

## History of oceanic front development in the New Zealand sector of the Southern Ocean during the Cenozoic—a synthesis

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**Abstract** The New Zealand sector of the Southern Ocean (NZSSO) has opened about the Indian-Pacific spreading ridge throughout the Cenozoic. Today the NZSSO is characterised by broad zonal belts of antarctic (cold), subantarctic (cool), and subtropical (warm) surface-water masses separated by prominent oceanic fronts: the Subtropical Front (STF) c. 43°S, Subantarctic Front (SAF) c. 50°S, and Antarctic Polar Front (AAPF) c. 60°S. Despite a meagre database, the broad pattern of Cenozoic evolution of these fronts is reviewed from the results of Deep Sea Drilling Project-based studies of sediment facies, microfossil assemblages and diversity, and stable isotope records, as well as from evidence in onland New Zealand Cenozoic sequences. Results are depicted schematically on seven paleogeographic maps covering the NZSSO at 10 m.y. intervals through the Cenozoic.

During the Paleocene and most of the Eocene (65–35 Ma), the entire NZSSO was under the influence of warm to cool subtropical waters, with no detectable oceanic fronts. In the latest Eocene (c. 35 Ma), a proto-STF is shown separating subantarctic and subtropical waters offshore from Antarctica, near 65°S paleolatitude. During the earliest Oligocene, this front was displaced northwards by development of an AAPF following major global cooling and biotic turnover associated with ice sheet expansion to sea level on East Antarctica. Early Oligocene full opening (c. 31 Ma) of the Tasmanian gateway initiated vigorous proto-circum-Antarctic flow of cold/cool waters, possibly through a West Antarctic seaway linking the southern Pacific and Atlantic Oceans, including detached northwards “jetting” onto the New Zealand plateau where condensation and unconformity development was widespread in cool-water carbonate facies. Since this time, a broad tripartite division of antarctic, subantarctic, and subtropical waters has existed in the NZSSO, including possible development of a proto-SAF within the subantarctic belt. In the Early–early Middle Miocene (25–15 Ma), warm subtropical waters expanded southwards into the northern NZSSO, possibly associated with reduced ice volume on East Antarctica but

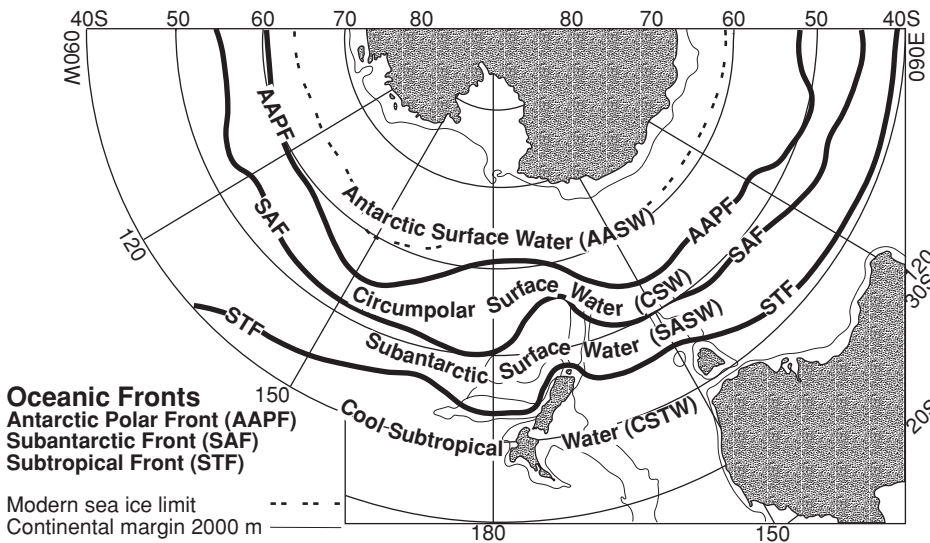
particularly with restriction of the Indonesian gateway and redirection of intensified warm surface flows southwards into the Tasman Sea, as well as complete opening of the Drake gateway by 23 Ma allowing more complete decoupling of cool circum-Antarctic flow from the subtropical waters. During the late Middle–Late Miocene (15–5 Ma), both the STF and SAF proper were established in their present relative positions across and about the Campbell Plateau, respectively, accompanying renewed ice buildup on East Antarctica and formation of a permanent ice sheet on West Antarctica, as well as generally more expansive and intensified circum-Antarctic flow.

The ultimate control on the history of oceanic front development in the NZSSO has been plate tectonics through its influence on the paleogeographic changes of the Australian–New Zealand–Antarctic continents and their intervening oceanic basins, the timing of opening and closing of critical seaways, the potential for submarine ridges and plateaus to exert some bathymetric control on the location of fronts, and the evolving ice budget on the Antarctic continent. The broad trends of the Cenozoic climate curve for New Zealand deduced from fossil evidence in the uplifted marine sedimentary record correspond well to the principal paleoceanographic events controlling the evolution and migration of the oceanic fronts in the NZSSO.

**Keywords** New Zealand; Southwest Pacific; Antarctica; Southern Ocean; Cenozoic; paleoclimate; paleoceanography; oceanic fronts; DSDP cores; ice sheets

### INTRODUCTION

The New Zealand subcontinent lies in the global oceanic hemisphere at the interface of the Southwest Pacific Ocean and the Southern Ocean. It is proximal to both the frigid Antarctic continent to the south, and the Western Pacific Warm Pool to the north (Tomczak & Godfrey 1994). Consequently, seafloor deposits in the vicinity of New Zealand have the potential for being a sensitive monitor of present and past oceanographic changes driven by any changes in these cold and warm source regions. The most prominent feature evident on satellite imagery of the modern Southern Ocean is the conspicuous bands of circumpolar surface-water masses separated by oceanic fronts (Fig. 1), each marked by sharp changes in vertical water structure, temperature, salinity, and nutrients. This paper overviews some of the geological evidence for the timing and development of these oceanic fronts in the New Zealand sector of the Southern Ocean (NZSSO) during the Cenozoic, an evolution that is closely linked to the changing configuration of the southern continents in relation to their surrounding ocean basins as a consequence of seafloor spreading, and the resultant dramatic changes in the ice budget of Antarctica over this period.



**Fig. 1** Modern surface-water masses and their bounding oceanic fronts in the New Zealand sector of the Southern Ocean (adapted from Belkin & Gordon 1996).

**SOUTHERN OCEAN FRONTS**

Despite various definitions of the Southern Ocean (e.g., Lazarus & Caulet 1993; Belkin & Gordon 1996), it is conveniently treated here as including all antarctic and subantarctic water masses south of the Subtropical Front which, in the New Zealand region, presently lies near 43–45°S latitude (Fig. 1). The Southern Ocean is a key component of the Earth’s ocean-climate system through the major role it plays in the meridional transfer of heat. Gordon (1988) estimated that presently at least 60% of the oceanic volume is cooled around Antarctica before being transferred north. In the deep ocean, the transfer of cold water occurs mainly via deep western boundary currents as portrayed in the “thermohaline conveyor belt” model of Broecker & Denton (1990). For surface waters, the heat transfer relates to a combination of wind drift and eddies associated with oceanic fronts.

Oceanic fronts are characterised by marked changes in vertical structures from one side to the other. Typically these are manifested at various levels by enhanced horizontal gradients in temperature and/or salinity, and by concentrated geostrophic flow. A comprehensive review of the position, definition, and structure of the oceanic fronts in the circum-Antarctic Southern Ocean as a whole is provided by Belkin & Gordon (1996). Between New Zealand and Antarctica

there are presently three main oceanic fronts separated by four main surface water masses (Fig. 1; Table 1). Although other fronts lie to the north (Tasman Front at c. 30–36°S and Southern Tropical Convergence at c. 20°S) and in the far south (Antarctic Divergence at c. 65°S) of this region, it is the history of development of the three main NZSSO fronts—the Subtropical Front (STF), Subantarctic Front (SAF), and Antarctic Polar Front (AAPF) (Table 1)—that are the principal topic of this review.

**ESTABLISHING PALEOPOSITIONS OF WATER MASSES**

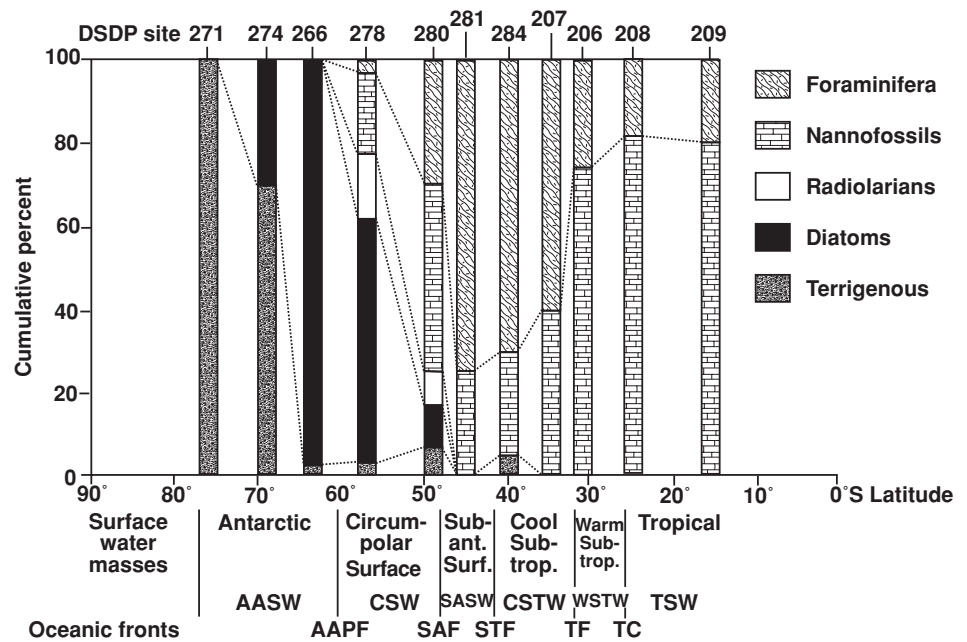
The evidence for determining past positions of oceanic fronts is essentially limited by our ability to distinguish between cold, cool, and warm surface-water provinces in the geological record of marine sedimentary deposits. Proxy estimations of past sea-water temperatures can be made from various lithological, paleontological, and geochemical properties of sedimentary deposits (e.g., Boggs 1987). Lithological features include the type of deep-sea sediment facies, their textural properties, and compositional data such as the occurrence of ice-rafted debris or particular clay mineral assemblages. Paleontological criteria relate especially to the relative abundances of calcareous and

**Table 1** Major oceanic front characteristics and their intervening surface-water masses in the modern NZSSO (see also Fig. 1).

Water mass <i>or</i> oceanic front	Symbol	Latitude (°S)	Temperature (°C)	Salinity (‰)
Subtropical Water	STW			
<b>Subtropical Front</b>	STF	c. 43–45	15 summer 10 winter	34.8
Subantarctic Surface Water*	SASW			
<b>Subantarctic Front</b>	SAF	c. 52	8 summer	34.5
Circumpolar Surface Water	CSW			
<b>Antarctic Polar Front</b>	AAPF	c. 56	2	34.2
Antarctic Surface Water	AASW			

\* In the New Zealand region previously named Australasian Subantarctic Water (ASW).

**Fig. 2** Composition of core-top sediment samples in relation to modern surface-water masses in a north-south transect of DSDP sites from well north of New Zealand to offshore Antarctic continent (based on data from Burns 1977). Abbreviations defined in Table 1, plus CSTW, Cool Subtropical Water; TF, Tasman Front; WSTW, Warm Subtropical Water; TC, Tropical Convergence; TSW, Tropical Surface Water.

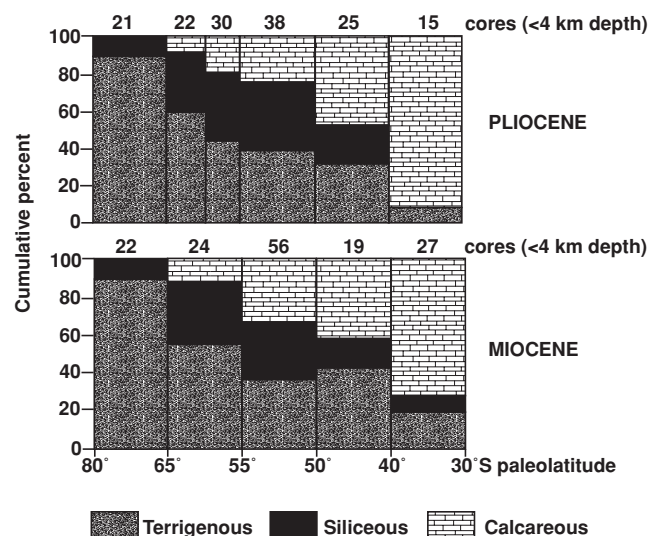


siliceous or other microfossils in the sediments, identifying the key species and species assemblages present, noting species diversity, and recording certain morphometric features of tests, such as coiling directions in some planktic foraminifera (e.g., Arnold & Parker 1999) or degree of silicification and ornamentation in radiolarians (e.g., Lazarus & Caulet 1993). Geochemical information relevant to past oceanic climates comes primarily from measuring the oxygen and carbon isotope composition ( $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ ) of calcareous microfossil shells (e.g., Shackleton & Kennett 1975; Rohling & Cooke 1999).

Burns (1977) showed that a general relationship exists between surficial deep-sea bottom sediment types and overlying modern surface-water masses in the wider Southwest Pacific region by determining the main sediment components in a transect of Deep Sea Drilling Project (DSDP) core-top samples stretching from north of New Zealand through the NZSSO to Antarctica (Fig. 2). North of the SAF, biocalcareous sediments dominate, with the proportion of nannofossils to foraminifera increasing northwards. South of the AAPF, the modern seafloor deposits are essentially non-calcareous and are either biosiliceous, consisting predominantly of diatoms, or become increasingly enriched in terrigenous material as the Antarctic continent is approached. Between the AAPF and SAF there is a mix of biosiliceous and biocalcareous components, the former usually dominating and comprising predominantly diatoms, but with a conspicuous contribution from radiolarians (Fig. 2). A broadly comparable kind of zonal relationship between bottom sediment composition and surface-water mass appears to have existed more widely for at least Neogene core sections in the Southern Ocean, which show an overall north-south change in the content of biocalcareous versus biosiliceous versus terrigenous components in both Pliocene and Miocene deposits with paleolatitude (Fig. 3). Consequently, a first-order estimation of possible surface-water masses can be made from trends in the spatial and temporal distribution of different sediment types. Potential problems are well known, and include such matters as poor preservation potential of especially

coccoliths and diatoms, dissolution of calcareous microfossils at deep core sites, winnowing of fines in areas of strong bottom currents, and the need to distinguish between local occurrences of biosiliceous sediment that may develop in areas of focused upwelling about continental margins and those indicative of more widespread open-ocean upwelling in cold waters.

For the NZSSO, the primary database of published geological and paleoclimatic information is available in a widely scattered array of 34 long cores obtained during DSDP Legs 21, 28, 29, 30, and 90 (Table 2; Fig. 4), and to a more limited extent from Cenozoic sedimentary sections in onland New Zealand. In this study, the DSDP core



**Fig. 3** Broadscale distribution of sediment types with paleolatitude for Pliocene and Miocene intervals of circum-Antarctic Southern Ocean cores from <4 km water depth (adapted from Lazarus & Caulet 1993). Number of cores used to determine percent values for each paleolatitudinal band is shown above tops of bands. Compare with general latitudinal trend shown in Fig. 2 for modern surficial bottom sediments.

lithologies have first been re-assessed in terms of their relative abundances of biocalcareous versus biosiliceous versus terrigenous components, and re-drawn against an age scale including local New Zealand Cenozoic stages (Fig. 5). Second, a variety of paleoclimatic data and interpretations based on the lithological, microfossil, and  $\delta^{18}\text{O}$  data from these cores is already available (Appendix 1), and this information was compiled and summarised on worksheets. The key references incorporating data most relevant to the Cenozoic as a whole for the NZSSO include those of Shackleton & Kennett (1975) for stable oxygen isotopes, Jenkins (1993) for planktic foraminifera, Lazarus & Caulet (1993) for radiolarians, Hornibrook (1992) for shallow-water macrofauna and microfauna, and Edwards (1975) and Burns (1977) for a variety of microfossil and sedimentologic properties. Third, note was also taken of paleoceanographic and paleoclimatic inferences drawn from studies of other Southern Ocean cores (e.g., Kennett 1980; Kennett & Barker 1990; Stott et al. 1990; Wise et al. 1991; Lazarus & Caulet 1993) and from Cenozoic sections in onland New Zealand (e.g., Carter 1985; Hornibrook et al. 1989; Beu & Maxwell 1990; Hornibrook 1992). By integrating all these kinds of information, it is possible to compile some generalised scenarios for the sequential development of surface-water masses in the NZSSO.

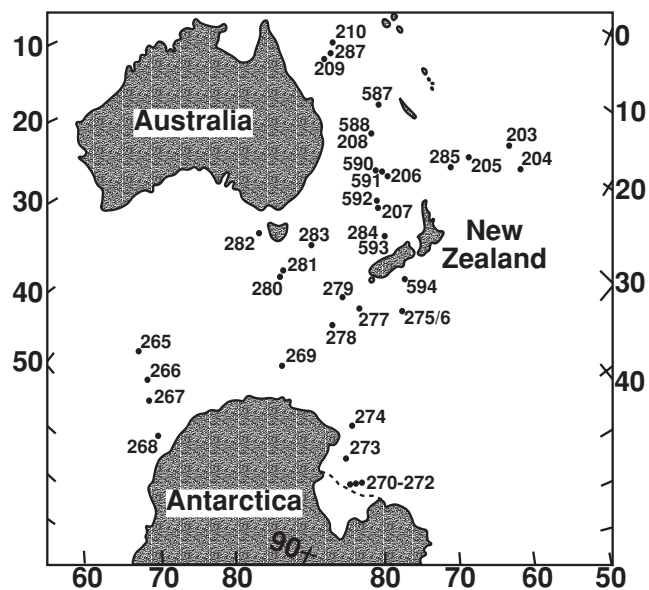


Fig. 4 Location of DSDP core sites in the wider Southwest Pacific region that form the primary basis for the paleoceanographic reconstructions in this study (see also Table 2).

Table 2 Locality information for DSDP cores in the vicinity of the NZSSO (see also Fig. 4).

No.	Leg	Site	Region	Latitude	Longitude	Depth (m)
1	21	210	Coral Sea	13°45.99'S	152°53.78'E	4653
2	21	209	Coral Sea	15°56.19'S	152°11.27'E	1438
3	30	287	Coral Sea	15°54.67'S	153°15.93'E	4653
4	21	203	Fiji Sea	22°09.22'S	177°32.77'W	2730
5	21	204	Fiji Sea	24°57.27'S	174°06.69'W	5364
6	21	205	Fiji Sea	25°30.99'S	177°53.95'E	4330
7	30	285	Fiji Sea	26°49.16'S	175°48.24'E	4658
8	90	587	North Tasman Sea	21°11.87'S	161°19.99'E	1101
9	90	588 <sup>1</sup>	North Tasman Sea	26°06.70'S	161°13.60'E	1533
10	90	590	North Tasman Sea	31°10.02'S	163°21.51'E	1299
11	90	591	North Tasman Sea	31°35.06'S	164°26.92'E	2131
12	21	206	North Tasman Sea	32°00.75'S	165°27.15'E	3206
13	90	592	South Tasman Sea	36°28.40'S	165°26.06'E	1098
14	21	207	South Tasman Sea	36°57.75'S	165°26.53'E	1389
15	90	593 <sup>2</sup>	South Tasman Sea	40°30.47'S	167°40.47'E	1068
16	29	283	South Tasman Sea	43°54.60'S	154°16.96'E	4729
17	29	282	West Tasmania	42°14.76'S	143°29.18'E	4202
18	29	281	South Tasmania	47°59.84'S	147°45.85'E	1591
19	29	280	South Tasmania	48°57.44'S	147°14.08'E	4176
20	90	594	South New Zealand	45°31.41'S	174°56.88'E	1204
21	29	275/6	South New Zealand	50°26.34'S	176°18.99'E	>2800
22	29	279	South New Zealand	51°20.14'S	162°38.10'E	3341
23	29	277	South New Zealand	52°13.43'S	166°04.29'E	1214
24	29	278	South New Zealand	56°33.42'S	160°11.48'E	3675
25	28	269	Antarctica (New Zealand)	61°40.57'S	140°04.21'E	4285
26	28	274	Antarctica (New Zealand)	68°59.81'S	173°25.64'E	3326
27	28	273	Ross Sea	74°32.29'S	174°37.57'E	495
28	28	271	Ross Sea	76°43.27'S	175°02.86'W	554
29	28	272	Ross Sea	77°07.62'S	176°45.61'W	629
30	28	270	Ross Sea	77°26.48'S	178°30.19'W	634
31	28	265	Antarctica (West Australia)	53°32.45'S	109°56.74'E	3582
32	28	266	Antarctica (West Australia)	56°24.13'S	110°06.70'E	4173
33	28	267	Antarctica (West Australia)	59°15.74'S	104°29.30'E	4564
34	28	268	Antarctica (West Australia)	63°56.99'S	105°09.34'E	3544

<sup>1</sup>Equivalent to Leg 21, Site 208.

<sup>2</sup>Equivalent to Leg 29, Site 284.

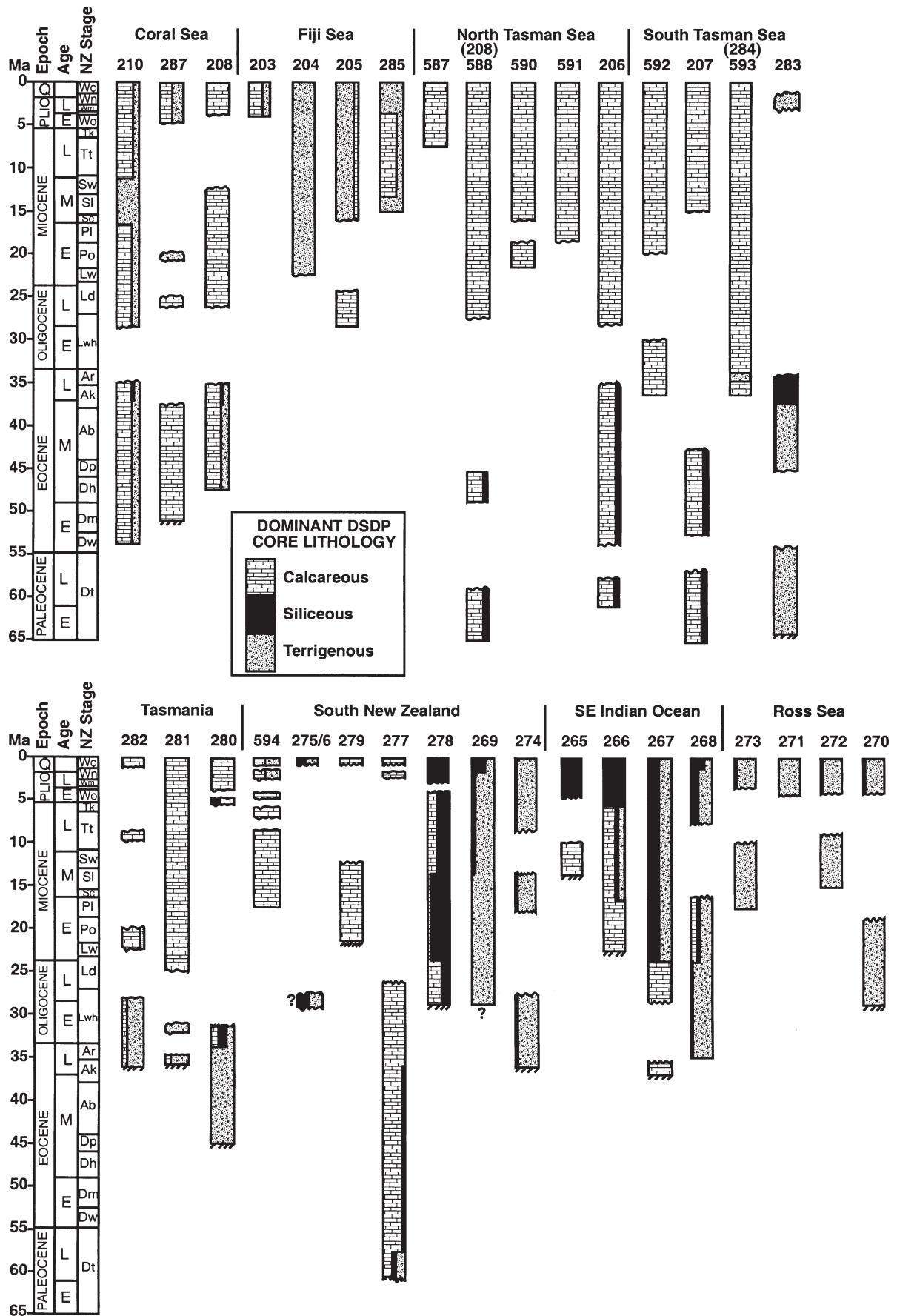


Fig. 5 Generalised stratigraphies for DSDP cores in the wider Southwest Pacific region based mainly on lithological syntheses contained in the relevant DSDP Leg volumes. See Fig. 4 and Table 2 for locality and other information. Ages include New Zealand stage symbols defined in Hornibrook et al. (1989). Diagonal lines at the base of some cores indicate hole drilled to local basement.

## CENOZOIC EVOLUTION OF FRONTS

The set of plate tectonic reconstructions generated by Lawver et al. (1992) for the evolution of the Antarctica-Southern Ocean region have been used to compile schematic paleogeographic/paleoceanographic maps for six broad periods in the Cenozoic (Fig. 6A–F), which can be compared with the modern situation (Fig. 6G). The “time slices” adopted are simply conveniently spaced ones through the Cenozoic, and effectively each map represents a “summation” of the major paleoceanographic changes occurring during the 5 m.y. intervals either side of the map age. To attempt to produce a full series of paleoceanographic maps at any higher age resolution that might identify much shorter term fluctuations in the nature and position of water mass and front types is presently premature because of the small number and widespread distribution of available NZSSO cores (Fig. 4).

The map ages, their absolute time ranges, and the approximate New Zealand stages for each interval (see also abbreviated stage symbols in Fig. 5), are as follows:

- (A) Paleocene (Teurian, Dt) 60(±5) Ma  
 (B) Early–early Middle Eocene (Waipawan-Porangan, Dw-Dp) 50(±5) Ma  
 (C) Late Middle–Late Eocene (Bortonian-Runangan, Ab-Ar) 40(±5) Ma  
 (D) Oligocene (Whaingaroan-Duntroonian, Lwh-Ld) 30(±5) Ma  
 (E) Early–early Middle Miocene (Waitakian-Lillburnian, Lw-Sl) 20(±5) Ma

- (F) Late Middle–Late Miocene (Lillburnian-Kapitean, Sl-Tk) 10(±5) Ma  
 (G) Present day 0 Ma

Dominant sediment types forming the core sediments for each time slice, along with some inferred important paleoceanographic conditions and events, are noted in Table 3.

### Paleocene (65–55 Ma) (Fig. 6A)

Records are scanty because few DSDP holes penetrate Paleocene strata (Fig. 5). At this time, both the Tasmanian (between South Tasman Rise and Antarctica) and Drake (between South America and Antarctica) gateways were closed, and Antarctica was probably free of ice (Wise et al. 1991; Abreu & Anderson 1998; Zachos et al. 2001). Sediments are almost everywhere biocalcareous, with nanofossils exceeding planktic foraminifera in abundance, and the assemblages of these two groups show moderate diversity and relatively little variation with latitude. The microfossil data suggest that no distinctive Southern Ocean biogeographic province existed, but rather there were separate Pacific and Indo-Atlantic faunal provinces at intermediate to high-southern latitudes throughout most of the Paleogene, before inception of a full circum-Antarctic current (Jenkins 1993). Biosiliceous oozes are restricted to areas of localised upwelling in shallow waters, including in eastern New Zealand (Hollis 1991), but are not indicative of more regional oceanic upwelling. This is consistent with both the generally low sedimentation rates (c. 1 cm/ka) of

**Table 3** Dominant core lithologies for mapped Cenozoic time slices in the NZSSO (see Fig. 6), including some inferred paleoenvironmental conditions and times of oceanic front development.

Time slices	Dominant sediments	Antarctic ice sheets	Surface currents <sup>1</sup>	Surface gateways	Oceanic fronts <sup>2</sup>
Paleocene 65–55 Ma (Fig. 6A)	calcareous	no	Warm (I-P)	Tasmanian closed Drake closed	none
Early–Middle Eocene 55–45 Ma (Fig. 6B)	calcareous	no	Warm (I-P)	Tasmanian closed Drake closed	none
Middle–Late Eocene 45–35 Ma (Fig. 6C)	calcareous	mainly no, but growing	Warm (I-P)	Tasmanian closed Drake closed	none
Latest Eocene only	terrigenous-siliceous calcareous	yes - East	Cool (Ant)	Tasmanian leaking West Antarctic open	proto-STF
Oligocene 35–25 Ma (Fig. 6D)	terrigenous calcareous-siliceous calcareous	yes - East no - West	Cold (Ant) Cool (Ant) Warm (I-P)	Tasmanian open West Antarctic open Drake leaking-open	AAPF ?proto-SAF proto-STF
Early–Middle Miocene 25–15 Ma (Fig. 6E)	terrigenous-siliceous siliceous-calcareous calcareous	yes - East no - West	Cold (Ant) Cool (Ant) Warm (I-P)	Tasmanian open West Antarctic closed Drake open Indonesian restricted	AAPF proto-SAF proto-STF
Middle–Late Miocene 15–5 Ma (Fig. 6F)	terrigenous-siliceous siliceous-calcareous calcareous	yes - East yes - West	Cold (Ant) Cool (Ant) Warm (I-P)	Tasmanian open Drake open	AAPF SAF STF
Pliocene–Present day 5–0 Ma (Fig. 6G)	terrigenous-siliceous siliceous-calcareous calcareous	yes - East yes - West	Cold (Ant) Cool (Ant) Warm (I-P)	Tasmanian open Drake open	AAPF SAF STF

<sup>1</sup>I-P, Indonesian-Pacific origin; Ant, Antarctic origin.

<sup>2</sup>AAPF, Antarctic Polar Front; proto-SAF, proto-Subantarctic Front; SAF, Subantarctic Front; proto-STF, proto-Subtropical Front; STF, Subtropical Front.

the calcareous oozes at southern latitudes, values more typical of oligotrophic than upwelling environments today (Lazarus & Caulet 1993), and also the isotope results from Weddell Sea (Kennett & Barker 1990) and Kerguelen Plateau (Barrera & Huber 1991), which suggest the Paleocene Southern Ocean was well stratified.

Thus, the picture that emerges for the Paleocene is an NZSSO influenced predominantly by undifferentiated subtropical surface waters circulating from (north)west to east through the region as part of a large South Pacific warm-water gyre (Fig. 6A) (Barron & Peterson 1991). No faunal evidence exists for the presence of any oceanic frontal system in the region. Based on the lack of warm-water species of the keeled planktic foraminifera *Morozovella* in the Late Paleocene record at Site 277, but by its presence in northern South Island sections of New Zealand, Jenkins (1993) proposed that a transition zone between warm subtropical and cool subtropical (= temperate) waters occurred in the vicinity of 50–55°S paleolatitude at this time. All the fossil evidence from New Zealand supports a predominantly warm subtropical marine climate throughout the Paleocene (Hornibrook 1992), with probably the warmest surface waters occurring in the Late Paleocene, as registered by an increase in the species diversity of both planktic foraminifera (Jenkins 1974) and molluscs (Beu & Maxwell 1990). The low resolution of the core dataset and onland fossil records used here appear insufficiently detailed to positively detect the short-lived extreme event, known as the Late Paleocene Thermal Maximum, at c. 55 Ma near the Paleocene/Eocene boundary (e.g., Kennett & Stott 1991; Zachos et al. 2001).

#### Early–early Middle Eocene (55–45 Ma) (Fig. 6B)

The surface-water paleoceanographic situation throughout most of the Early–Middle Eocene in the NZSSO remained similar to that in the Paleocene. Deep-sea sediments continue to be dominated by biocalcareous oozes composed of planktic foraminifera and nannofossils with subtropical affinities, while in the vicinity of the Antarctic and Australian coasts the offshore marine deposits were influenced by an increased terrigenous content associated with the inception of continental separation (Burns 1977). Rare occurrences of biosiliceous sediment at Sites 206, 207, and 277 (Fig. 5) again appear to reflect local zones of upwelling and enhanced productivity about some oceanic pedestals.

A notably warm Southern Ocean during the Early–Middle Eocene is supported by near-maximum Cenozoic isotope temperature estimates at this time off southern New Zealand (Fig. 7) (Shackleton & Kennett 1975) and in the Antarctic (Stott et al. 1990). The warming trend during the Late Paleocene in New Zealand continued into this period, which was characterised by consistently warm subtropical or marginally tropical types of marine biota and coastal mangroves and *Cocos* (Hornibrook 1992). Because of this, we infer that the transition zone between warm and cool subtropical surface waters was for a time farther south than it lay in the Paleocene, possibly as far as 60°S paleolatitude (cf. Fig. 6A, B). Certainly, according to the oxygen isotope synthesis of Paleogene marine climates by Zachos et al. (1994), the flattest gradient in sea-surface temperatures between low and high latitudes was during the Early Eocene, amounting possibly to only c. 10°C or less, and the interval includes the so-called Early Eocene Climatic Optimum (Zachos et al. 2001).

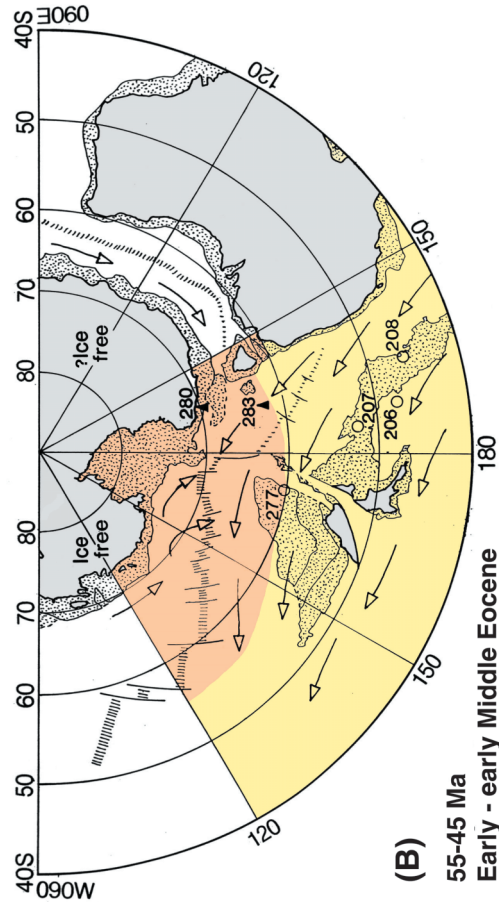
However, passage into the Middle Eocene saw the sudden extinction in New Zealand of keeled planktic foraminifera of the genus *Morozovella*, which Hornibrook (1992) interpreted to be the result of a brief cooling episode. McGowran et al. (1997) presented evidence from the southern Australian margin for a comparable early Middle Eocene cooling event which they labelled Chill 1, and suggested it may have resulted from either a Monterey effect involving CO<sub>2</sub> drawdown due to marine burial of light carbon or to an albedo effect due to widespread ocean basin subsidence associated with the collision of India and Asia. This temperature drop in high-latitude surface waters was at most only a few degrees centigrade (Zachos et al. 1994), and was presumably accompanied by a northwards return towards 50°S paleolatitude of the transition zone between cool and warm subtropical waters.

Consequently, apart from cessation of seafloor spreading in the Tasman Sea at c. 55 Ma (Sutherland 1994), and the continued slow drift of the New Zealand subcontinent northwards away from the Pacific–Antarctic Ridge, effectively increasing the oceanic area of the NZSSO, the surface waters and circulation patterns for the first half of the Eocene (Fig. 6B) are similar to those in the Paleocene. East Antarctica probably remained free of ice caps (Wise et al. 1991; Abreu & Anderson 1998; Barker et al. 1999; Zachos et al. 2001), the Tasmanian gateway had not yet opened, the surface waters of the NZSSO were everywhere cool to warm subtropical and fed by the western limb of a south Pacific gyre, and no oceanic fronts were present in the region.

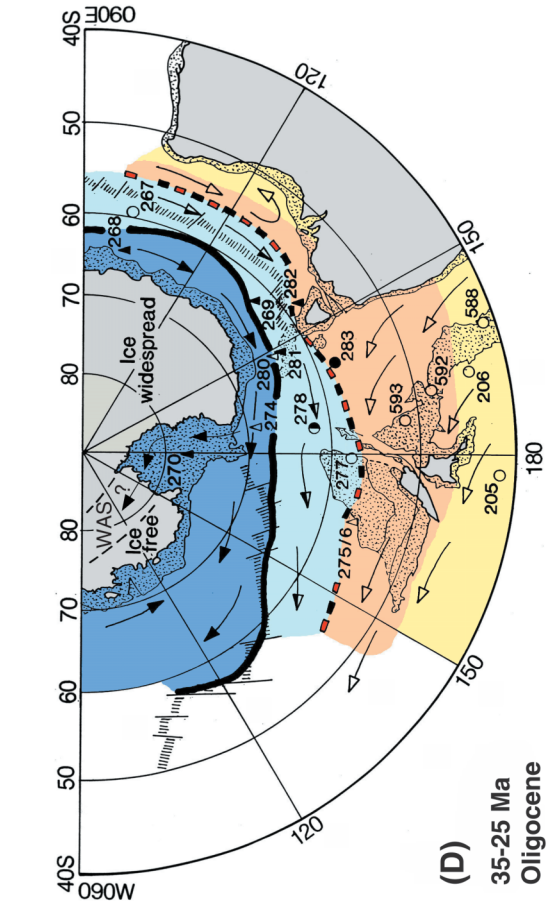
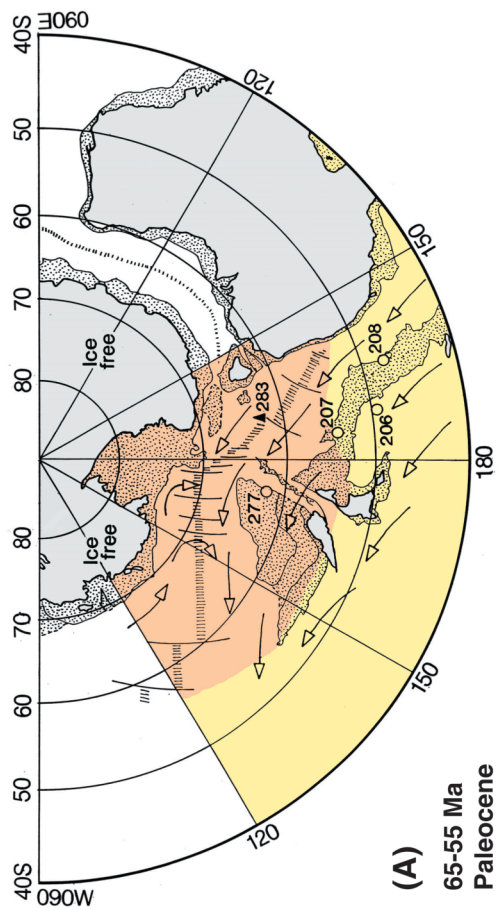
#### Late Middle–Late Eocene (45–35 Ma) (Fig. 6C)

For much of the first part of this interval, the deep-sea core data from the NZSSO suggest that the broad paleoceanographic characteristics of the surface waters in the region remained similar to those occurring in the earlier Eocene and Paleocene. Sediments continue to be carbonate dominated, comprising assemblages of nannofossils and planktic foraminifera having subtropical affinities, with terrigenous and locally biosiliceous deposits in the vicinity of continental margins.

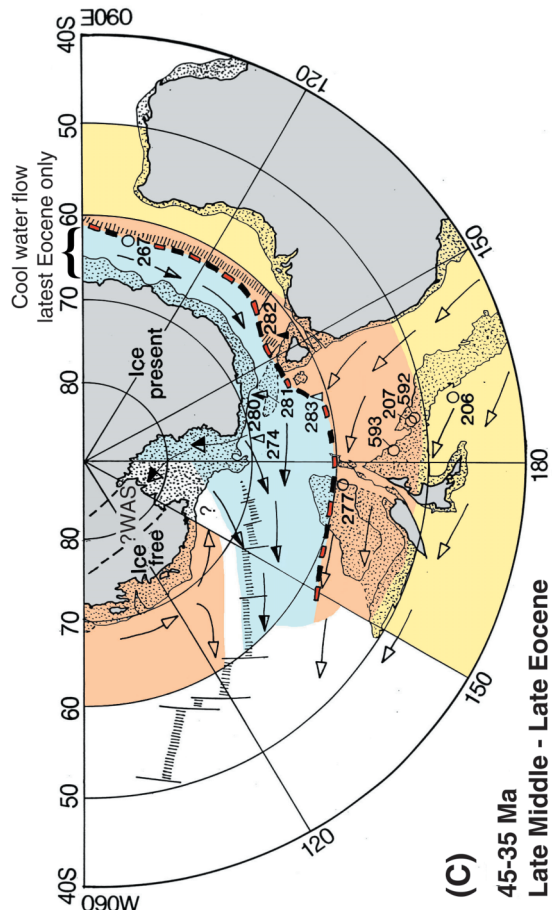
However, by the Late Eocene there is considerable evidence for the onset of changing paleoceanographic conditions in the NZSSO. Deep-water marine sediments appear for the first time at drill sites between Australia and Antarctica, and attest to the ongoing separation since c. 50 Ma of these continents about a maturing oceanic ridge system (Fig. 6C). Wise et al. (1991) and Zachos et al. (1994) compiled evidence from oxygen isotopes, ice-rafted debris, and microfossil and mineralogical data for the appearance by the early Late Eocene of the first major, but still probably ephemeral, ice sheets on East Antarctica, consistent with the ice history synthesis presented by Abreu & Anderson (1998). Lazarus & Caulet (1993) reported that radiolarian faunas close to Antarctica became increasingly endemic at this time, involving distinctive cold-water assemblages. They suggested that a mix of cold and warmer radiolarian species away from the continent may reflect the introduction of the former in a northward-moving cool intermediate water mass developed in, and sinking from, the surface waters near Antarctica. The presence of the cold-water nannofossil *Isthmolithus recurvus* at Site 267 is clear evidence of cool seas first entering the southern portion of the Australian–Antarctic seaway (Burns 1977), and cool-water assemblages of nannofossils appear elsewhere in the Southern Ocean at

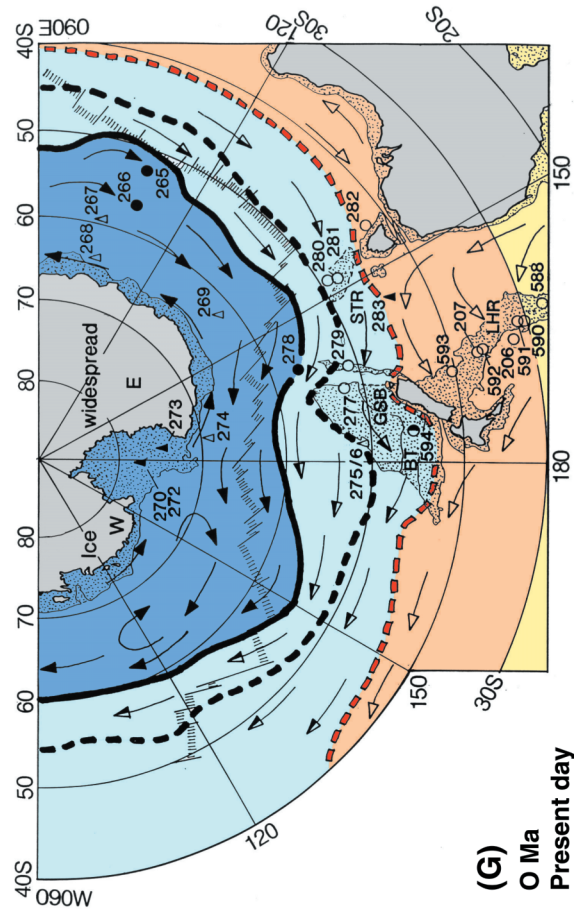
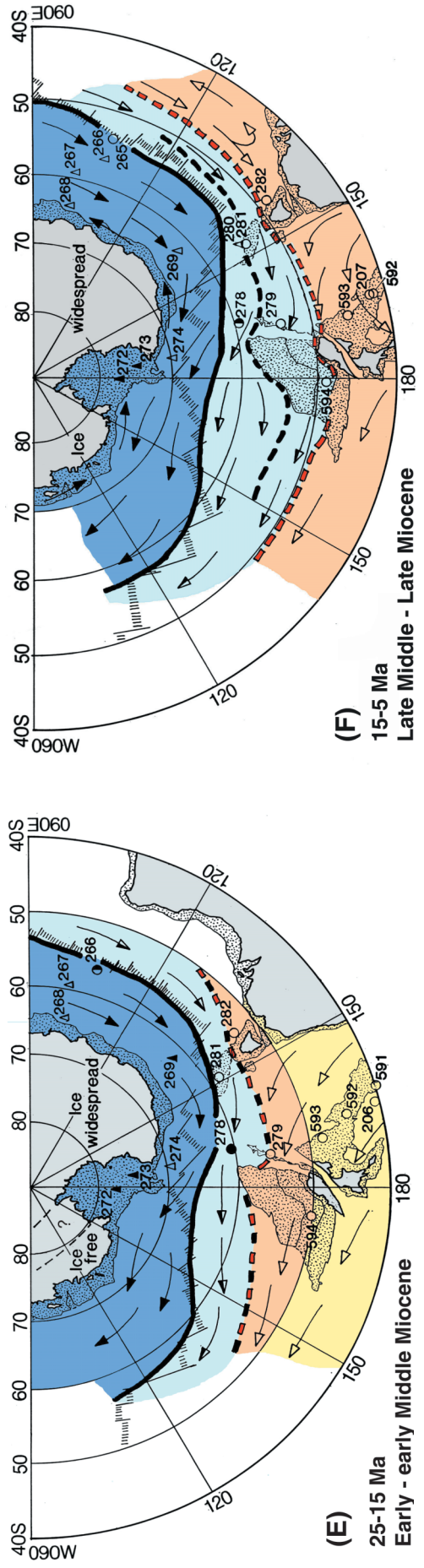


**(B)** 55-45 Ma  
Early - early Middle Eocene



**(D)** 35-25 Ma  
Oligocene





**Fig. 6** Series of schematic paleogeographic/paleoceanographic maps for the NZSSO at roughly 10 m.y. intervals through the Cenozoic. The base maps for the paleogeographic reconstructions are adapted from Lawver et al. (1992). Note the changing ice budget through time on East and West Antarctica (e.g., Abreu & Anderson 1998; Zachos et al. 2001). WAS = West Antarctic seaway. Colour versions of this figure can be downloaded from [http://sci.waikato.ac.nz/cgi-bin/show\\_staff.pl?dept=erth&name=erth0033](http://sci.waikato.ac.nz/cgi-bin/show_staff.pl?dept=erth&name=erth0033)

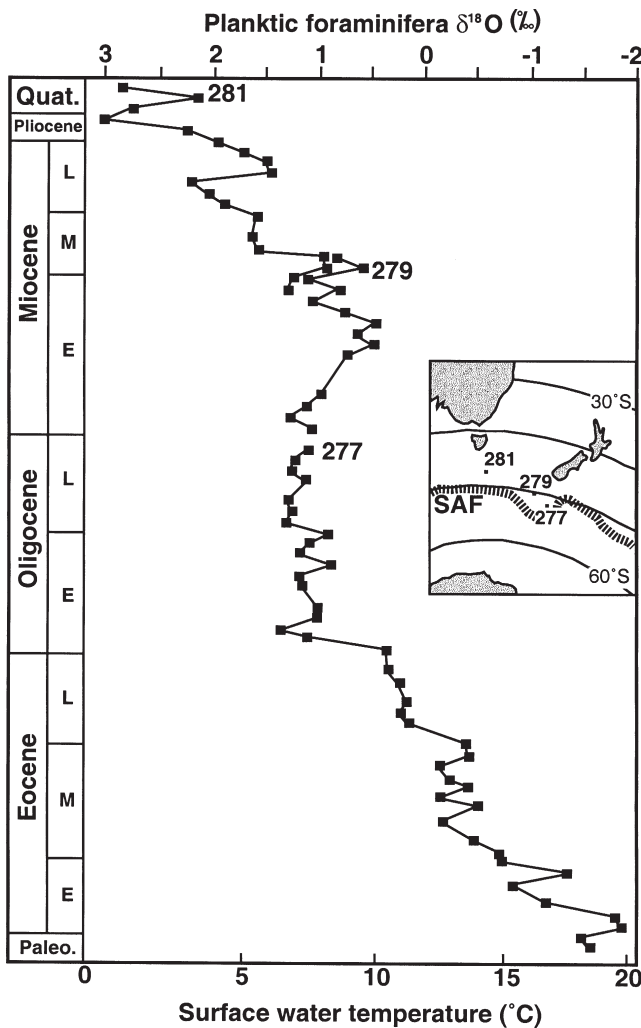


Fig. 7 Planktic foraminiferal  $\delta^{18}\text{O}$  record and inferred near-surface water temperatures off southern New Zealand (DSDP sites 277, 279, and 281) since the Eocene (after Shackleton & Kennett 1975).

this time (e.g., Crux 1991). A sharp temperature drop into the Late Eocene of several degrees centigrade is suggested by the DSDP Site 277 stable isotope record from south of New Zealand (Fig. 7). This cooling coincides with a significant increase in bolboform numbers at the core site (Grützmacher 1993), a microfossil group known elsewhere at this time to be associated with sediments having a polar character (Kennett & Kennett 1990; Stott et al. 1990). Both cooler temperatures and decreased water column stratification have been inferred from other Southern Ocean isotope records for the Late Eocene (e.g., Stott et al. 1990; Barrera & Huber 1991). Occurrences of widespread mixed terrigenous-biosiliceous deposits in the vicinity of the shallow Tasman Rise suggest intensified upwelling and current circulation (e.g., Hampton 1975), possibly as an embryonic circum-Antarctic current began to sweep through the region once the Tasmanian gateway began to leak (e.g., Barron & Peterson 1991). This increasing differentiation of Southern Ocean surface waters may account for the increase in biogeographic gradients and biotic turnover registered at southern latitudes in the Indo-Pacific region for several microfossil groups during the Middle–Late Eocene (e.g.,

Sancetta 1979; Aubry 1992; Baldauf 1992; Keller et al. 1992). Significantly, the major extinction event in the entire Cenozoic occurred between the Middle and Late Eocene, affecting a wide range of both planktic marine and terrestrial biota (Berggren & Prothero 1992).

To account for the partitioning of surface waters in the NZSSO during the latest Eocene, a proto-Subtropical Front is portrayed here in the relevant paleoceanographic map (Fig. 6C) as separating distinctive cool and warm water masses. Such a thermal boundary was suggested by Murphy & Kennett (1986) on the basis of isotope-derived surface-water temperature comparisons between DSDP Sites 277 and 593 in the southern Tasman Sea. The scenario shown in Fig. 6C relates strictly to the latest Eocene portion of the time slice; otherwise, the situation envisaged is closer to that depicted in the Early Eocene map (Fig. 6B). As before, the warm surface currents bathing the wider New Zealand region originate out of the tropical west Pacific, whereas by the Late Eocene, when the buildup of ice sheets on East Antarctica had begun (Abreu & Anderson 1998; Zachos et al. 2001), the cool surface waters developed south of the proto-Subtropical Front are inferred to be part of a developing embryonic circum-Antarctic current system (e.g., Barron & Peterson 1991) that was possible because of shallow leakage over the Tasmanian gateway.

Whether or not such a flow was truly circum-Antarctic depends on whether the Drake gateway between South America and Antarctica was also leaking. This matter remains controversial. For example, Barker & Burrell (1982) suggested the Drake gateway did not open until much later in the Oligocene, or even younger (Barker et al. 1999), while Lawver & Gahagan (1998) advocated an early Oligocene opening. A closed Drake gateway possibly allowed development of a small clockwise gyre of warm surface waters to be recirculated off West Antarctica, as shown in Fig. 6C, to eventually mix with the cool currents. If the Drake gateway was indeed closed or only leaking, then we suggest that cool surface flows passing through the Tasmanian gateway may have been directed between East and West Antarctica, along the general strike of the West Antarctic rift system. We label this feature the West Antarctic seaway (WAS) in Fig. 6C, D. The rift experienced an episode of significant extension in the Eocene–Oligocene (Cande et al. 2000), and may have formed a critical marine linkage between the Pacific and Atlantic Oceans at this time. Lawver & Gahagan (1998) also noted the possibility of such a Pacific–Atlantic connection, but rather earlier in the Tertiary than we suggest here. Lazarus & Caulet (1993) inferred an unnamed regional oceanic front in the southern Atlantic and Indian Oceans in a (Late) Eocene reconstruction of surface circulation about Antarctica but, unlike here, showed no front in the NZSSO.

#### Oligocene (35–25 Ma) (Fig. 6D)

The changing paleoceanographic conditions in the NZSSO during the Late Eocene presaged those that continued, and intensified, into the Early Oligocene. The so-called “Terminal Eocene Event”, first enunciated by Wolfe (1978), has become a catch-all expression for the significant changes that occurred in climate, biota, geochemistry, and lithology in the records of both marine and terrestrial deposits in the vicinity of the Eocene/Oligocene boundary, near 34 Ma (e.g., Van Couvering et al. 1981). However, despite some often

sudden and dramatic shifts, the prevailing view is that the biotic changes occurred mainly in sequential or step-wise fashion during the Late Eocene–Early Oligocene, rather than being “instantaneous” and related to some catastrophic event (e.g., Prothero & Berggren 1992).

The well-established global climatic cooling and biotic turnover at this time has long been linked to the development of Antarctic glaciation (e.g., Kennett 1977, 1978, 1980; Miller et al. 1991). Zachos et al. (1994) showed that the first major and permanent ice sheets had developed on East Antarctica by the earliest Oligocene, involving an ice volume at least 50% that of the present day, and that by this time sea-surface temperatures off Antarctica in the NZSSO had declined to values in the order of 2–6°C. Oxygen isotope records from both deep-water (e.g., Shackleton & Kennett 1975; Stott et al. 1990; Barrera & Huber 1991; Wei 1991; Miller 1992) (Fig. 7) and shallow-water (e.g., Devereux 1967; Burns & Nelson 1981; Kamp et al. 1990; Buening et al. 1998) sites throughout the Southern Ocean all show a conspicuous  $\delta^{18}\text{O}$  enrichment of c. 1‰ in the earliest Oligocene, consistent with an abrupt cooling of southern high-latitude surface waters. This feature was labelled Chill II by McGowran et al. (1997) in their chronicle of important Cenozoic paleoceanographic events affecting the southern Australian margin. It was accompanied by the development of the psychrospheric ocean as we know it today (Kennett & Shackleton 1976) and subsequent widespread development of mid-Tertiary hiatuses along the paths of bottom-water movement through the NZSSO (Kennett et al. 1975; Kennett & von der Borch 1986). Pronounced latitudinal differentiation of surface-dwelling plankton associations occurred throughout the Southern Ocean, with northward migration and/or extinction of many former high-latitude taxa, and a reduction in the diversity of species, including, for example, amongst the planktic foraminifera (e.g., Keller et al. 1992; Jenkins 1993), calcareous nannoplankton (e.g., Wei 1991; Aubry 1992), diatoms (Baldauf 1992), and radiolarians (Lazarus & Caulet 1993). Also, bolboforms, inferred to be good subantarctic indicators (Crundwell et al. 1997), reached their maximum Paleogene diversity in the Late Eocene and Early Oligocene Southern Ocean core sites (Spiegler & von Daniels 1991).

Accompanying the Early Oligocene glaciation to sea level on East Antarctica and refrigeration of southern high-latitude surface waters was the final separation of the Antarctic and Australian continents, and full oceanic opening of the Tasmanian gateway south of Tasmania (Kennett et al. 1975; Kennett 1977). Jenkins (1993) suggested this seaway was fully open by c. 31 Ma, allowing unimpeded dispersal of previously Austral gulf planktic taxa, such as the foraminiferan *Jenkinsina samwelli*, into the Southwest Pacific and beyond. The nascent cool-water circum-Antarctic flows postulated for the Late Eocene (Fig. 6C) now evolved into a fuller and much intensified proto-Antarctic Circumpolar Current, traversing the NZSSO and possibly entering the Atlantic by either shallow-water leakage through the Drake gateway or via the West Antarctic seaway resulting from rifting between East and West Antarctica at this time (Fig. 6D) (Barron & Peterson 1991; Lazarus & Caulet 1993; Cande et al. 2000). Lazarus & Caulet (1993) advocated an extensive cold to cool water Southern Ocean in the Early Oligocene, locally extending as far north as 50°S paleolatitude in the Indian Ocean sector. An AAPF is envisaged separating distinctly antarctic from subantarctic radiolarian

assemblages and is positioned in the NZSSO in the vicinity of the Early Oligocene spreading ridge, meandering between c. 60° and 65°S paleolatitude (Fig. 6D). The location of several modern oceanic fronts appears to track, and be partly controlled by, deep bottom topography (Lazarus & Caulet 1993), and, given the weak stratification of the water column in the Early Oligocene (Stott et al. 1990; Barrera & Huber 1991), it is possible the surface circulation system likewise penetrated deeply and was linked to the paleoridge position. The Early Oligocene proto-STF is inferred to have been displaced well northwards in the NZSSO, reaching the vicinity of 55°S paleolatitude (Fig. 6D), a conclusion also reached by Kamp et al. (1990) and Buening et al. (1998) from faunal and isotope evidence in southern Australia and New Zealand, respectively. Based on the occurrence of Oligocene diatomaceous sediments within southern portions of the intervening subantarctic water mass (e.g., DSDP Sites 278 and 280), a situation also apparent from some other Southern Ocean sites at this time (e.g., Shipboard Scientific Party 1988; O’Connell 1990; Zachos et al. 1992), it is possible that a proto-SAF may have begun to differentiate this cool-water zone in the Oligocene (see Fig. 9). However, there is insufficient information to positively locate such a proto-SAF on the relevant NZSSO map (Fig. 6D).

The shallow-marine fossil record for the Oligocene in New Zealand is problematical from a paleoclimatic viewpoint (Hornibrook 1992). Foraminiferal extinctions near the Eocene/Oligocene boundary probably relate to the significant cooling associated with the boundary event mentioned above (Hornibrook et al. 1989), a view supported by oxygen isotope temperature records from New Zealand (Fig. 7) (Devereux 1967; Burns & Nelson 1981). However, any dramatic cooling appears to have been short lived because a variety of warm-water molluscan taxa (Beu & Maxwell 1990) and dispersed occurrences of the benthic foraminiferan *Amphistegina* (Hornibrook et al. 1989) are reported from several New Zealand Oligocene sections. A widespread Oligocene lithology in New Zealand is bryozoan limestone having all the characteristics of temperate-latitude cool-water carbonate facies (Nelson 1978; Nelson et al. 1988), and the abundance of fossil cetaceans and penguins associated with these sediments is supportive of cool water (Fordyce 1992). On balance, we infer that several shallow warm-water taxa survived earliest Oligocene cooling in New Zealand in sheltered coastal niches atop a diversified, island-dotted carbonate platform sitting in mainly temperate (cool subtropical) seas during the Oligocene. The occurrence of several widespread unconformity horizons within these mid-Tertiary carbonate deposits (Nelson 1978), the most celebrated of which is the mid-Oligocene Marshall Paraconformity in South Island (Carter 1985), record condensation, bypassing, and erosion by strong current flows crossing portions of the New Zealand plateau. These flows probably relate to topographically guided, northward-moving filaments of cool (subantarctic) water derived from the rapidly evolving circum-Antarctic current to the south (Fulthorpe et al. 1996).

#### Early–early Middle Miocene (25–15 Ma) (Fig. 6E)

Throughout this period, a south–north tripartite division of detrital-siliceous, siliceous-calcareous, and calcareous sediments continues to define, respectively, circumpolar belts of cold, cool, and warm surface-water masses (Fig. 6E), first evident in the Early Oligocene. According to Jenkins

(1993), whereas previously the Southern Ocean effectively supported separate South Pacific and Indo-Atlantic faunal provinces, by the Late Oligocene a latitudinally zoned, single major Southern Ocean faunal province prevailed. For example, Jenkins noted that planktic foraminiferal faunas are similar from southern Australia to New Zealand to southeast Atlantic at this time, and no major changes mark the Oligocene/Miocene boundary. Influential factors contributing to a breakdown of faunal provincialism include the continued widening of the Tasmanian gateway and particularly the inception of unimpeded circum-Antarctic flow through the Drake gateway off southern South America, which by this time was certainly fully open (Lawver & Gahagan 1998; Barker et al. 1999).

One consequence of invigorated subsurface flows is the occurrence of widespread hiatuses in several of the Late Oligocene–Early Miocene sections (Fig. 5), limiting paleoceanographic reconstructions. Assignment of radiolarian and diatom assemblages to antarctic or subantarctic waters is at some sites problematical (Burns 1977; Lazarus & Caulet 1993), which could reflect short-term fluctuations in position or eddying at the boundaries of water masses. But, overall, by the Early Miocene, the AAPF had shifted northwards from its Early Oligocene position by c. 5° of latitude, possibly tracking roughly the mid-ocean ridge system now lying between 55 and 65°S paleolatitude as the Southern Ocean continued to expand (Fig. 6E).

The marine fossil record from New Zealand in the Early Miocene includes widespread warm-water molluscan genera (Beu & Maxwell 1990) and a variety of larger foraminifera (Chaproniere 1984), as well as isolated heads of reef coral in northern localities (Hayward 1977). The evidence supports development of increasingly warm subtropical conditions throughout the Early Miocene, culminating in a Neogene climatic optimum in the vicinity of the Early–Middle Miocene boundary zone. Peak warmth is supported by maximum Miocene diversity amongst planktic foraminifera (Jenkins 1993) and the nature of the calcareous nannofossil taxa (Edwards 1968). Tsuchi (1992) noted that a comparable Neogene climatic maximum is characteristic of several circum-Pacific regions at c. 16 Ma. Compared to the Oligocene, the influence of warm subtropical water masses expanded southwards at the expense of cool subtropical and subantarctic flows to bathe the entire New Zealand plateau. Only during the Late Paleocene–Early Eocene was there previously such a sustained period of climatic warmth across the New Zealand region.

The 16 Ma culmination of the Early Miocene warming event is such that a likely major contributing factor was continental-arc collision in the Indonesian region (Jaques & Robinson 1977), significantly restricting the Indonesian gateway (Kennett et al. 1985). This would have prevented westward-flowing Pacific equatorial currents from directly entering the Indian Ocean. Because of a gyral circulation pattern, the effect was probably to gradually redirect and greatly intensify the Early Miocene equivalent of the warm East Australian Current flowing south into the Tasman Sea and across the New Zealand plateau. Additionally, the completed opening of both the Tasmanian and Drake gateways to fuller circum-Antarctic transport of cool water probably fostered an increased decoupling of cool and warm surface waters. The local oxygen isotope record from Site 279 supports climatic amelioration through the Early Miocene (Fig. 7), but the changes are not dramatic as it lies

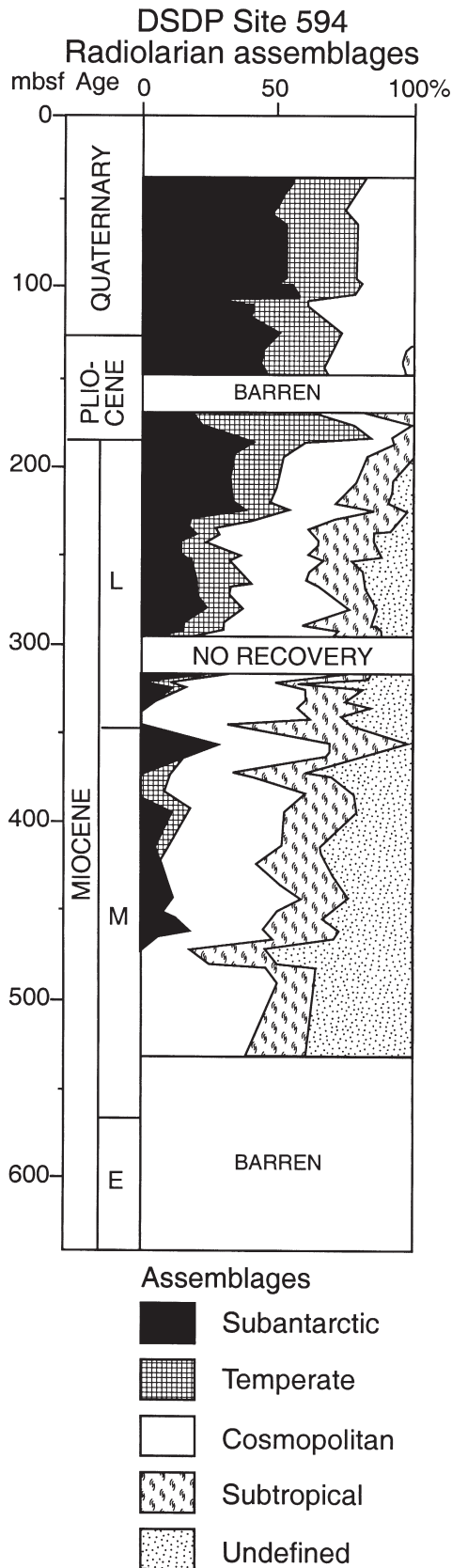
near the southern limit of subtropical surface water incursions at this time (Fig. 6E).

#### Late Middle–Late Miocene (15–5 Ma) (Fig. 6F)

Following the Neogene climatic optimum near 16 Ma, there was long-term climatic deterioration throughout the remainder of the Cenozoic. This was associated first with increased permanent ice accumulation on East Antarctica in the late Middle Miocene (Chill III phase of McGowran et al. 1997), and second with the development of a permanent ice sheet on West Antarctica in the latest Miocene (e.g., Hodell & Kennett 1986; Kennett & von der Borch 1986). Stable isotope records demonstrate these dual cooling events well (Fig. 7) (Miller et al. 1987). During this Middle–Late Miocene period, the greatly increased buildup of ice on Antarctica, and ongoing widening of the Southern Ocean by seafloor spreading, caused more expansive and intense circum-Antarctic flows. By the Late Miocene, localities such as Sites 279 and 594 that were previously dominated by subtropical microfossil taxa now register a dramatic increase in subantarctic assemblages (Fig. 8) (Lazarus & Caulet 1993). The microfossil characteristics suggest the former proto-STF had now become a full STF resembling the modern, which in the New Zealand region occupied a breached location across the Campbell Plateau before following the trend of the upstanding Chatham Rise out into the South Pacific (Fig. 6F). Moreover, during this period, there is microfossil assemblage evidence (e.g., Burns 1977; Jenkins 1993) to support clear partitioning of the circumpolar belt of subantarctic waters into two zones by a recognisably “modern” SAF. Within the New Zealand region, the position of the SAF is shown to be bathymetrically constrained by the margins of the Campbell Plateau (Fig. 6F), as is the situation in the modern (Fig. 6G). By the latest Miocene, the STF, SAF, and AAPF south of New Zealand lay near 50°S, 58°S (because of southwards deflection by the Campbell Plateau), and possibly near 62°S paleolatitude, respectively (Fig. 6F).

The Middle–Late Miocene interval in New Zealand is mainly characterised by deep-water facies so that fossil assemblages are rather nonspecific as to marine climate (Hornibrook 1992). A decline in foraminiferal diversity is consistent with overall climatic cooling in the Middle Miocene, but with some warm-water incursions suggested by brief appearances in North Island of a few larger foraminiferal taxa (Chaproniere 1984) and of the warm subtropical planktic species *Globorotalia menardii* (Jenkins 1993). However, the close of the Middle Miocene marks the final extinction of most larger foraminifera in New Zealand (Hornibrook 1992). Throughout the Late Miocene, cooling continued as shown by the increasingly lower generic diversity and high percentage of extinctions of molluscs (Beu 1990) and, in the latest Miocene, the appearance for the first time of sinistral populations of the cold-water planktic foraminiferan *Neogloboquadrina pachyderma* in south-eastern New Zealand (Vella & Kennett 1975).

In summary, compared to the predominantly warm subtropical surface waters over the New Zealand region during the previous Early–early Middle Miocene period (25–15 Ma), the late Middle–Late Miocene interval (15–5 Ma) became increasingly influenced by cool subtropical waters, with fluctuating incursions of subantarctic water affecting southeastern New Zealand by the close of the period.



**Fig. 8** Neogene development of radiolarian assemblages at DSDP Site 594 off southeastern New Zealand, presently sited in subantarctic water just south of the STF (adapted from Lazarus & Caulet 1993). Note the appearance and increasing significance of radiolarians with subantarctic affinities since the late Middle Miocene, supporting STF establishment north of the site by this time.

**Pliocene–Quaternary (5–0 Ma)**

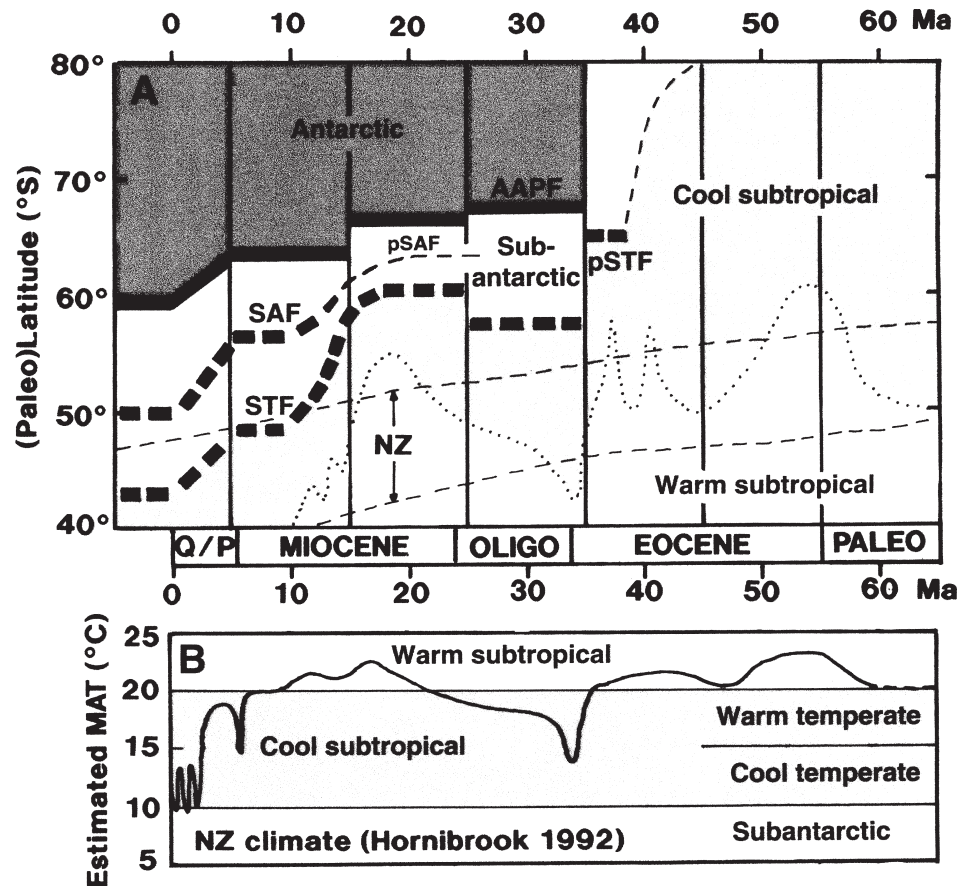
Other than the modern situation (Fig. 6G), no paleoceanographic maps are presented for this interval because “average conditions” concerning sediment types, taxa distribution, and oceanic features are broadly similar to those of the present day. During this period of known rapid climatic oscillations between interglacial and glacial episodes (Head & Nelson 1994; Shackleton et al. 1995), incorporating the middle Pliocene Chill IV phase of McGowran et al. (1997) and subsequent expansion of ice sheets in the Northern Hemisphere (Raymo 1994), we infer a “maturing” of all three fronts (AAPF, SAF, and STF) in the NZSSO whose relative positions were maintained during at least the interglacial periods, appearing much like the scenario portrayed by an amalgam of Fig. 6F, G.

However, based mainly on evidence from Last Glacial to Holocene records (marine isotope stages 2 to 1) in offshore cores from the New Zealand region, it appears that during glacial times there has been temporary but considerable northward shifts of the AAPF and the SAF by up to 5–10° of latitude in open oceanic sites south of New Zealand (e.g., Nelson et al. 1993, 1994, 2000; Weaver et al. 1998; Barrows et al. 2000). Whether or not the SAF broke through the bathymetric constraint imposed by the southern margin of Campbell Plateau (Fig. 6G), and whether or not the open ocean movements of the southern fronts were accompanied by compensatory shifts in the STF, are presently debatable. Some existing data suggest no, or not by much, to both propositions (Nelson et al. 1993, 2000; Mackie 1998; Weaver et al. 1998), in which case the much intensified oceanic flows associated with dramatic compression of subantarctic water mass belts, increased westerly windiness, and lowered sea levels during glacials account well for the particularly harsh climatic conditions experienced in southeastern New Zealand at these times (e.g., Nelson et al. 1994). Like the last glaciation, it is probable that, to a greater or lesser degree, depending on global ice volume and extent of sea ice development about the Antarctic continent (Fig. 1), comparable kinds of shifts in Southern Ocean fronts and hydrographic conditions accompanied all the major glacial periods affecting the NZSSO during the latest Miocene–Quaternary (Nelson et al. 2000). Undoubtedly, paleoceanographic results from the recent (late 1998) ODP Leg 181 off eastern New Zealand (Carter et al. 1998) will contribute substantially to this question in the future.

**CONCLUSIONS**

1. Presently, there exist far too few quality long cores to track in any detail the evolution and migration of oceanic fronts in the NZSSO during the Quaternary, let alone for the Tertiary. However, despite this shortcoming, we have presented a series of schematic generalised paleoceanographic maps (Fig. 6) through the Cenozoic based on a review of published marine paleoclimatic data derived mainly from existing DSDP core and onland New Zealand marine sections. Given the proposition that the Southern Ocean probably holds the key to global climate (Hanna 1996; Pearce 1997), and that paleoceanographic changes therein have played a fundamental role in the development of Cenozoic climatic evolution, sea-level changes, and in terrestrial and biotic evolution (e.g., Kennett 1995), topics being revisited within the NZSSO by recent ODP Leg 181

**Fig. 9** A, Summary of the Cenozoic evolution of oceanic fronts and their associated surface-water masses (colour coded as in Fig. 6) in relation to paleolatitudes in the NZSSO. B, Comparison of the development in (A) with the New Zealand (NZ) marine paleoclimate curve compiled by Hornibrook (1992). The pair of lightly dashed lines in (A) mark the approximate northern and southern latitudinal extent of the "present" New Zealand landmass through the Cenozoic. AAPF, Antarctic Polar Front (thick black line); pSAF, proto-Subantarctic Front (thin dashed black line from the Oligocene); Subantarctic Front (thick dashed black line), pSTF, proto-Subantarctic Front (thick dashed red and black line); STF, Subtropical Front (thick dashed red line). Colour versions of this figure can be downloaded from the web site given in Fig. 6 caption.



(late 1998 off eastern New Zealand), Leg 182 (early 1999 off southern Australia), and Leg 189 (early 2000 off southern Tasmania), the principal intention here has been to provide a background framework into which future, more specific paleoceanographic studies can be slotted and compared. Inevitably, major amendments, improvements, and refinements to this skeletal framework are anticipated.

2. Important large-scale controls on the evolution and position of oceanic fronts in the NZSSO during the Cenozoic have been: (1) tectonic control on the distribution of continents and basin topography in the region; and (2) global ice budget on the distribution of surface albedo, in particular the step-wise growth of ice sheets first on East Antarctica and later on West Antarctica (Table 3), which in turn is closely related to the plate tectonic changes that progressively thermally isolated the Antarctic continent. With respect to tectonic control, the NZSSO is itself a consequence of c. 80 m.y. of seafloor expansion about the Pacific-Antarctic(-Indian) spreading ridge separating the Antarctic continent in the south from the New Zealand (-Australian) continents to the north (Lawver et al. 1992). The position of the AAPF through time appears to have been guided by this ridge system in parts of the NZSSO, suggestive of a bathymetric influence on location. Likewise, the SAF off southern New Zealand closely follows the edge of the upstanding Campbell Plateau, and the STF east of New Zealand tracks the crest of Chatham Rise. Critical to the inception of full circum-Antarctic flow that eventually thermally isolated Antarctica was complete opening of first the Tasmanian gateway (by c. 31 Ma) and later the Drake gateway (certainly by c. 25 Ma), while restriction of the

Indonesian gateway (c. 16 Ma) probably accounts for the Neogene climatic optimum recorded near the Early/Middle Miocene boundary in the Southwest Pacific.

3. A summary history of oceanic front development in the NZSSO follows.

(1) About 65–45 Ma (Fig. 6A, B) – From Paleocene through Middle Eocene, the entire NZSSO was under the influence of subtropical surface flows sourced out of the western Pacific. No oceanic fronts existed, although a transition zone from warm to cool subtropical conditions is registered near 55°S paleolatitude at this time.

(2) About 45–25 Ma (Fig. 6C, D) – Following ice buildup on East Antarctica during the Late Eocene, we suggest development by the latest Eocene of a proto-STF separating cool-water and warm-water masses offshore from Antarctica. In the vicinity of the Eocene/Oligocene boundary, and certainly by the earliest Oligocene, the position of this proto-STF was displaced by an AAPF at c. 65°S paleolatitude as glaciation reached sea level about East Antarctica. North of the AAPF, an associated belt of subantarctic water continued to be bounded by the proto-STF now positioned north of the Southern Ocean spreading ridge. Mid-Oligocene full opening of the Tasmanian gateway initiated development of a vigorous proto-circum-Antarctic current through the NZSSO, possibly linked to the Atlantic via a West Antarctic seaway. Northeastward-flowing filaments of these cool waters periodically impinged directly upon the New Zealand subcontinent, causing erosion and widespread

unconformity development in Oligocene–earliest Miocene cool-water carbonate deposits on the New Zealand plateau, forcing subtropical circulation northwards.

(3) About 25–15 Ma (Fig. 6E) – During the Early–early Middle Miocene, the influence of warm subtropical waters expanded south onto the New Zealand plateau at the expense of both cool subtropical and subantarctic surface flows. Contributing factors were by now a definitely fully opened Drake gateway, enabling intensified circum-Antarctic current circulation and stronger decoupling of cool from warm water belts; and perhaps more importantly, final closure of the Indonesian gateway by 16 Ma with redirection of intensified warm equatorial water flows southwards into the Tasman Sea.

(4) 15–5 Ma (Fig. 6F) – In the late Middle–Late Miocene interval we recognise the existence of first the STF, and later the SAF, in the vicinity of their present relative positions across and about the Campbell Plateau, respectively. Their development is associated with continued major buildup of ice on East Antarctica and initiation of a significant ice sheet on West Antarctica, coupled with generally more expansive and intensified circum-Antarctic flow.

(5) About 5–0 Ma (Fig. 6G) – During the latest Miocene–Quaternary period of rapidly fluctuating climatic conditions, the relative positions of the AAPF, SAF, and STF in the NZSSO were probably maintained during interglacial episodes, although their average paleolatitude positions continued to decrease by up to c. 5° to the present day because of general northwards drift of the New Zealand subcontinent. However, there is evidence for some significant differential shifts in the location of coeval oceanic fronts during major periods of glaciation within the latest Neogene, ranging from possibly remaining stationary to northward movements (of the AAPF) by as much as 10° of latitude. Details of these short-term oscillations in glacial front migrations within the NZSSO are presently virtually unknown.

4. Finally, an attempt is made in Fig. 9A to summarise the Cenozoic evolution of oceanic fronts and their associated surface-water masses in relation to paleolatitudes in the NZSSO. Superimposed on the diagram is the approximate northern and southern latitudinal extent of the New Zealand “landmass” through the Cenozoic, read simply off the paleogeographic reconstructions (Fig. 6). In turn, this synthesis can be compared in Fig. 9B to the most recent New Zealand Cenozoic marine climate record compiled by Hornibrook (1992), which is based on the southernmost fossil occurrences of warm shallow-water invertebrates and plants, normalised to modern latitude 42°S. Not unexpectedly, the broad trends in the New Zealand paleoclimate curve correspond well to the principal paleoceanographic events controlling the evolution and migration of oceanic fronts in the NZSSO (see also Table 3).

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**Appendix 1** Selection of papers relevant to the surface-water paleoceanography of the NZSSO, especially those marked by an asterisk.

Date	Author(s)	Region	Age	Fronts	Basis <sup>1</sup>	Comment
1963	Kustanowich	Southwest Pacific	Modern	STF	PF	Five latitudinal PF zones east and north of New Zealand
1967	Devereux	New Zealand	Cenozoic	—	OI	First New Zealand-based oxygen isotope climate record
1968	Kennett	New Zealand	Mio-Pliocene	AAPF, SAF	PF	Dramatic latest Miocene cooling in eastern North Island; warming in early Pliocene
1972	Keany & Kennett	Southern Ocean	Plio-Pleistocene	AAPF, SAF	PF, R	Late Neogene climate fluctuations
1973	Vella	New Zealand	Late Neogene	STF	PF	Progressive decline in mean temperature of STW and ASW; STF fluctuations
1975*	Edwards	NZSSO	Cenozoic	AAPF, SAF, STF	PT	Infers surface-water paleocirculation patterns from changing paleogeography
1975*	Shackleton & Kennett	Southern New Zealand	Cenozoic	—	OI	One of first oxygen isotope temperature records for the entire Cenozoic
1977*	Burns	NZSSO	Cenozoic	AAPF, SAF, STF	PF, NF, R	Reconstructions of water mass evolution using microfossil evidence
1978*	Kennett	Southern Ocean	Cenozoic	—	PF, NF, R, D, S	Relates Cenozoic planktic biogeography to evolution of SO water masses
1978	Sancetta	Pacific Ocean	Neogene	—	PF, NF, R	Establishes planktic provinces for four Neogene time slices
1979	Sancetta	Pacific Ocean	Paleogene	—	PF, NF, R, D	Establishes planktic provinces for six Paleogene time slices
1980*	Kennett	Southern Ocean	Cenozoic	—	various	Paleoceanographic and biogeographic overview
1986	Hodell & Kennett	Tasman Sea	Mio-Pliocene	STF	OI, PF, NF	Establishes some late Neogene paleoceanographic events in Tasman Sea
1987	Harwood	Ross Sea (SO)	Cenozoic	AAPF	D	Biosiliceous record off Antarctica
1990	Abelmann et al.	Weddell Sea (SO)	Plio-Pleistocene	AAPF	R, D, S	Biosiliceous record off Antarctica
1990	Baldauf & Barron	Global	Eocene-Quaternary	—	R, D, S	Biosiliceous record global oceans
1990*	Kamp et al.	Southern Australia	Eo-Oligocene	proto-STF	OI, PF, NF	Warm waters decoupled from circumpolar flow and possible proto-STF development
1990	Kennett & Barker	Weddell Sea	Cenozoic	—	OI, various	Relevant to Antarctic ice history
1991	Wei	Southern Ocean	Eo-Oligocene	—	NF	Abrupt temperature decrease in earliest Oligocene from nannofossil evidence
1991	Wise et al.	Southern Ocean	Paleogene	—	OI, Sed, D, NF, PF	Paleogene glacial history of Antarctica
1992*	Hornibrook	New Zealand	Cenozoic	—	FF	Most recent compilation of New Zealand Cenozoic paleoclimate record based on fossils
1992	Kennett & Warnke	Southern Ocean	Cenozoic	various	various	Collection of 18 papers bearing on geology, paleoceanography and paleoclimatology
1992	Shafik	Southern Australia	Eo-Oligocene	—	NF	Seafloor erosion and ocean cooling across boundary
1993*	Jenkins	Southern Ocean	Cenozoic	AAPF, SAF, STF	PF	Traces evolution of five Cenozoic faunal provinces in Southern Hemisphere
1993	Kennett & Warnke	Southern Ocean	Cenozoic	various	various	Collection of 13 papers bearing on geology, paleoceanography and paleoclimatology
1993*	Lazarus & Cautlet	Southern Ocean	Cenozoic	AAPF, SAF	R, Sed	Links evolving radiolarian assemblages to changing surface-water circulation patterns
1994*	Zachos et al.	Southern Ocean	Paleogene	—	OI	Establishes absolute sea-surface temperatures for Southern Ocean
1996	Carter et al.	New Zealand	Cenozoic	—	Sed	Traces evolution of shallow through deep water current systems off eastern New Zealand
1998	Buening et al.	New Zealand	Eo-Miocene	proto-STF	OI	Early Oligocene development of proto-STF off eastern New Zealand
1998	Lawver & Gahagan	Southern Ocean	Cenozoic	—	PT	Suggests Early Oligocene opening of Drake Passage

<sup>1</sup>D, diatoms; FF, fossils; OI, oxygen isotopes; NF, nannofossils; PF, planktic foraminifera; PT, plate tectonics; R, radiolarians; S, silicoflagellates; Sed, sediments.