accommodating an ever-increasing circumpolar flow, was effective in all water depths and eroded and dissolved older sediments. The Drake Passage, south of South America, may have opened to deep water in the early Oligocene (Lawver and Gahagan, 1998, 2003) or at the Oligocene/Miocene boundary (Barker and Burrell, 1977). The expansion of the Antarctic cryosphere during the middle and late Cenozoic, and its effect of strengthening thermohaline circulation at deep and intermediate water depths, contributed to very widespread deep ocean erosion and the formation of hiatuses.

Why was there such a change from siliciclastic to carbonate sedimentation at the Eocene/Oligocene boundary rather than early in the late Eocene? A very broad, shallow Australian-Antarctic continental shelf had been supplied with siliciclastic sediments since early in the Cretaceous. Although rifting, subsidence, and compaction had commenced then, sedimentation had kept up, and shallow-marine sediments were deposited rapidly until the end of the middle Eocene. Australia and Antarctica were almost completely separated when fast spreading began in the middle Eocene (~43 Ma), and this could be expected to increase the rate of subsidence. In the Tasmanian region, slower siliciclastic sedimentation continued in deepening but largely shelfal water at Sites 1170, 1171, and 1172 in the late Eocene until the Eocene/Oligocene boundary (~33.5 Ma), some 10 m.y. after fast spreading started. We suggest that the slower sedimentation resulted from current winnowing, bypassing, and probably also falling sediment supply. Subsidence curves (Hill and Exon, in press) suggest faster subsidence at the Eocene/Oligocene boundary in the Tasmanian region, like that which formed the Victoria Land Basin in nearby Antarctica (Cape Roberts Science Team, 2000). Such subsidence would have rapidly reduced the area of potential erosion in the Tasmanian region and drastically reduced sediment supply. However, only in the earliest Oligocene did pelagic carbonate sedimentation rapidly replace the siliciclastic and diatomaceous sedimentation at the eastern sites. The change in the biogenic component of sedimentation, from diatomaceous in the Eocene to calcareous in the Oligocene, must have been related to the changes in oceanography and latitude. At the western Site 1168, the transition began at the same time but continued through the entire Oligocene.

The Eocene/Oligocene change to carbonate sedimentation probably was also related to contemporaneous climatic cooling, which would have greatly reduced rainfall, and thus weathering and erosion, reducing siliciclastic supply. Thereafter, slow deposition of pelagic carbonate completely dominated off southern and eastern Tasmania and was increasingly important west of Tasmania. The sequence of changes in the sediments over the transition is remarkably consistent over the STR and ETP, as determined from our deep cored sequences. Differences in detail are clearly related to individual setting at the time of deposition (such as latitude) and proximity to the ocean and landmasses. Sequences from elsewhere on the Antarctic margin show a similar drastic reduction in siliciclastic sedimentation and increase in biogenic sedimentation during the Eocene–Oligocene transition. The earliest Oligocene is often marked by an increase in biogenic sediments or components in otherwise relatively slowly deposited siliciclastic sediments, including diamictites (Diester-Hass and Zahn, 1996; Kennett and Barker, 1990; Salamy and Zachos, 1999). However, outside the Tasmanian region, the biogenic component is usually biogenic silica (diatoms) rather than biogenic carbonate (calcareous nannofossils and foraminifers). On the shallow (probably neritic) northwest margin of the Weddell Sea, carbonate-free diatom ooze was deposited during the earliest Oligocene, suggesting significant cool-water upwelling (Barker, Kennett, et al., 1988). On the margins in Prydz Bay and the southern Ross Sea, diatoms became an important component in diamictites (Barron et al., 1991a, 1991b; O'Brien, Cooper, Richter, et al., 2001).

Evaluation of the sedimentary sequences cored in the Tasmanian Gateway region (**Stickley et al.,** this volume) suggests opening of the Tasmanian Gateway to cool shallow-water flow occurred during the latest Eocene, with intensifying current flow toward the Eocene/Oligocene boundary. This was followed in the earliest Oligocene by expansion of the Antarctic cryosphere and deepwater interchange between the southern Indian and Pacific Oceans. This interchange heralds the ACC in this part of the Southern Ocean. Although planktonic microfossils in the Leg 189 cores indicate climatic cooling, there is no evidence of glaciation in these sequences. Indeed, the calcareous nannofossil assemblages suggest somewhat warmer conditions at equivalent latitudes elsewhere in the Southern Ocean (Wei and Wise, 1990; Wei and Thierstein, 1991; Wei et al., 1992).

The late Eocene glauconitic siltstones in the sites closest to Antarctica are overlain, with little gradation, by ooze and chalk of early Oligocene age, whereas near western Tasmania there is more gradation upward into the Oligocene. From the earliest Oligocene onward, sedimentation at the eastern Leg 189 sites was completely dominated by deposition of nannofossil ooze. Sedimentation rates of these oozes were faster than those of the glauconitic silts. At the eastern sites, Oligocene rates were slower than those of the lower and middle Eocene siliciclastic sediments, but later rates were comparable. In contrast, at Site 1168 rates were slower across the Eocene/Oligocene boundary but comparable in the upper Eocene siliciclastic and upper Oligocene to lower Miocene marly sequences. Although the age of the base of the carbonates requires better constraint, existing stratigraphic data suggest deposition commenced at ~30 Ma (Stickley et al., submitted [**N1**]), following the oxygen isotope shift, which is dated at ~33.5 Ma. The isotopic shift represents major cooling and the initial major cryospheric development of East Antarctica (Shackleton and Kennett, 1975; Miller et al., 1991; Wei, 1991; Zachos et al., 1994) and major expansion of the psychrosphere with its deep ocean circulation (Kennett and Shackleton, 1976). On northwest Tasmania there is an alpine glacial tillite, dated palynologically as latest Eocene or earliest Oligocene (Macphail et al., 1993). In summary, the synchronous commencement of biogenic carbonate deposition appears to reflect major tectonic, climatic, and oceanographic changes that affected broad regions in the Southern Ocean near Tasmania. At the eastern Leg 189 sites, these changes created a more dynamic, well-ventilated ocean with increased upwelling and higher surface water biogenic productivity, which increased rates of sedimentation of calcareous nannofossils and diatoms and decreased preservation of organic carbon. Open-ocean planktonic diatoms replaced neritic diatoms, reflecting this deepening and also suggesting initiation of limited coastal upwelling on the STR and Tasmania during the earliest Oligocene (**Stickley et al.,** this volume). Furthermore, associated cooling of the Antarctic and Australian continents apparently decreased weathering rates and transport of siliciclastic sediments to the margins. In addition, subsidence rapidly reduced land areas, which also became more remote from the depocenters on the continental margins, dramatically decreasing the transport of siliciclastic sediment to those depocenters. The environment of deposition was thus transformed from the late Eocene to the earliest Oligocene from siliciclastic to deep-sea carbonate sediments. At the relatively nearshore western Site 1168 there was a long transition, extending from the earliest Oligocene until the early Miocene.

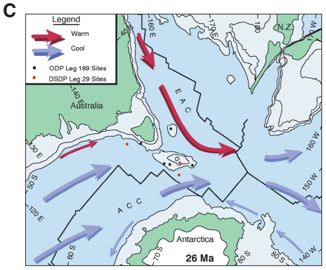
# OLIGOCENE AND YOUNGER HISTORY: SUBSIDENCE AND FLIGHT NORTHWARD

## Oligocene

During the Oligocene, Antarctica and the South Tasman Rise separated further (Fig. F7C). By the late Oligocene, the ACC was well established at all water depths south of the STR and currents also moved through the South Tasman Saddle between Tasmania and the STR. Much of the early Oligocene (~33–30 Ma) at all sites except Site 1168 is represented by a hiatus considered to be equivalent to the regional Marshall Paraconformity (**Pfuhl and McCave,** this volume) and to have been caused by initiation of the ACC. At Site 1168, farther to the north and to the west of Tasmania, the interval usually represented by the Marshall Paraconformity is represented only by an interval of reduced sedimentation rates (**Pfuhl and McCave,** this volume). In spite of Oligocene cooling, conditions remained temperate in the vicinity of Tasmania and the South Tasman Rise. By this time the development of the proto-ACC prevented a countercurrent like that of the late Eocene from flowing northward across the South Tasman Rise. As a result, the warm East Australia Current began to influence the Tasmanian region.

F7C. Early Oligocene situation, p. 35.

C




Relatively thin deepwater Oligocene chalks at Sites 1170–1172, where current action greatly compressed the section, grade westward into the thick (~300 m) marly Oligocene sequence at Site 1168. A brief hiatus seems to be present at the abrupt Eocene/Oligocene lithologic boundary at Sites 1170–1172 (Shipboard Scientific Party, 2001c, 2001d, 2001e; Fuller and Touchard, in press), although it can be clearly dated only at Site 1172 (Stickley et al., submitted [N1]). At the current-swept southern sites (1170 and 1171) the late Oligocene unconformity, common in much of the Southern Ocean, is well developed. Overall, the assemblages suggest well-ventilated cool temperate conditions and bathyal water depths at Sites 1170–1172. At Site 1172, the Oligocene sequence is ~20 m of pale foraminifer-bearing nannofossil chalk with some thin, greenish glass-bearing mudstone horizons (Shipboard Scientific Party, 2001e). Nannofossils and planktonic foraminifers dominate, but palynomorphs are largely absent. Diatoms and nannofossils (and dinocysts present in one sample) indicate relatively warm well-ventilated conditions and bathyal water depths. $CaCO_3$ increases upcore from 55 to 85 wt%, with a rapid decline in siliciclastic debris, siliceous organisms, and organic walled palynomorphs as open-ocean and oxidizing conditions were established. At Site 1171, the Oligocene sequence is only ~10 m thick, and at Site 1170 it is ~60 m thick. At both sites it consists of pale foraminifer-bearing nannofossil chalk.

At Site 1168, the Oligocene sequence is represented by ~310 m of multicolored calcareous mudstone (Shipboard Scientific Party, 2001b). The ~40-m-thick lower Oligocene sequence consists of varicolored silty claystone, clayey siltstone, and sandy claystone with <20 wt% $CaCO_3$. The ~270-m-thick upper Oligocene sequence is more calcareous (<40 wt% $CaCO_3$). Robert (in press) shows that quartz, clay, and biogenic calcite are roughly subequal; illite again predominates over kaolinite, indicating reduction of relief but ongoing intense weathering. Calcareous nannofossils and planktonic foraminifers dominate, and molluskan fragments are present. Benthic foraminifers increased in diversity because oxygenation increased while the water depth deepened from neritic to upper bathyal. Dinocysts increasingly dominated over spores and pollen as the sea level rose and distance from land increased. Conditions were cool to warm temperate. This was a quiet, restricted, relatively oxygen poor environment. In contrast to the other sites, there is no abrupt lithologic change at the Eocene/Oligocene boundary, but rather a steady increase in water depth, a steady decrease in sand fraction (mainly quartz), and an increase in carbonate dominated by calcareous nannofossils through the Oligocene.

## Comparison with the Antarctic Margin

Oligocene carbonates are common in the Tasmanian region because of the interplay of tectonics, climate, and oceanography. The sequences at the southerly Sites 1170 and 1171 have a markedly different Eocene–Oligocene sediment transition compared with nearby parts of Antarctica. We do not know of Antarctic margin sectors that experienced pelagic carbonate deposition in the earliest Oligocene. The Antarctic margin was marked by deposition of biosiliceous sediments or more slowly accumulating siliciclastic sediments with an increased siliceous biogenic component. Why did the environment near the Tasmanian margin apparently favor biogenic carbonate preservation and relatively low biosiliceous productivity? Here, even Eocene siliciclastic sediments generally contain a better record of better preserved calcareous nannofossils and foraminifers than elsewhere.

These observations suggest that different climatic regimes existed near the Tasmanian and Antarctic margins during the Eocene and Oligocene. The earliest Oligocene was a time of major cryospheric expansion in the southern Indian Ocean sector and in the southern Ross Sea. But in the Tasmanian region, biogeographic evidence from calcareous nannofossils, as well as lack of any evidence for glaciation, indicate that conditions were slightly warmer than elsewhere, even during the Oligocene.

Why are carbonates preserved off Tasmania during the Oligocene but not on the nearby Antarctic margin? We hypothesize that warmer surface waters were carried southward from the subtropics, along the eastern margin of Australia by the East Australian Current, and southward around western Australia into the Australo-Antarctic Gulf. The beginning of constriction of the Indonesian Seaway in the Oligocene (Hall, 1996) would have increased southward flow of warm waters along the east Australian margin. These subtropical waters would have been relatively saline and thus would have helped promote production of deep waters. Hence, this sector of the margin may have operated in an antiestuarine mode (Berger et al., 1996), marked by downward flux of deep waters and inward flow of surface waters, as in the modern North Atlantic. In this case, upwelling of nutrient-rich waters is diminished and carbonate accumulation is favored over biosiliceous accumulation.

The Antarctic margin was already separated from warm waters by the onset of the ACC. There was strong carbonate dissolution at shallow water depths and high biosiliceous accumulation, and the margin may have operated in estuarine mode, marked by upwelling of nutrient-rich deep waters and outflow of surface waters. There, carbonate dissolution is favored by the upwelling of old, deep, low-alkalinity, high-$pCO_2$ waters like those in the modern North Pacific Ocean.

A major strengthening of oceanic thermohaline circulation occurred at the climatic threshold of the Eocene–Oligocene transition. This resulted largely from the major cooling and cryospheric development of Antarctica (Kennett and Shackleton, 1976). This cooling, in turn, led to increased onshore aridity and a major reduction of freshwater flow to the surrounding continental margin, which is reflected by the marked reduction in transport of siliciclastic sediments to the Tasmanian margin. Surface waters near the margin would have increased in salinity. A major positive feedback almost certainly would have resulted, with further strengthening of bottom water production and expansion of the oceanic psychrosphere (deep-ocean circulation). Thus, the delivery of high-salinity surface waters to the Tasmanian margin, caused by its plate tectonic setting, may well have enhanced bottom water production and, in turn, increased carbonate biogenic accumulation.

## Neogene History

Neogene sedimentation at Leg 189 sites on the STR and the Tasmanian margin was completely dominated by nannofossil oozes with a significant foraminiferal component. Pelagic carbonate sedimentation was largely continuous, except during the late Miocene and earliest Pliocene, at a number of sites. Miocene deepwater calcareous ooze is thickest at Site 1168 (~300 m) and thinnest at Site 1171 (~170 m). Pliocene oozes are remarkably consistent in thickness (~70 m) at all sites. Pleistocene oozes are thickest at the deepwater STR Site 1170 and thinnest at the shallower, current-swept STR Site 1171. The Miocene–Pliocene transition is missing at Sites 1169 and 1171, and the lower upper Miocene is missing at Site 1168. Otherwise, the lower and upper Miocene and the Pliocene to Quaternary appear to be largely complete sequences. The uppermost Miocene hiatus may have resulted from increased thermohaline circulation associated with Antarctic cryosphere expansion at that time (Hodell et al., 1986). Altogether, the Neogene sediments cored during Leg 189 provide a fine suite of sequences deposited in cool temperate and subantarctic water masses of the Southern Ocean. These represent a treasure chest for high-resolution Neogene paleoclimatic and biostratigraphic investigations of the Southern Ocean. The Neogene carbonates exhibit changes that record changing environmental conditions in response to the northward movement of the STR, Tasmania, and the ETP from Antarctica and shifting positions of the Subtropical Convergence and the Subantarctic Front. The pelagic carbonates accumulated at relatively low rates (~1–2 cm/k.y.) typical of the open ocean. Relatively low diversity benthic foraminiferal assemblages indicate deposition in abyssal depths under generally well ventilated conditions characteristic of the Antarctic Circumpolar Current region. Other than a small, pervasive clay fraction, siliciclastic sediments are absent throughout the Neogene, except in the lower Neogene of Site 1168, which is the site closest to a present land mass. Nannofossil oozes are conspicuously pure white on the STR in the lower Neogene, which corresponds to a period when the STR was well clear of the siliciclastic influences of Antarctica and yet had not come under the late Neogene influence of increasing aridification and associated dustiness of Australia. Diatoms are present consistently throughout the Neogene carbonates but exhibit a distinct increase in abundance and diversity after the middle Miocene. This almost certainly reflects an increase in upwelling within the Southern Ocean at that time in response to the well-known expansion of the Antarctic cryosphere. A marked increase in carbonate ooze deposition during the early Pliocene at Sites 1169 and 1170, on the southwestern STR, is not observed at other sites, suggesting local concentrations of calcareous nannofossils rather than any regional trend like that in the southwest Pacific (Kennett and von der Borch, 1986). During the latest Neogene, planktonic foraminifers become much more important relative to calcareous nannofossils. This may reflect increased winnowing by deep currents and/or a decrease in relative production of calcareous nannofossils compared to planktonic foraminifers.

Postcruise investigations of Leg 189 Neogene sequences are leading to a significant increase in understanding of paleoclimatic and paleoceanographic history of the Southern Ocean. Upper Neogene sections have been satisfactorily spliced from multiple cores from four of the sites (Sites 1168 and 1170–1172) to provide essentially continuous paleoclimatic records. Pervasive sedimentary cycles are apparent throughout the entire Neogene, based on observations of the sediment record and changes in the physical properties of the sediments. Investigations of clay assemblages suggest relatively warmer conditions during the early Neogene until ~15 Ma. After that, clay assemblages show increases in chlorite, illite, and/or kaolinite, suggesting general regional cooling and Antarctic glacial expansion (**Robert**, this volume).

Sequences cored during Leg 189 have provided stable isotopic records with the highest chronologic resolution so far of the early Miocene (**Ennyu and Arthur**, this volume, in press) and the middle Miocene (Shevenell and Kennett, in press) from the Southern Ocean. These well-dated stable isotopic records clearly exhibit the well-known major oxygen isotopic shift of the middle Miocene at ~14 Ma as well as regional ocean circulation changes (at depths >1500 m) commensurate with the middle Miocene global climate transition (16.8–12 Ma). Regional oxygen and carbon isotopic trends have been considered to support hypotheses relating middle Miocene cooling and Antarctic cryosphere expansion to reorganization of ocean circulation and related changes in meridional heat flux (Shevenell and Kennett, in press).

Kelly and Elkins-Tanton (in press) describe an occurrence in a single sample of microtektites from the upper middle Miocene–lowermost Pliocene of Site 1169. Although precise biostratigraphic dating of deposition is not possible, by using major element composition they attribute the origin of the microtektites to the HNa Australite field considered to be of late Miocene age (~10.2 Ma) (Bottomley and Koeberl, 1999).

During the late Neogene, clays become increasingly important in the pelagic carbonates, in part because of increasing dust transport from Australia. A distinct influx of kaolinite at several sites, including the southern STR, during the late Pliocene and Quaternary probably reflects increasing southeastward wind transport of relict clays from an increasingly arid Australia. The uppermost Neogene sediments at Site 1172, which is downwind from Tasmania, exhibit distinct cycles in clay abundance in the biogenic oozes, almost certainly in response to glacial–interglacial oscillations in Australian continental aridity. This increase in aridity was almost certainly linked with a cooling trend during the late Neogene. The disappearance in the Tasmanian region of large gephyrocapsids above the middle Pleistocene (**Stant et al.,** this volume) is consistent with this long-term trend toward cooler conditions. **Stant et al.** (this volume) also showed from the distribution of warm-loving discoasters in Pliocene sediments the presence of a subtropical watermass front (~45°S), south of which the discoasters did not extend during the late Pliocene. Furthermore, their distribution indicates the stronger influence of the East Australia Current compared with the Leeuwin Current in transporting subtropical waters to the region during the late Pliocene.

The Leg 189 sites also provided opportunities for studies of Quaternary paleoclimatology. Nürnberg et al. (in press) used geochemical proxy data from four Leg 189 sites to reconstruct the regional history of glacial and interglacial changes near the subtropical convergence in the last 500 k.y. There is a complex story of variations in paleoexport production, terrigenous flux, sea-surface temperature, and movements of water masses and oceanographic fronts through time. Each glacial period and each interglacial period was different from the others; however, the authors did find that interglacial periods were commonly times of lower productivity and that their deposits contained less terrigenous matter than those of glacial periods, indicating that the subtropical convergence was south of most sites during most interglacials.

Malone et al. (2004) used a diffusion-advection model to calculate the glacial–interglacial change in bottom water $\delta^{18}O$ from pore water oxygen isotopic profiles at Sites 1168 and 1170. The results indicate that Circumpolar Deep Water temperatures were –0.2°C (Site 1170) and –0.5°C (Site 1168) at the Last Glacial Maximum. Since the last glacial maximum, $\delta^{18}O$ changed by 1.0‰–1.1‰ (±0.15‰) and bottom water temperatures increased by ~1.9° and ~2.6°C, respectively, at the sites.

## DISCUSSION AND CONCLUSIONS

As noted in Exon, Kennett, Malone, et al. (2001), the Leg 189 drill sites, in 2463–3568 m water depths, have tested, refined, and extended the hypothesis that climatic cooling and an Antarctic ice sheet (cryosphere) developed in late Eocene to early Oligocene times, as the ACC progressively isolated Antarctica thermally (Kennett et al., 1975). This has led to improved understanding of Southern Ocean evolution and its relationship to Antarctic climatic development. The relatively shallow region off Tasmania is one of the few locations where well-preserved and almost complete marine Cenozoic sequences can be drilled at present-day latitudes of 40°–50°S and paleolatitudes of up to 70°S. The Oligocene and younger sequences are carbonate rich and not deeply buried and are hence suitable for stable isotopic investigations. The broad geological history of all the sites is comparable, although there are important pre-Miocene differences between Site 1168 in the AAG and the sites in the Pacific Ocean, as well as from north to south.

The drill sites are on submerged continental blocks extending to 600 km south of Tasmania. These blocks were at polar latitudes in the Late Cretaceous when Australia and Antarctica were still united, although rifts had developed associated with commencement of slow separation and northward movement of Australia. In all, 4539 m of core was recovered with average recovery of 89%. The deepest core hole penetrated 960 m beneath the seafloor. The entire sedimentary sequence cored is marine and contains varied microfossil assemblages that record conditions from the Late Cretaceous (Maastrichtian) to the late Quaternary. Until the earliest Oligocene, terrestrially derived siliciclastic sediments predominate at all sites. During the Oligocene there was an abrupt change to pelagic carbonate deposition at the eastern sites, but siliciclastic debris remained important into the early Miocene at Site 1168.

The record in the cores indicates that the Tasmanian land bridge almost completely blocked the eastern end of the widening AAG during both the slow-spreading phase and the fast-spreading phase (starting at ~43 Ma) until the late Eocene. Drilling evidence, especially that from clay minerals, and other geological and geophysical evidence points to a number of tectonic events during the Cenozoic in the Tasmanian region:

1. Paleocene north–south strike-slip movement within the STR, terminated at ~55 Ma by seafloor spreading south of STR;
2. Uplift and erosion on the Tasmanian margins near the Paleocene/Eocene boundary;
3. Termination of northwest–southeast strike-slip movement west of Tasmania when fast spreading began at ~43 Ma;
4. Eocene (post ~43 Ma) north–south strike-slip movement along the western boundary between the STR and Antarctica, terminating in the latest Eocene at ~33.5 Ma; and
5. Early Oligocene subsidence of the STR 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.

Prior to the late Eocene, marine siliciclastic sediments (largely mudstones at Leg 189 sites) were deposited in a temperate sea on broad, shallow, tranquil shelves. There was little or no circulation of marine waters between the AAG and the Pacific Ocean. Sediment supply kept up with subsidence despite the rifting, drifting, and compaction during largely deltaic deposition. Dinocysts, spores, and pollen are ever present. Reducing conditions in the often organic-rich sediments helped ensure that especially calcareous and, to some extent siliceous, microfossils were preserved only sporadically. The spores and pollen indicate that this part of Antarctica was temperate (with little ice) during this time and supported rain forests with southern beeches and ferns—part of the Late Cretaceous to Eocene "Greenhouse" world. During the late Eocene the sequences still document marked differences between east and west, when the eastern AAG was warmer and more poorly ventilated than the gradually widening Pacific Ocean. Hence, marine circulation across the former land bridge must still have been very limited. Microfossil biogeography suggests that the east Tasmanian region (Sites 1170–1172) was influenced by a northwestward-flowing cool countercurrent during the Eocene (Fig. F7A). This circulation pattern may well have been in operation from the Maastrichtian, when the proto-Pacific Ocean first existed east of Australia and north of Antarctica (Cande and Stock, in press), until the beginning of the Oligocene.

By the late Eocene (37 Ma), the Tasmanian land bridge had largely separated from Antarctica and the bridge and its broad shelves began to subside. Surface currents affected the deepening shelves. These swept the still-shallow offshore areas, and glauconitic siltstones were deposited slowly as condensed sequences. Palynological and diatom evidence suggest that there were fluctuations in temperature superimposed on a general cooling and that the amount of upwelling also fluctuated in response to the changing oceanic circulation. Calcareous microfossils remained rare. Benthic foraminifers and other evidence indicate that the sites began to deepen slightly at ~37 Ma, although shelf depths continued. Final separation of the southwestern tip of the STR from Antarctica occurred at ~33.5 Ma, leading to profound changes in sediment deposition, climate, and ocean history (Fig. **F7B**).

By the earliest Oligocene, bathyal pelagic carbonates were being deposited at the eastern sites and marls at Site 1168. The developing Antarctic Circumpolar Current cut off warm currents from the north, leading to cooling and some ice sheet formation. These events contributed to global cooling. Conditions were significantly cooler in the Tasmanian offshore region, and there is no positive evidence of terrestrial vegetation in the sediments, although vegetation then existed on Tasmania. However, almost all organic matter deposited during the early Oligocene would have been oxidized in well-ventilated waters.

There were several reasons for the change to pelagic carbonate deposition. 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 and, hence, decreasing precipitation and erosion. Therefore, far less siliciclastic sediment was transported from the land. The reduced flow of detrital organic matter ended the earlier reducing conditions in the sediments and ensured that calcareous organisms were now preserved. Generally slow deposition of deepwater pelagic sediments was initiated. Currents from the north kept the Tasmanian region relatively warm, supporting carbonate deposition rather than the siliceous biogenic deposition that marks much of the Antarctic margin. In the Tasmanian region, and even in the Cape Adare region on the conjugate Antarctic margin, there is no sign of widespread glaciation during the early Oligocene.

The Drake Passage probably opened in the Oligocene, and the Tasmanian Seaway continued to open. In the late Oligocene (Fig. **F7C**) and Neogene, the ACC strengthened and widened, strongly isolating Antarctica from warm-water influences. At ~15 Ma, the east Antarctic cryosphere evolved into ice sheets comparable to those of the present day. This intensified global cooling and thermohaline circulation. The "Icehouse" world had arrived, but temperatures and current activity fluctuated and dissolution and erosion varied over time. The steady northward movement of the Tasmanian region kept sedimentation north of the Polar Front, and pelagic carbonate continued to accumulate in deep waters at average rates of 1–2 cm/k.y. Australia's movement northward into the drier mid-latitudes, along with the global climate change associated with high-latitude ice sheet expansion, led to massive aridity in Australia and an increase in windblown dust abundance at Site 1172 after 5 Ma.

Comparisons with sequences drilled elsewhere on the Antarctic margin are improving our understanding of these momentous changes in Earth history and some of the constraints on modern climates. We suggest that if Australia had not broken away from Antarctica and moved northward, the Earth might not have experienced its Cenozoic ice ages.

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**Figure F1.** Locality map showing Cretaceous–Cenozoic sedimentary basins of southeast Australia, after Exon et al. (in press a). Stipple indicates depocenters with >1500 m of Cretaceous and Cenozoic sedimentary section. Also shown are ODP and DSDP sites and bathymetry. CS = Cape Sorell No. 1 petroleum exploration well, ETS = East Tasman Saddle, STS = South Tasman Saddle, NB = Ninene Basin. Since Eocene or Oligocene times, strong easterly currents have swept shallower South Tasman Rise (STR) areas, the southern Tasmanian margin, and the South Tasman Saddle between Tasmania and the STR, reducing sedimentation rates.

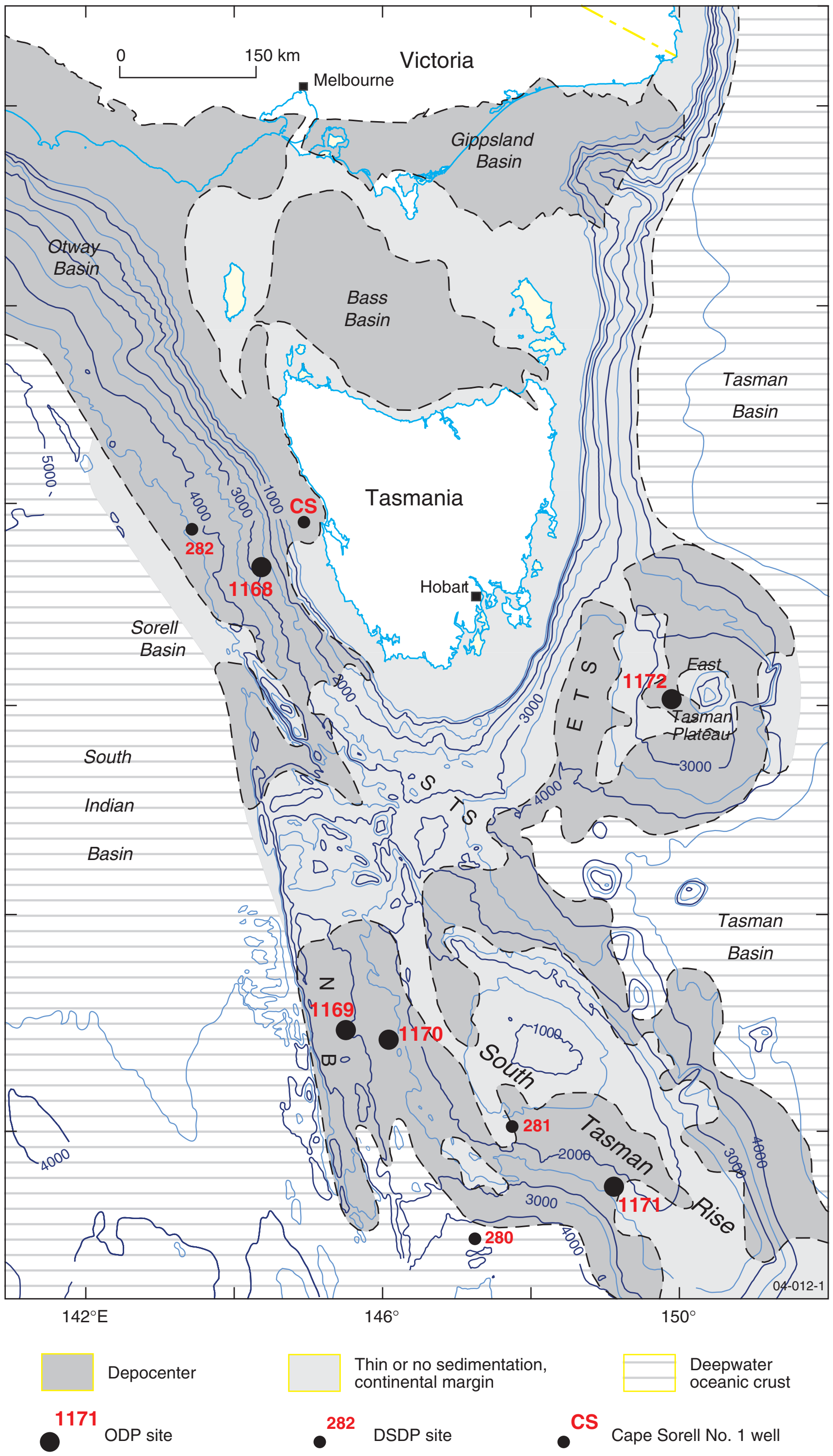


**Figure F2.** Global temperature changes from oxygen isotopes of deep-sea benthic foraminifers (after Crowley and Kim, 1995).

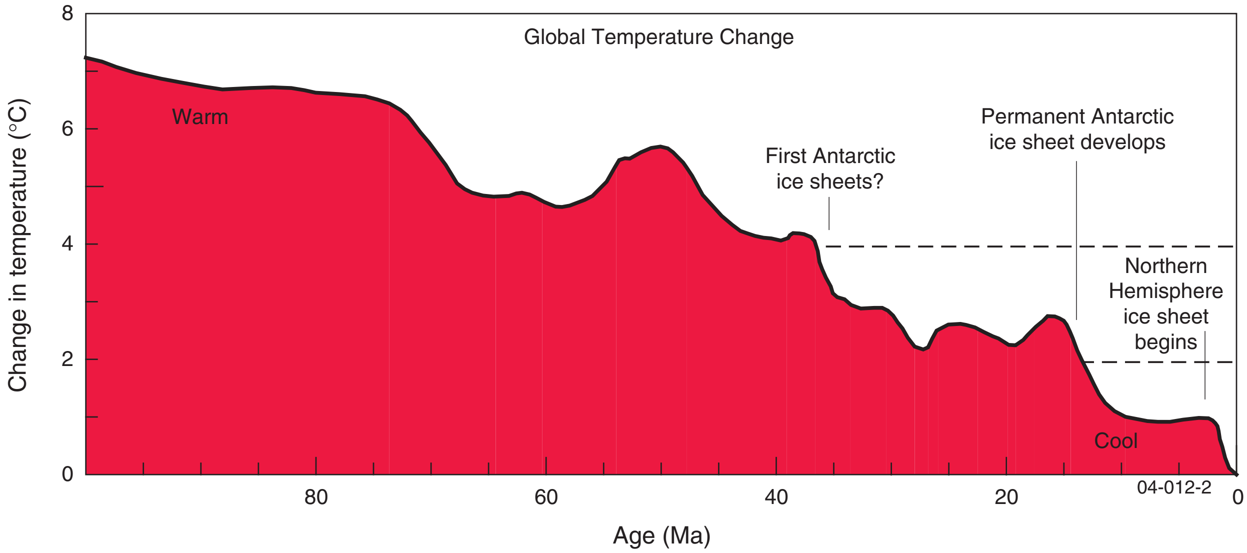


**Figure F3.** Leg 189 sequences drilled. NGR = natural gamma radiation.

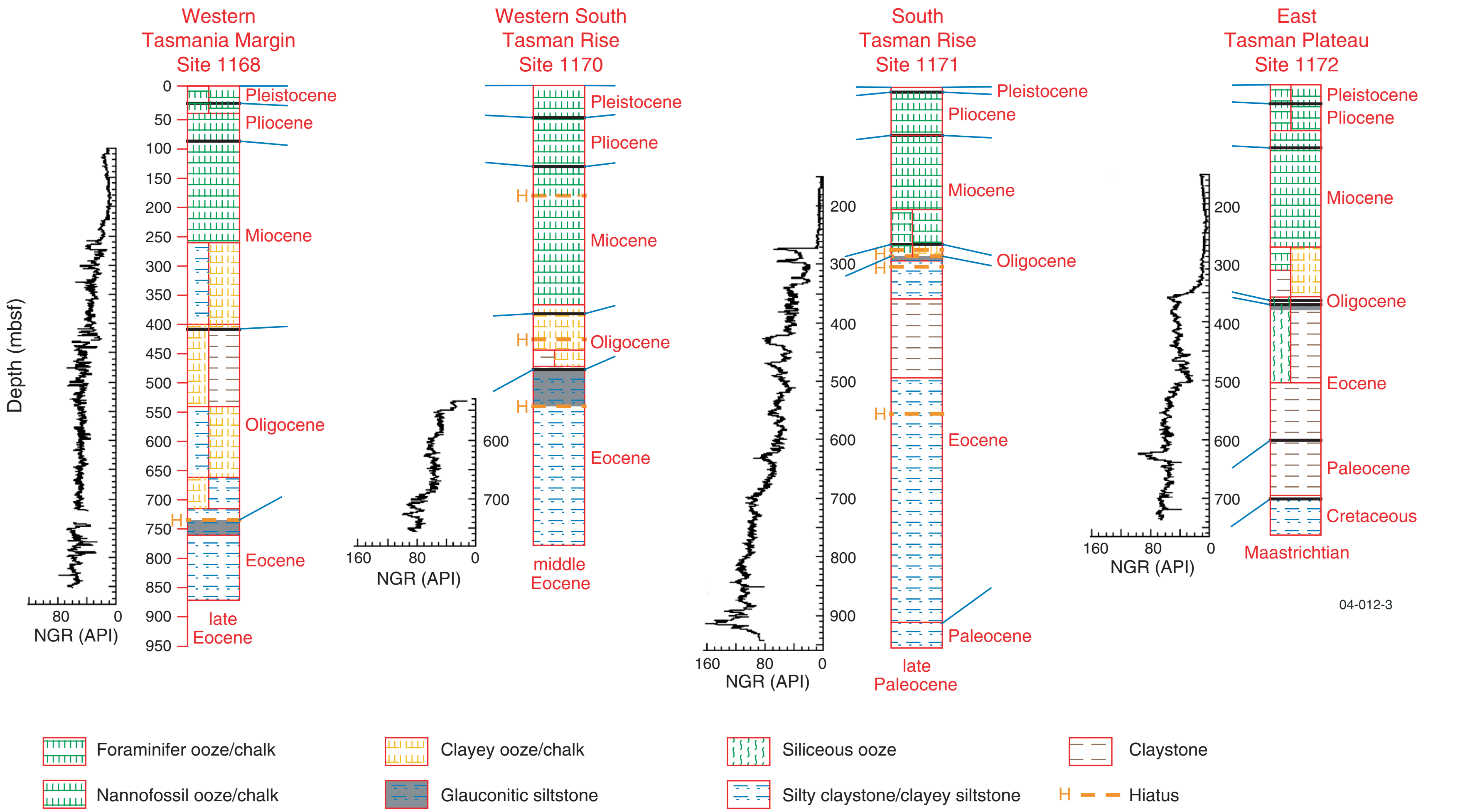


**Figure F4.** Leg 189 time stratigraphy and sediment facies diagram.

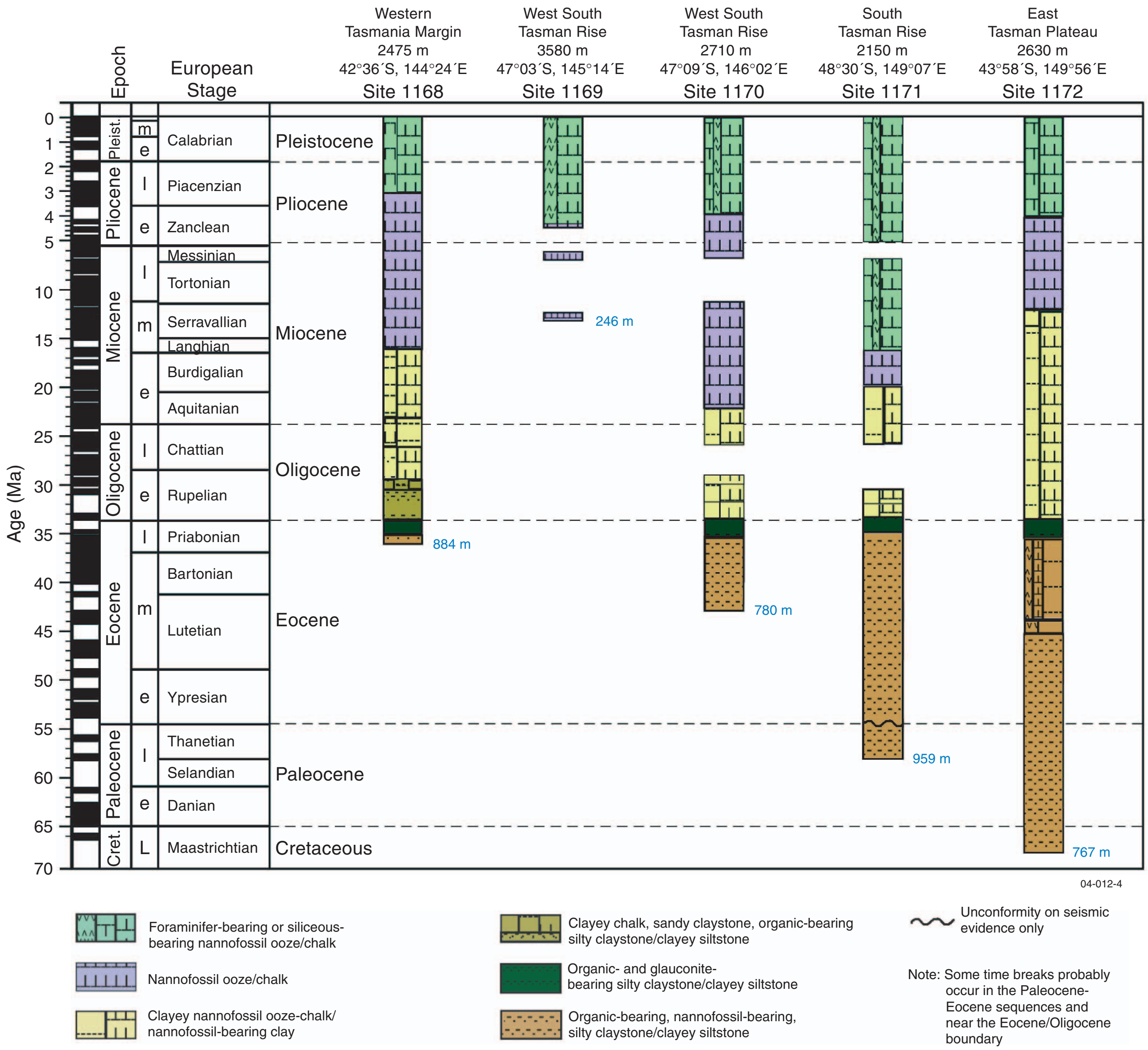


**Figure F5.** Sedimentation rate curves (courtesy of Kristeen McGonigal, after Stickley et al., this volume).

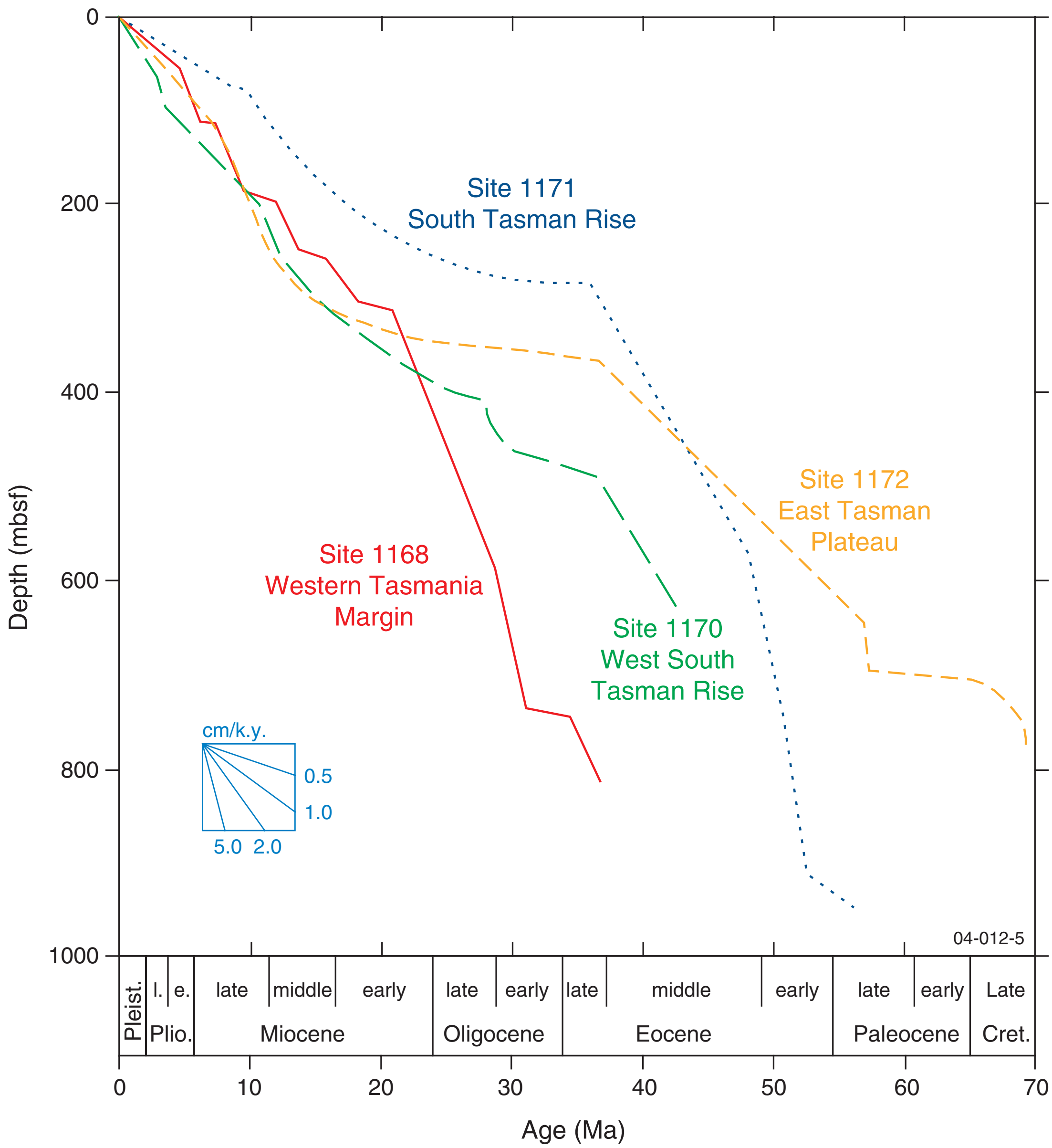


**Figure F6.** Setting of the Tasmanian region within Gondwana during the Late Cretaceous (95 Ma) using the plate tectonic reconstruction of Royer and Rollet (1997). The figure shows the Tasmanian-Antarctic Shear Zone (TASZ) and areas of rift sedimentation. W-STR = west South Tasman Rise, E-STR = east South Tasman Rise, ETP = East Tasman Plateau.

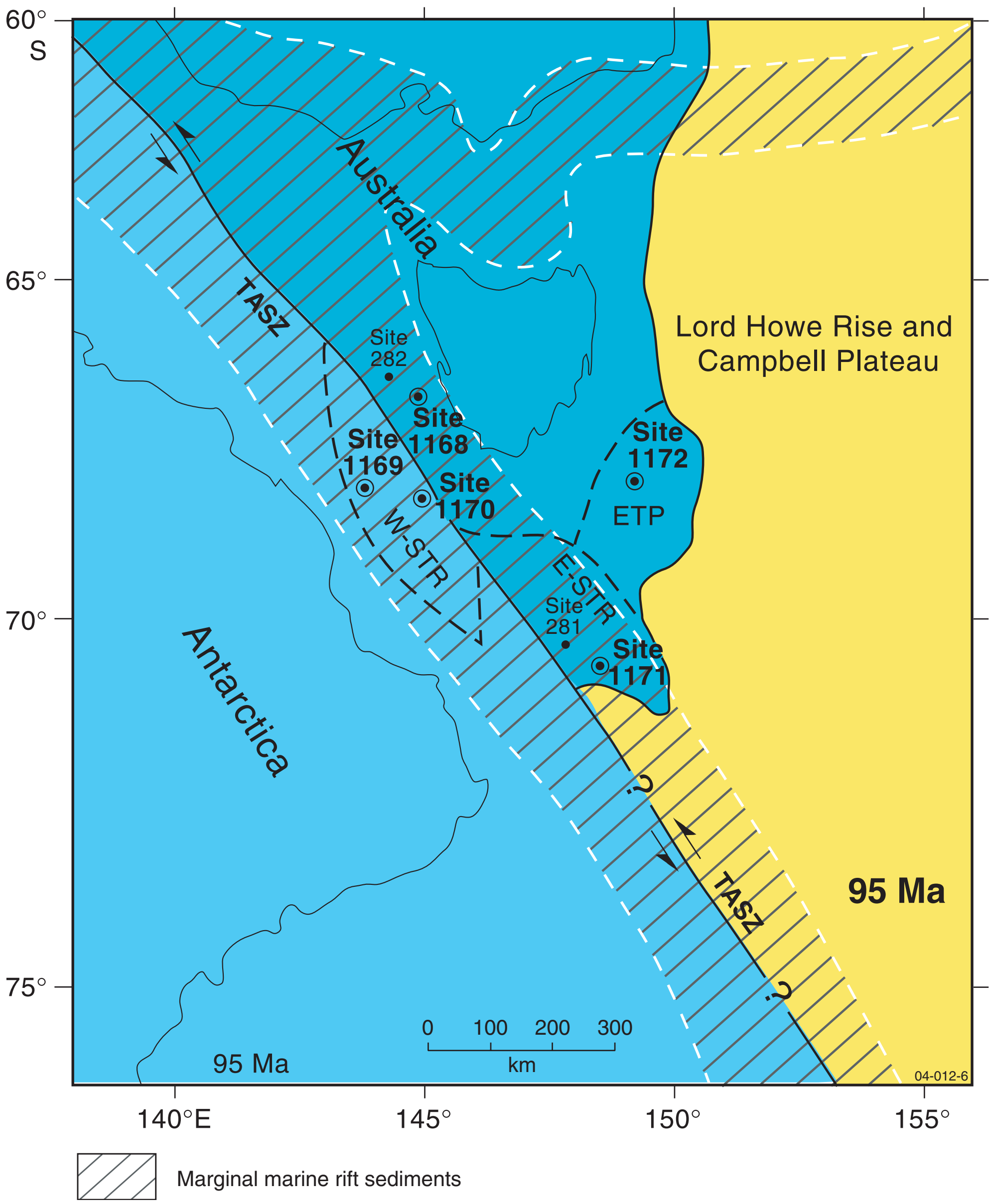
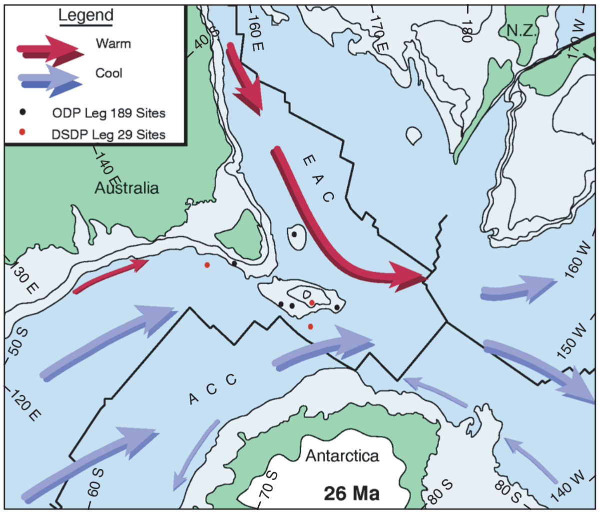


**Figure F7.** Changes through time in the Tasmanian Gateway region as Australia and Antarctica separated. The changes contributed to Antarctic glaciation and thermohaline oceanic circulation (TOC). Maps after Exon et al. (2002) and based on Cande et al. (2000). **A.** 43.7 Ma (middle Eocene). **B.** 33 Ma (Eocene/Oligocene boundary. **C.** 26 Ma (early Oligocene). AAG = Australo-Antarctic Gulf, TLB = Tasmanian land bridge, PP = proto-Pacific Ocean, EAC = Eastern Australian Current, N.Z. = New Zealand. (**Figure shown on next page.**)

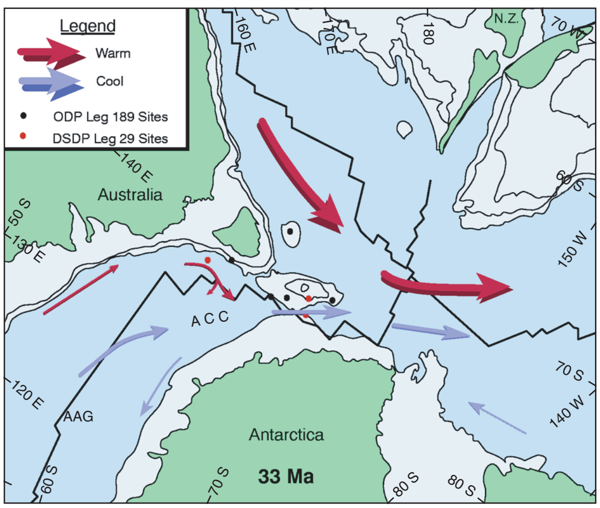
**Figure F7 (continued).** (Caption shown on previous page.).

C



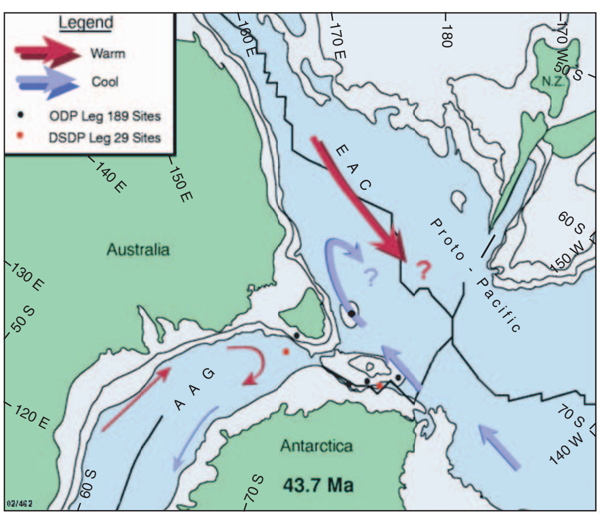

**C. Early Oligocene**
- Fast spreading continues
- TLB subsiding rapidly
- Pelagic carbonates on TLB
- No AAG
- Southern Ocean developing
- Deep AAG-PP connection
- EAC not to Antarctica
- ACC in full flow
- TOC in existence
- Antarctic glaciation

B




**B. Eocene/Oligocene boundary**
- Fast spreading continues
- TLB subsiding rapidly
- Glauconitic silts on TLB
- AAG restricted
- Shallow AAP-PP connection
- EAC not to Antarctica
- ACC forming
- Global cooling soon after
- TOC soon after
- Onset of Antarctic glaciation

A

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**A. Middle Eocene**
- AAG fast spreading starts
- TLB in place
- Shallow marine muds on TLB
- AAG very restricted
- No AAG-PP connection
- EAC warms Antarctic
- No TOC

**Table T1.** ODP Leg 189 sites.

| Site | Location | Water depth (m) | Depth cored (mbsf) | Total recovered (m) | Total recovery (%) | Oldest sediment cored |
|---|---|---|---|---|---|---|
| 189- | | | | | | |
| 1168 | 42°36.6′S, 144°24.8′E | 2464 | 883.5 | 1191 | 93 | upper Eocene |
| 1169 | 47°03.9′S, 145°14.2′E | 3568 | 246.3 | 225 | 91 | middle Miocene |
| 1170 | 47°09.0′S, 146°03.0′E | 2407 | 779.8 | 1027 | 87 | middle Eocene |
| 1171 | 48°30.0′S, 149°06.7′E | 2148 | 958.8 | 995 | 82 | upper Paleocene |
| 1172 | 43°75.6′S, 149°55.7′E | 2622 | 776.5 | 1100 | 92 | Maastrichtian |

# CHAPTER NOTES*

**N1.** Stickley, C.E., Brinkhuis H., Schellenberg S.A., Sluijs, A., Röhl, U., Fuller, M., Grauert, M., Huber, M., Warnaar J., and Williams, G.L., submitted. Timing and nature of the opening of the Tasmanian Gateway: the Eocene/Oligocene transition of ODP Leg 189 sites. *Paleoceanography.*

*Dates reflect file corrections or revisions.