LEG 177
SOUTHERN OCEAN PALEOCEANOGRAPHY

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ABSTRACT

Leg 177 will core sediments in the southeast Atlantic sector of the Southern Ocean to study the paleoceanographic history of the Antarctic region on short (millennial) to long (Cenozoic) time scales. Six primary sites are located along a latitudinal transect across the Antarctic Circumpolar Current (ACC) from 41° to 53°S, including two sites (TSO-6A/B, TSO-7C/B) within the circum-Antarctic siliceous belt. The sites are also arranged along a bathymetric transect ranging from 2100 to 4600 m water depths, intersecting all of the major deep and bottom water masses in the Southern Ocean.

The general goals of Leg 177 are two-fold: (1) to augment the biostratigraphic, biogeographic, and paleoceanographic history of the earlier Cenozoic, a period marked by the establishment of the Antarctic cryosphere and the ACC; and (2) to target expanded sections of late Neogene sediments that will resolve the timing of Southern Hemisphere climatic events on orbital and suborbital time scales, which can be compared with similar records from other ocean basins and with ice cores from Greenland and Antarctica. Drilling the proposed sites will provide the sedimentary sequences needed to address a number of first-order problems in southern high-latitude paleoclimatology and stratigraphy including (1) the evolution of the ACC and past changes in the position of the Polar Front Zone and the Antarctic sea-ice field; (2) the evolutionary history and stability of the Antarctic cryosphere; (3) changes in Southern Ocean productivity, nutrient cycling, and pCO_2 and their role in global biogeochemical cycles; (4) changes in the mixing ratio of various deep and bottom water masses in the Antarctic (e.g., North Atlantic Deep Water); (5) the response of the Southern Ocean to orbital forcing and the

phase relationships to climatic changes in the high-latitude Northern Hemisphere; and (6) correlation and comparison of marine sediment cores from the Southern Hemisphere with polar ice-core records and documentation of abrupt climate change on millennial time scales.

INTRODUCTION

Leg 177 will core sediments in the southeast Atlantic sector of the Southern Ocean to study the paleoceanographic history of the Antarctic region on short (millennial) to long (Cenozoic) time scales. Six primary sites are located along a latitudinal transect across the Antarctic Circumpolar Current (ACC) from 41° to 53°S (Fig. 1), including two sites (TSO-6A, TSO-7C) within the circum-Antarctic siliceous belt. The sites are also arranged along a bathymetric transect ranging from 2100 to 4600 m water depths, intersecting all of the major deep (Circumpolar Deep Water [CPDW], North Atlantic Deep Water [NADW]) and bottom (Antarctic Bottom Water [AABW]) water masses in the Southern Ocean (Fig. 2). Two deep holes (TSO-2B, TSO-6A) are planned that will recover Cenozoic sequences. Several sites (SubSAT-1A, TSO-6A, and TSO-7C) exhibit average sedimentation rates exceeding 20 cm/k.y. during the late Neogene, which offers an opportunity for paleoclimatic studies on millennial time scales.

Paleoceanographers, climatologists, and geochemists have recognized over the last decade that processes occurring in the Southern Ocean have played a major role in defining the Earth's climate system. The Southern Ocean is an extraordinarily important region because:

1. The Antarctic cryosphere represents the largest accumulation of ice on the Earth's surface. The development and evolution of the Antarctic ice sheets and sea-ice field has had a profound influence on global sea-level history, the Earth's heat budget, atmospheric circulation, surface and deep-water circulation, and the evolution of Antarctic biota.

2. The Southern Ocean is one of the primary sites of intermediate, deep, and bottom water formation. For example, almost two-thirds of the ocean floor is bathed by AABW that mainly originates in the Weddell Sea region. AABW depresses the temperature of at least 55%-60% of the world´s ocean volume to below 2°C (Gordon, 1988). In addition, the Southern Ocean represents the "junction box" of deep-water circulation where mixing occurs among water masses from other ocean basins (Fig. 3). As such, the Southern Ocean is perhaps the only region where the relative mixing ratios of deep-water masses can be

monitored (e.g., fluxes of NADW production). As one of the primary sites of deep and intermediate-water mass formation, the geochemical and climatic fingerprint of Southern Ocean processes is transmitted throughout the world's deep oceans.

3. The Antarctic continent is thermally and biogeographically isolated from the subtropics by the Antarctic Circumpolar Current, a circum-global ring of cold water that contains complex frontal features and upwelling/downwelling cells. The zonal temperature, sea-ice distribution, and nutrient structure within the ACC control the biogenic sedimentary provinces that are characteristic of the Southern Ocean. Upwelling of deep, nutrient-rich water in the Southern Ocean results in significant primary productivity and constitutes nearly one-third of total marine productivity (Berger, 1989). As a result, about two-thirds of the silica supplied annually to the ocean is removed as hard parts of planktonic siliceous microorganisms in the Southern Ocean. This leads to high accumulation rates of biogenic opal and the formation of a circum-Antarctic biogenic silica belt, located between the Polar Frontal Zone (PFZ) and the northern seasonally sea-ice covered Antarctic Zone of the ACC (e.g., DeMaster, 1981; Lisitzin, 1985). Surface waters in the circum-Antarctic are also important globally because upwelling of deep water and sea-ice formation link the thermal and gas composition of the ocean's interior with the atmosphere through air-sea exchange. As a result, most paleogeochemical models of atmospheric CO_2 are highly sensitive to changes in nutrient utilization and/or alkalinity of Antarctic surface waters.

Although Antarctica and the adjacent Southern Ocean represent one of the most important components of the Earth’s climate system, significant gaps exist in our knowledge of its paleoceanographic and paleoclimatic history. The main hindrance for improving our knowledge of Southern Ocean paleoceanography has been the lack of continuous deep-sea sedimentary sequences from the region. To improve the present latitudinal and bathymetric coverage in the Southern Ocean, Leg 177 will drill six primary sites in the high latitudes of the southeast Atlantic Ocean (Fig. 1). Specific sites have been targeted that contain expanded Quaternary, Neogene, and Paleogene sequences not adequately recovered at these depths and latitudes by past drilling. As such, Leg 177 will fill a critical gap in the distribution of drilled ocean sites.

BACKGROUND

Previous deep-sea drilling in the Southern Ocean, especially cores recovered with the hydraulic piston corer (HPC), advanced hydraulic piston corer (APC), and extended core barrel (XCB) systems (Deep Sea Drilling Project [DSDP] Leg 71, Ocean Drilling Program [ODP] Legs 113, 114, 119, and 120), have provided a basic understanding of the paleoceanographic and paleoclimatic evolution of the southern high latitudes during the Cenozoic, which is closely related to paleogeographic changes (i.e., Gondwana breakup). Isotopic and microfossil evidence suggests that ice sheets were established during the earliest Oligocene (Webb, 1990), but little agreement exists on the presence of ice sheets during the Eocene, particularly during the early-middle Eocene (Barron et al., 1991, Wise et al. 1992). Prior to the growth of large Northern Hemisphere ice sheets during the late Pliocene, the Southern Hemisphere cryosphere is implicated as a major driving force for global climate change. There are large differences of opinion, however, regarding the details of Antarctic cryospheric evolution, arising primarily from differences in the interpretation of continental and marine records. For example, one of these differences concerns the extent and volume of the Antarctic ice sheet during the early-late Pliocene (during the Gauss Chron). There are those who assume an essentially stable, combined East and West Antarctic ice sheet since the early Pliocene (Kennett and Barker, 1990; Clapperton and Sugden, 1990), and those who envision a highly dynamic Antarctic ice sheet during the early and early-late Pliocene (Webb and Harwood, 1991; Hambrey and Barrett, 1993). Strongly related to these controversies is the unresolved question of how to partition the temperature, salinity, and ice-volume signals embedded in the Cenozoic oxygen isotopic record (see discussion in Wise et al., 1992). This problem might be addressed by the reconstruction of latitudinal oxygen isotopic gradients across the Southern Ocean (see Zachos et al., 1992) in conjunction with patterns of biogeographic distribution of microfossil assemblages, which reflect changes in water-mass properties. In addition, tandem measurements of oxygen isotopes in diatoms and foraminifers may deconvolve the temperature from the ice-volume signal in oxygen isotopic records, although this novel approach has only been attempted thus far in the latest

Pleistocene (Shemesh et al. 1992). The main stumbling block for reconstructing latitudinal gradients in the Southern Ocean has been the lack of suitable core material. Drilling during ODP Legs 113, 119, and 120 was concentrated in the Antarctic Zone south of the Polar Front, and most of the ODP Leg 114 and previous DSDP sites that used modern drilling techniques are aligned around 50°S in the Atlantic sector of the Southern Ocean. As a result, a true latitudinal transect of cores does not exist to study the response of surface water masses in the Southern Ocean to the glacial evolution on the Antarctic continent.

Another deficiency in the distribution of ocean-drilled cores is the lack of Quaternary, Neogene, and older sequences from the southern high latitudes that would permit the generation of high-resolution stratigraphic and paleoenvironmental signals. Compared to the superb records now available from the high-latitude North Atlantic Ocean (ODP Legs 94, 154, 162, and 172), the Southern Ocean has relatively few sites that are suitable for high-resolution paleoclimatic studies. One of the fundamental tasks in paleoclimatology today is documenting and explaining phase relationships between climatic proxies from different oceanographic regions. Cores with high sedimentation rates are needed to study the timing and response of the southern high latitudes to orbital forcing and the phase relationships to climatic changes in the high-latitude Northern Hemisphere (Imbrie et al., 1989, 1992). Targeting ultra-high-resolution sequences is also important to study rapid climate change on suborbital (millennial) time scales, and to understand the nature of abrupt triggering and feedback processes in the ocean/sea-ice/atmosphere system.

Previous ODP drilling in the Southern Ocean has resulted in only a few sites that recovered Pleistocene and Neogene sections with high-sedimentation rates (Site 704, Meteor Rise; Site 594, Chatham Rise; Site 695, east of South Orkney; Site 514, Subantarctic southwest Atlantic). Sediment drifts and the region of the circum-Antarctic biogenic silica belt in the South Atlantic are ideal targets for the recovery of sediments deposited at high and ultra-high-sedimentation rates. On Leg 177, we expect to recover expanded late Neogene sections with good biocalcareous and biosiliceous preservation at several sites (SubSAT-1, TSO-6A, and TSO-7C) between 41° and 53°S. Piston cores at these sites indicate sedimentation rates in excess of 20 cm/k.y. In addition, the high flux of organic materials to the seafloor in the circum-Antarctic biogenic silica belt may lead to the formation of laminated biosiliceous sediments, which develop when oxygen is depleted periodically in sediment pore waters. Biosiliceous sediments deposited above the carbonate compensation depth (CCD) in the biogenic silica belt also generally contain sufficient calcareous microfossils (foraminifers) for stable isotopic analysis. Together with quantitative reconstructions of paleoenvironmental conditions using statistical methods developed recently for diatoms (Pichon et al., 1987; Zielinski, 1993; Zielinski and Gersonde, 1997) and radiolarians (Brathauer, 1996; A. Abelmann, pers. comm.), these records can be used to reconstruct surface water hydrography, nutrients, and productivity. In addition, sea-ice distribution can be deciphered using diatom taxa that are indicative of sea-ice (Gersonde et al., 1996; Zielinski and Gersonde, 1997).

SCIENTIFIC OBJECTIVES

The broad scientific themes of Leg 177 are two-fold:

1. To augment the biostratigraphic, biogeographic, paleoceanographic, and paleoclimatic history of the Southern Ocean during the Cenozoic, including the evolution and stability of the Antarctic cryosphere; and
2. To construct high and ultra-high-resolution records during the Quaternary and late Neogene to better understand the role of the Southern Ocean in climate change on orbital and suborbital time scales.

Specific paleoceanographic problems to be addressed within the context of these broad themes include:

- *Evolutionary history and stability of the Antarctic cryosphere.* The Leg 177 transect will permit reconstruction of latitudinal isotopic gradients and analysis of biogeographic distribution and abundance patterns of microfossil assemblages that should lead to improved understanding of the growth and stability of the Antarctic ice sheets and help address existing discrepancies between land-based and marine records.

- *Thermal isolation of Southern Ocean surface waters by development of the ACC and its associated frontal systems.* Thermal isolation of the Antarctic continent was intimately linked to tectonic and paleoceanographic changes that led to the establishment of a zonal circulation system, the ACC. Knowledge of the timing and strength of thermal isolation is important for understanding polar heat transport and its effect on the development and stability of the Antarctic ice sheets. The establishment and expansion of the ACC has also influenced intermediate-, deep-, and bottom-water formation in the Southern Ocean. Accurate reconstruction of frontal boundaries requires a latitudinal transect of sites that encompass the dynamic range of the frontal movements. Leg 177 sites will permit us to reconstruct the changes in the paleolatitudinal position of frontal boundaries, similar to studies carried out on piston cores during the late Quaternary (Prell et al., 1979; Morley, 1989; Howard and Prell, 1992).

- *History and distribution of sea ice and its seasonal variation to better understand its role in the global climate system.* Sea ice is a fast changing environmental parameter, which is presently characterized by strong seasonal variations. Changes in sea-ice distribution have been among the most important controls on the Southern Hemisphere climate during the late Pleistocene and affect gas and heat exchange between ocean and atmosphere, ocean circulation and the formation of water masses by the rejection of salt, atmospheric circulation and wind speeds, surface albedo, and the biological production and distribution of organisms.

- *History of primary productivity in the Southern Ocean and evolution of the Antarctic biogenic silica belt.* Since about 36 Ma, the Southern Ocean has acted as a major sink for biogenic opal reflecting increased surface-water productivity as a result of polar cooling and upwelling in the circum-Antarctic (Baldauf et al., 1992). Changes in Southern Ocean productivity and the expansion of the biogenic silica belt have significantly influenced the distribution of nutrients in the World Ocean and has probably played a role in atmospheric pCO_2 variation (Keir, 1988).

- *Southern high-latitude calcareous and siliceous biozonations.* ODP Legs 113, 114, 119, and 120 provided an enormous improvement in southern high-latitude stratigraphy, but further refinement of these stratigraphies is desirable. Leg 177 will provide the opportunity to improve dating of Neogene biostratigraphic markers by correlation with orbital-tuned paleoenvironmental signals. In addition, Leg 177 sequences will permit study of evolutionary processes (patterns, modes, and timing of speciation and diversification), the development of Southern Hemisphere bioprovinces (e.g., endemism), and the response of the biota to long- and short-term environmental changes.

- *Changes in the production and the mixing ratios of various deep and bottom water masses, and their role in affecting the global climate system* . The Southern Ocean is unique in that its deep water (mainly Circumpolar Deep Water) is a mixture of deep-water masses from all ocean basins. As such, monitoring changes in the chemistry of Southern Ocean deep water provides an opportunity to reconstruct changes in the mean composition of the deep ocean. The Southern Ocean is perhaps the only region where fluctuations in the production rate of NADW can be monitored unambiguously (Oppo and Fairbanks, 1987; Charles and Fairbanks, 1992). The Leg 177 depth transect will be ideal for reconstructing the long-term evolution of the dominant subsurface water masses in the Southern Ocean (Fig. 2).

- *Timing and response of Southern Ocean surface and deep waters to orbital forcing, including the phase relationships to climatic changes in the Northern Hemisphere.* Relatively little is known about the interhemispheric phase response (lead, lag, or in-phase) between the high-latitude northern and Southern Hemispheres. Based upon limited data from the Southern Ocean, Imbrie et al. (1989, 1992) suggested an early response of surface and deep waters in the Southern Ocean relative to other regional proxy data. This early response has also been observed by other studies (Charles et al., 1996; Bender et al., 1994; Sowers and Bender, 1995), implying that the Antarctic region plays a key role in the driving mechanism of glacial-to-interglacial climate change. Leg 177 sediments will provide the material needed to study the response of the Southern Ocean to orbital forcing and the phase relationships to climatic changes in other regions.

- *Rapid (suborbital) climate change in the Southern Ocean by correlation and comparison of millennial signals from the Southern Hemisphere with polar ice cores and marine records.* Leg 177 will recover cores with highly expanded sections at three sites (SubSAT-1, TSO-6A, TSO-7C), which will permit the study of climatic variations in the Southern Ocean at suborbital (millennial) time scales. These cores will test if abrupt climate changes occurred in the southern high latitudes similar to those documented in Greenland ice cores (Dansgaard et al., 1993) and marine records from the high-latitude North Atlantic (Bond et al., 1993; Bond and Lotti, 1995). Expanded sections will also permit study of the structure of glacial and interglacial cycles in the Southern Ocean, including the trajectories of deglacial meltwater from the Antarctic continent (Labeyrie et al., 1986). Lastly, correlation between Antarctic sediment cores and ice cores from Greenland and Antarctica will reveal the phase relationships between various variables in the atmosphere and ocean systems, and contribute to identifying the mechanisms responsible for rapid climate change.

DRILLING STRATEGY

The drill plan includes six primary sites that span water depths from 2100 to 4600 m (Tables 1, 2). Targets will be drilled from north to south (TSO-2B, SubSAT-1C, TSO-3C, TSO-5B, TSO-6A, and TSO-7C). Alternate sites were selected for TSO-6A and TSO-7C in the event an iceberg is sitting atop the primary target. Because of time constrains, three alternate sites (TSO-4B, SubSAT-3B, and SubSAT-4B/C) cannot be included in the proposed one-leg effort of 56 days; however, these alternate sites will serve as back-ups to the primary targets. If time savings are realized due to early departure from port or conservative drilling time estimates, the possibility of deepening many of the primary sites would be desirable to obtain longer records. Any time available at the end of the leg will be used to deepen the last hole (TSO-7C).

Successful recovery at the primary sites will provide the following:

- Two deep holes (700 to 800 m) at Sites TSO-2B and TSO-6A that will complete a Cenozoic latitudinal transect between 35° and 72°S when combined with ODP Site 704 (Meteor Rise, and other Leg 114 sites), Sites 689 and 690 (Leg 113, Maud Rise), and Site 360 (South African Continental Rise).

- A depth transect on the Agulhas Ridge around 43°S that includes Sites TSO-2B (2104 m), TSO-3C (3718 m), SubSAT-1C (4620 m) and one site on the Meteor Rise around 47°S when Site TSO-5B (4418 M) is combined with Site 704 (2532 m).

- Complete composite sections of the late Neogene with moderate sedimentation rates by triple APC penetration to 200 m at Sites TSO-3 (3 cm/k.y.) and TSO-5B (8 cm/k.y.).

- One ultra-high resolution transect between 41° and 53°S (SubSAT-1C, TSO-6A, and TSO-7C) recovered by triple APC/XCB.

LOGGING PLAN

This leg offers an opportunity to reconstruct continuous records of Southern Ocean paleoclimate variability using core and log data. Sediments encountered at these sites will consist of periodically alternating layers of biosiliceous and carbonate sediments, with variable amounts of fine (clays) and coarse (ice-rafted debris) terrigenous clastics. Because of the strong density and porosity variations associated with this lithologic variability, core and log physical property indices will very likely be extremely valuable proxy measurements for reconstructing sediment composition time series. Some sites have very high-sedimentation rates, so there is great potential for generating very high-resolution records of regional paleoclimatic and paleoceanographic variability. Previous ODP logging at the sites indicates that some of them have strong physical property variability related to the paleoclimatic opal-carbonate-terrigenous bedding cycles. The deployment of the Formation MicroScanner (FMS) and the Geological High-resolution Magnetometer (GHMT) at each site is planned based on their critical contribution toward developing continuous high-resolution paleoclimate records.

Downhole logging will augment and complement the results of coring. Only holes deeper than 400 m will be logged using standard tools: Quad combo, geochemical (GLT), GHMT, and FMS.

PROPOSED SITES

Primary Sites

Site TSO-2B

Proposed Site TSO-2B is located on the northern Agulhas Ridge in a water depth of 2104 m near the boundary between upper CPDW and NADW (Figs. 1, 2). The Agulhas Ridge in this region is a narrow feature that trends approximately northeast/southwest, and is covered by a thick (>1000 m) package of sediments. Quaternary and Neogene sediments in the region consist of biogenic calcareous oozes that have sedimentation rates of 1-3 cm/k.y. and are not disturbed by turbidites. We plan to drill an 800-m-thick Cenozoic calcareous sequence at Site TSO-2B to gain information from an upper mid-water depth (2104 m) site that is presently located near the northern boundary of the ACC. Because of the low sedimentation rates at Site TSO-2B, it is doubtful that a complete Plio-Pleistocene sequence can be recovered. Consequently, only a single APC hole is planned at this site. This is not a major compromise, however, because surface water signals at this latitude will be captured at Site SubSAT-1C .

The primary objective at Site TSO-2B is to recover a Cenozoic carbonate record that can be used to reconstruct long-term changes in:

- surface water parameters, and the evolution of the Subtropical Front (STF) and its response to southern-high latitude climate variability;
- paleoproductivity north of the PFZ;
- the mixing ratio between lower upper CPDW and upper NADW properties and the evolution of these water masses during the Cenozoic; and
- the paleodepth history of the Agulhas Ridge.

Site SubSAT-1C

Proposed Site SubSAT-1C is located on the northern flank of the Agulhas Ridge (Fig. 1) where a thick package of sediment overlies topographically irregular basement consisting of normal oceanic crust. This site was targeted because of the remarkably high-resolution isotopic record of the last climatic cycle obtained from nearby Core RC11-83 (Fig. 4, Charles et al., 1996), which has sedimentation rates of about 20 cm/k.y. Although the site is deep (4622 m), the high rain rates and quick burial of sediments promotes the preservation of calcium carbonate, which averages 35% in Core RC11-83. Site SubSAT-1C will be cored by triple APC/XCB to a depth of 300 m to recover a complete Pleistocene section at sedimentation rates of >20 cm/k.y. The primary objective is to recover an expanded Pleistocene section north of the present-day PFZ that can be used to study:

- the response of the Southern Ocean to orbital forcing and the phase relationships to climatic events occurring in the high-latitude Northern Hemisphere;
- rapid climate change on suborbital time scales in the Southern Ocean and its relation to climate signals from ice cores from Greenland and Antarctica;
- glacial-to-interglacial variations in the physical and chemical properties of bottom water masses in the South Atlantic Ocean and their relation to high-latitude climate change; and
- glacial-to-interglacial variations in Southern Ocean productivity, nutrient cycling, and pCO_2 and their role in global biogeochemical cycles.

Site TSO-3C

Proposed Site TSO-3C is located in the central part of the Subantarctic Zone on the southern flank of the Agulhas Ridge (Fig. 1). The topography of the ridge is more intricate here compared with its northern component. The water depth at Site TSO-3C is ~3700 m, which is close to the boundary between NADW and underlying lower CPDW (Fig. 2). Site TSO-3C will recover carbonate sediments at sedimentation rates averaging 3 cm/k.y. from the Subantarctic Zone of the ACC. Together with Sites TSO-2B (2104 m) on the Agulhas Ridge and SubSAT-1C (4620 m) north of the ridge, the sites form a depth transect that intersects most of the major water masses of the South Atlantic Ocean (Fig. 2). Site TSO-3C will be cored by APC to a depth of 200 m, which should penetrate to the late Miocene (~7 Ma) assuming a constant sedimentation rate. Specific objectives at Site TSO-3C include the recovery of a continuous Plio-Pleistocene composite section at moderate sedimentation rates to study:

- past migrations in the position of the PFZ;
- changes in the mixing ratios of lower NADW and CPDW in the Southern Ocean and its relation to high-latitude climate change;
- response of the Southern Ocean to orbital forcing and the phase relationships (leads and lags) to climatic changes in the high-latitude Northern Hemisphere; and
- stability of the Antarctic cryosphere during "warmer-than-present" climate during the Pliocene prior to the initiation of Northern Hemisphere glaciation.

Site TSO-5B

Proposed Site TSO-5B is located on the western flank of the Meteor Rise in the Polar Frontal Zone of the ACC (Fig. 1). It is located at about the same latitude as ODP Site 704, drilled on the Meteor Rise, but is significantly deeper (4418 m) than Site 704 (2532 m). Late Pleistocene sediments at Site TSO-5B consist of alternating diatom ooze with calcareous intercalations and an average sedimentation rate of 8 cm/k.y. It will be cored by triple APC to a depth of 200 m to obtain a continuous late Plio-Pleistocene record within the PFZ. Comparison of the deeper water record of Site TSO-5B with shallower results from ODP Site 704 on the Meteor Rise will be useful to study the history of lower CPDW/AABW and mid to upper NADW, respectively (Fig. 2). Specific objectives at Site TSO-5B include the reconstruction of:

- surface water parameters and the evolution of the PFZ;
- paleoproductivity changes in the present PFZ region; and
- lower CPDW and AABW properties and their response to high-latitude climate and the changes in flux of NADW during glacial and interglacial cycles.

Site TSO-6A

Proposed Site TSO-6A is located to the north of Shona Ridge (water depth 3680 m) close to the present day Polar Front (Fig. 1). This area also represents the southernmost extension of the southward spreading tongue of NADW, which mixes with cold Antarctic waters to form CPDW (Fig. 2). This site is located in the northern part of the biogenic silica belt, which is characterized by high biosiliceous accumulation rates. Cores recovered at and near the location of Site TSO-6A are marked by high biosiliceous accumulation with sedimentation rates as high as 80 cm/k.y. during the Holocene. These rates decrease greatly, however, during glacial periods. Today, Site TSO-6A is located about 5° north of the average winter sea-ice edge, but diatoms from glacial-aged sediments indicate that Site TSO-6A was covered by sea ice during late Quaternary glaciations (Gersonde, unpublished). Sediments consist of late Quaternary diatom ooze and diatomaceous mud, but foraminifers are present throughout the core for the establishment of stable isotopic stratigraphies. Site TSO-6A will be triple APC cored to 200 m, followed by single XCB coring to approximately 400 m, and RCB coring to a depth of 700 m to recover late Cenozoic biosiliceous and calcareous high-resolution sediments in mid-water depths on Shona Ridge. Specific objectives include the study of:

- surface water parameters and the evolution of the Polar Front;
- sea-ice distribution in the Southern Ocean;
- paleoproductivity changes (e.g., silica, carbon export rates) and the history of the circum-Antarctic biogenic silica belt in relation to surface water mass changes, deep water circulation, and sea-ice distribution;
- deep water circulation including changes in the physical and chemical properties of CPDW; and
- silica diagenesis (see also Site TSO-7C).

Site TSO-7C

Proposed Site TSO-7C is located in a small sedimentary basin north of Bouvet Island at a water depth of 2850 m. The site is located in the center of the ice-free Antarctic Zone and is bounded to the north by the Polar Front and to the south by the Weddell Gyre/ACC Boundary (Fig. 1). During glacial times, however, the site was covered by winter sea ice as indicated by the occurrence of sea-ice diagnostic diatoms. TSO-7C is one of two sites located in the biogenic silica belt south of the present-day Polar Front. Sedimentation rates in the late Quaternary range between 15 and 60 cm/k.y. An interesting feature of Site TSO-7C is the occurrence of a very early porcellanite in Marine Isotopic Stage 11 (Bohrmann et al., 1994). The occurrence of early porcellanites at TSO-7C will permit geochemical studies of low-temperature silica diagenesis in sediments and pore waters. The porcellanite beds in the sediment cores are only a few centimeters thick and thus should not impede APC penetration. Site TSO-7C will be cored by triple APC to a depth of 200 m to obtain an ultra-high-resolution record of biosiliceous sediments south of the present-day position of the Polar Front. Any time remaining at the end of Leg 177 will be used to deepen TSO-7C to a maximum depth of 730 m. The paleoclimatic record from this site will be used to study rapid climate change on suborbital time scales in Antarctic surface waters and will be correlated to similar ultra-high-resolution records from other marine cores, as well as with Antarctic and Greenland ice core records. Specific objectives include the reconstruction of:

- surface water parameters south of the present PFZ;
- sea-ice distribution in the Southern Ocean-
- paleoproductivity changes (e.g., silica, carbon export rates) in relation to surface water mass changes and sea-ice distribution;
- deep-water circulation including changes in the physical and chemical properties of CPDW; and
- early low-temperature silica diagenesis.

Alternate Sites

Site TSO-4B

Proposed Site TSO-4B is located in the deep northern Agulhas Basin (water depth 4630 m), and is situated in the central part of the Subantarctic Zone of the ACC (Fig. 1). The site is close to magnetic anomaly 32 according to Raymond and LaBrecque (1988), which indicates an early Maastrichtian basement age (~73 Ma, Cande and Kent, 1992). Site TSO-4B is positioned near an extinct spreading center in the Agulhas Basin that was abandoned ~65 Ma when the spreading axis jumped 825 km to the west. Late Quaternary sediments at Site TSO-4B consist of diatom ooze with calcareous intercalations. Site TSO-4B has been approved for single APC coring to 200 m, followed by XCB coring to 400 m, and RCB coring to 500 m. In addition to the reconstruction of surface-water parameters and paleoproductivity, Site TSO-4B will be used to study the history of deep- and bottom-water masses related to the establishment of the Southern Hemisphere cryosphere and its variability through time. The site will also permit a comparison and calibration of stratigraphic and paleoceanographic records based on both calcareous and siliceous microfossils in the present Subantarctic Zone. If basement is reached during drilling, the age will be useful for understanding plate reconstruction in the central South Atlantic.

Site SubSAT-3B

Proposed Site SubSAT-3B is located on the northern Meteor Rise in 2008 m water depth, approximately 34 nmi to the northwest of Site 704. During ODP Leg 114, a 500-m-thick Neogene sequence was recovered from Site 704, but significant core disturbance (e.g., missing and double-cored sections) is evident in Holes 704A and B during some intervals, and the core breaks occur at almost the same depth in the two holes making it impossible to retrieve missing or disturbed sections in the companion hole. Site SubSAT-3B is expected to provide an identical record to Site 704 in terms of age, sedimentation rate, and lithology, but will be far superior in terms of coring disturbance, gaps, and turbidites. Sediments at Site SubSAT-3B should be composed of alternating calcareous and siliceous ooze during the Pleistocene, grading into dominantly calcareous ooze with a significant biosiliceous component during the Pliocene. Average sedimentation rates are expected to be 3 cm per tens of years during the Brunhes Chron, increasing to an average of 7 cm per tens of years during the Matuyama Chron, and decreasing again to 2 cm per tens of years during the Gauss and Gilbert Chrons. Site SubSAT-3B is approved to be cored by triple APC in the upper 200 m. Because Hole 704B drilled 672 m of sediment to the early Oligocene, recovery beyond the depth of APC penetration (>200 m) at Site SubSAT-3B is not warranted. Site SubSAT-3B should penetrate to the early Pliocene (~4.0 Ma) according to the section recovered at Site 704. Specific objectives at Site SubSAT-3B include the recovery of a continuous composite section of the Plio-Pleistocene approximately 2.5°N of the present-day position of the PFZ in 2008 m of water.

Site SubSAT-4B

Site SubSAT-4B is located to the south of the Davis Seamounts in a region where high sedimentation rates occur, and is south of the present-day position of the Polar Front of the ACC in a water depth of 3661 m (Fig. 1). This site is located at 52°S in between Sites TSO-6A and TSO-7C and serves as a good backup to either of these sites in the event that weather or ice bergs prevent us from occupying either of them. Site SubSAT-4B is approved to be drilled using triple APC to 200 m, XCB to 400 m, and RCB to 800 m to recover late Cenozoic biosiliceous and calcareous sediments at high resolution south of the present day position of the PFZ. The objectives are essentially the same as those outlined for Sites TSO-6A and TSO-7C.

SubSAT-4C

Site SubSAT-4C has been selected as an alternate to Site SubSAT-4B in the unlikely event that an iceberg prevents occupation of the primary site.

Site TSO-6B

Site TSO-6B is an alternate to Site TSO-6A in the unlikely event that an iceberg prevents occupation of the primary site. The objectives and drilling strategy at TSO-6B are identical to those described for TSO-6A.

Site TSO-7B

Site TSO-7B is an alternate to Site TSO-7C in the unlikely event that an iceberg prevents occupation of the primary site. The objectives and drilling strategy at TSO-7B are identical to those described for TSO-7C.

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TABLE 1

PROPOSED SITE INFORMATION AND DRILLING STRATEGY

SITE: TSO-2B	**PRIORITY**: 1	**POSITION**: 41°8.20´S, 13°33.65´E
WATER DEPTH: 2104 m	**SEDIMENT THICKNESS**: 1300 m	**TOTAL PENETRATION**: 800 m
SEISMIC COVERAGE: TN057/TSO-2, shot point TN1100		

Objectives: Recover a Cenozoic carbonate record that can be used to reconstruct long-term changes in surface water parameters and the evolution of the Subtropical Front, paleoproductivity north of the Polar Front Zone, mixing ratio between CPDW and upper NADW, and paleodepth history of the Agulhas Ridge.

Drilling Program: Single APC to 200 m, XCB to 400 m, RCB to 800 m

Logging and Downhole Operations: Quad combo, GLT, GHMT, and FMS logs

Nature of Rock Anticipated: nannofossil-foraminiferal ooze, chalk, limestone

SITE: SubSAT-1C	**PRIORITY**: 1	**POSITION**: 40°54.83´S, 9°55.48´E
WATER DEPTH: 4620 m	**SEDIMENT THICKNESS**: 1500 m	**TOTAL PENETRATION**: 300 m
SEISMIC COVERAGE: TN057/SubSAT-1, shot point TN3060		

Objectives: Recover an expanded Pleistocene section at sedimentation rates >20 cm per 1000 yrs to study the response of Southern Ocean to orbital forcing, phase relationships with high-latitude Northern Hemisphere, rapid climate change on suborbital (millennial) time scales, correlation to Greenland and Antarctic ice cores.

Drilling Program: Triple APC/XCB to 300 m.

Logging and Downhole Operations: None

Nature of Rock Anticipated: Diatomaceous calcareous mud

SITE: TSO-3C	**PRIORITY**: 1	**POSITION**: 42° 54.82´S, 8°53.99´E
WATER DEPTH: 3718 m	**SEDIMENT THICKNESS**: 800 m	**TOTAL PENETRATION**: 200 m
SEISMIC COVERAGE: TN057/TSO3, shot point TN1850		

Objectives: Recovery of a continuous composite section of the Plio-Pleistocene at sedimentation rates of 3 cm per 1000 yrs to study past migrations in the PFZ, mixing ratios of lower NADW and CPDW, response of the Southern Ocean to orbital forcing and phase relationships with Northern Hemisphere, and stability of the Antarctic cryosphere under "warmer-than-present climate during the Pliocene.

Drilling Program: Triple APC to 200 m.

Logging and Downhole Operations: None

Nature of Rock Anticipated: Foram-nannofossil ooze

SITE: TSO-5B	**PRIORITY**: 1	**POSITION**: 47°7.22´S, 5°50.68´E
WATER DEPTH: 4418 m	**SEDIMENT THICKNESS**: 1200 m	**TOTAL PENETRATION**: 200 m
SEISMIC COVERAGE: TN057/TSO5, shot point TN3450		

Objectives: Recovery of a continuous composite section of the late Pliocene-Pleistocene at sedimentation rates of 8 cm per 1000 yrs to reconstruct surface water parameters and the PFZ, paleoproductivity changes, properties of CPDW and AABW, orbital forcing and phase relationships of proxy records.

Drilling Program: Triple APC to 200 m.

Logging and Downhole Operations: None

Nature of Rock Anticipated: Calcareous-bearing diatom ooze

SITE: TSO-6A	**PRIORITY**: 1	**POSITION**: 49°58.58´S, 5°51.92´E
WATER DEPTH: 3680 m	**SEDIMENT THICKNESS**: 1100 m	**TOTAL PENETRATION**: 700 m
SEISMIC COVERAGE: AWI94090, shot point PS916		

Objectives: Recovery of late Cenozoic biosiliceous and calcareous sediments in mid-water depths on Shona Ridge to study surface water parameters and evolution of the PFZ, sea-ice distribution in the Southern Ocean, paleoproductivity changes and history of circum-Antarctic biogenic silica belt, physical and chemical properties of CPDW, and silica diagenesis.

Drilling Program: Triple APC to 200 m, XCB to 400 m, RCB to 700 m

Logging and Downhole Operations: Quad combo, GLT, GHMT, and FMS logs

Nature of Rock Anticipated: Foram-bearing diatom ooze, calcareous diatom ooze, diatomaceous nannofossil chalk, limestone

SITE: TSO-6B	**PRIORITY**: 2	**POSITION**: 50°0.98´S, 5°50.13´E
WATER DEPTH: 3679 m	**SEDIMENT THICKNESS**: 1100 m	**TOTAL PENETRATION**: 700 m

SEISMIC COVERAGE: TN057/TSO6, shot point TN650

Objectives: Alternate to TSO-6A in the event primary site is occupied by ice berg. Objectives same as TSO-6A

Drilling Program: Triple APC to 200 m, XCB to 400 m, RCB to 700 m

Logging and Downhole Operations: Quad combo, GLT, GHMT, and FMS logs

Nature of Rock Anticipated: Foram-bearing diatom ooze, calcareous diatom ooze, diatomaceous nannofossil chalk, limestone

SITE: TSO-7C	**PRIORITY**: 1	**POSITION**: 53°10.84´S, 5°7.67´E
WATER DEPTH: 2850 m	**SEDIMENT THICKNESS**: 1000 m	**TOTAL PENETRATION**: 200 m
SEISMIC COVERAGE: AWI94080, CDP 660		*max 730 m

Objectives: Recovery of an ultra-high resolution record of biosiliceous sediments south of the PFZ to study rapid climate change on suborbital time scales, surface water parameters, sea-ice distribution, paleoproductivity changes, deep-water circulation changes and properties of CPDW, and early, low-temperature silica diagenesis.

Drilling Program: Triple APC to 200 m, XCB to 400 m, RCB to 730 m.
*This site may be deepened to maximum of 730 m, if time permits at the end of Leg 177.

Logging and Downhole Operations: None

Nature of Rock Anticipated: Foram-bearing diatom ooze

SITE: TSO-7B	**PRIORITY**: 2	**POSITION**: 53°12.95´S, 5°8.07´E
WATER DEPTH: 2925 m	**SEDIMENT THICKNESS**: 1000 m	**TOTAL PENETRATION**: 200 m
SEISMIC COVERAGE: AWI94080, shot point PS335		*max 730 m

Objectives: Alternate to TSO-7C in the event primary site is occupied by ice berg. Objectives same as TSO-7C

Drilling Program: Triple APC to 200 m, XCB to 400 m, RCB to 730 m.
*This site may be deepened to a maximum of 730 m, if time permits at the end of Leg 177.

Logging and Downhole Operations: None

Nature of Rock Anticipated: Foram-bearing diatom ooze

SITE: TSO-4B	**PRIORITY**: 2	**POSITION**: 43°11.33´S, 11°43.62´E
WATER DEPTH: 4630 m	**SEDIMENT THICKNESS**: 1600 m	**TOTAL PENETRATION**: 500 m

SEISMIC COVERAGE: AWI 94100, shot point PS3245

Objectives: Recovery of a Cenozoic sequence to reconstruct surface water parameters and paleoproductivity north of the Polar Front, history of deep and bottom water masses related to the establishment of Southern Hemisphere cryosphere, and calibration of biostratigraphic markers.

Drilling Program: Single APC to 200 m, XCB to 400 m, RCB to 500 m

Logging and Downhole Operations: Quad combo, GLT, GHMT, and FMS logs

Nature of Rock Anticipated: Calcareous diatomaceous mud and mudstone.

SITE: SubSAT-3B **PRIORITY**: 2 **POSITION**: 46°24.7´S, 7°4.79´E
WATER DEPTH: 2008 m **SEDIMENT THICKNESS**: 1600 m **TOTAL PENETRATION**: 200 m
SEISMIC COVERAGE: TN057/SubSAT3, shotpoint TN1200

Objectives: Recover upper 200 m of section that was disturbed and incomplete at ODP Site 704 to study past migrations in the position of the PFZ, changes in mixing ratios of upper NADW and CPDW, and stability of the Antarctic cryosphere during "warmer-than-present" climate during the Pliocene.

Drilling Program: Triple APC to 200 m

Logging and Downhole Operations: None

Nature of Rock Anticipated: Alternating calcareous and siliceous ooze

SITE: SubSAT-4B **PRIORITY**: 2 **POSITION**: 52° 3.01´S, 4° 31.01´E
WATER DEPTH: 3661 m **SEDIMENT THICKNESS**: 1100 m **TOTAL PENETRATION**: 700 m
SEISMIC COVERAGE: TN057/SubSAT4, shotpoint TN1800

Objectives: SubSAT-4B will serve as a backup to either TSO-6A or TSO-7C. The objectives are essentially the same as those outlined for those sites.

Drilling Program: Triple APC to 200 m, XCB to 400 m, RCB to 700 m

Logging and Downhole Operations: Quad combo, GLT, GHMT, and FMS logs

Nature of Rock Anticipated: Foram-bearing diatom ooze, calcareous diatom ooze, diatomaceous nannofossil chalk, limestone

SITE: SubSAT-4C **PRIORITY**: 2 **POSITION**: 51°59.08´S, 4°31.0´E
WATER DEPTH: 3701 m **SEDIMENT THICKNESS**: 1100 m **TOTAL PENETRATION**: 700 m
SEISMIC COVERAGE: TN057/SubSAT4, shotpoint TN4210

Objectives: SubSAT-4C will serve as a backup to SubSAT-4B.

Drilling Program: Triple APC to 200 m, XCB to 400 m, RCB to 700 m

Logging and Downhole Operations: Quad combo, GLT, GHMT, and FMS logs

Nature of Rock Anticipated: Foram-bearing diatom ooze, calcareous diatom ooze, diatomaceous nannofossil chalk, limestone

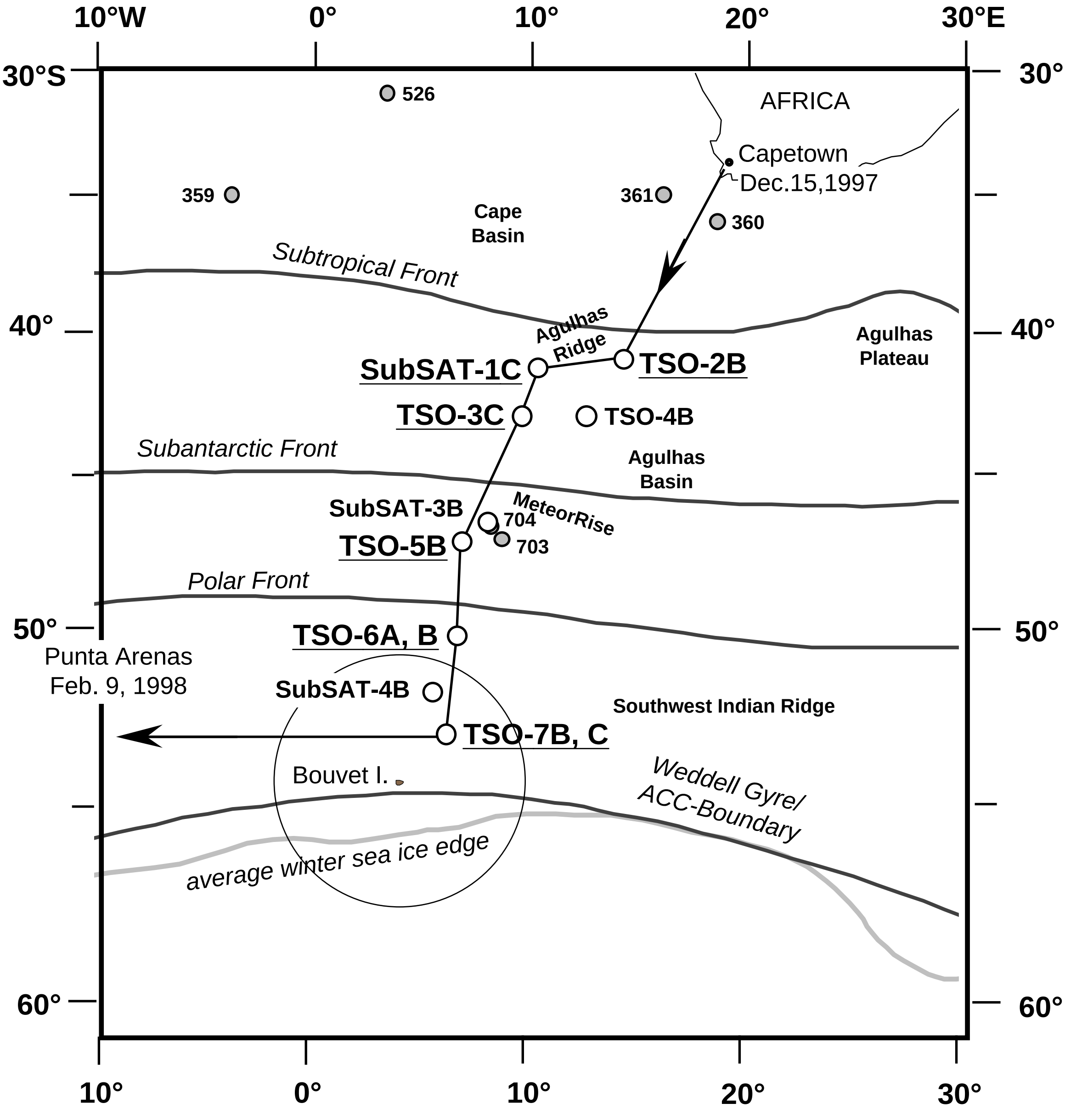

Figure 1. Location of Leg 177 drilling targets and previous DSDP/ODP sites in the South Atlantic. Primary sites are underlined. Circle indicates 200-nmi zone off Bouvet Island (Norway).

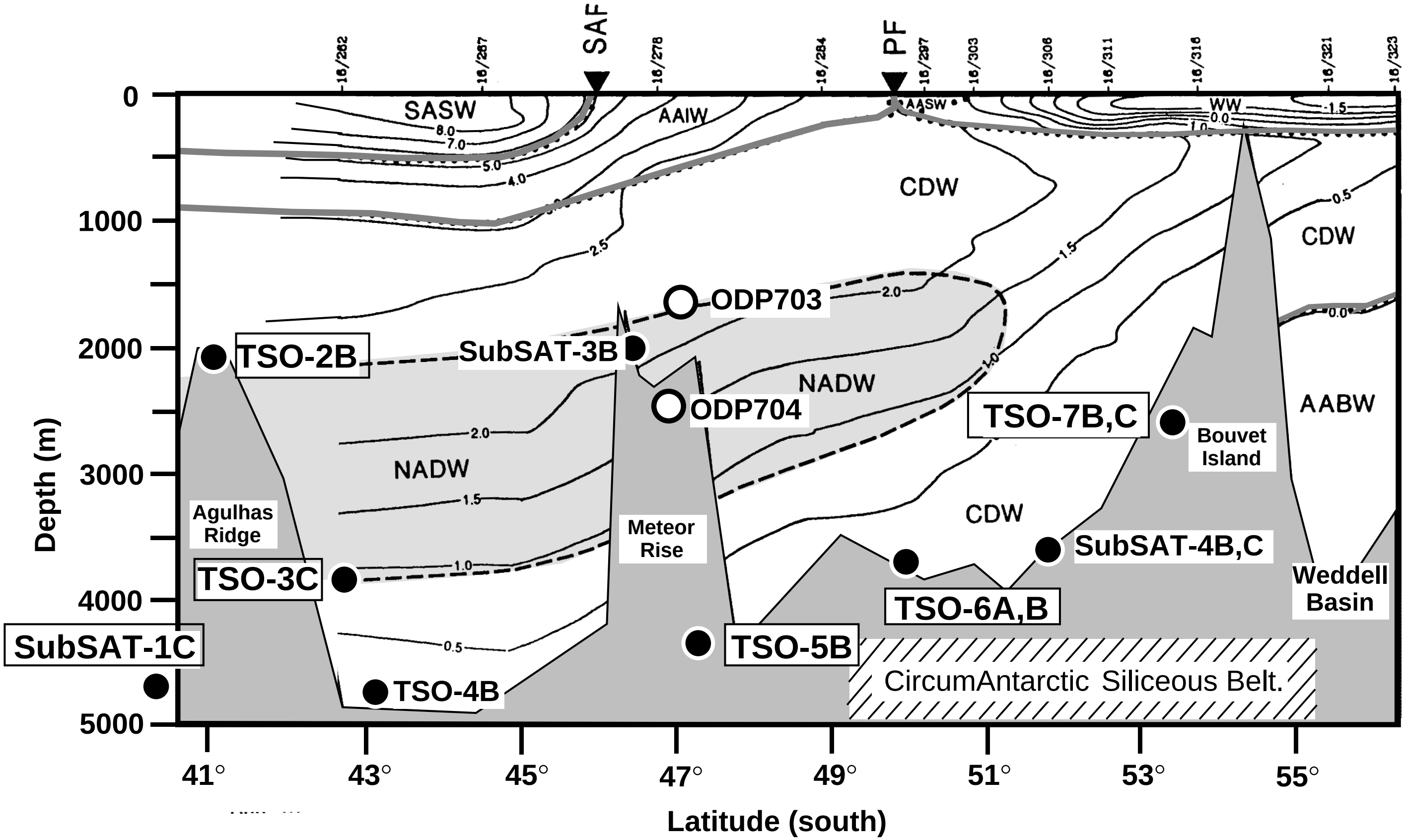

Figure 2. Schematic representation of the vertical distribution of potential temperature on a transect in the eastern Atlantic sector of the Southern Ocean (from Agulhas Ridge to Bouvet Island) relative to the proposed Leg 177 sites. The ratio numbers at the top of the figure indicate the hydrographic station used to contour the potential temperature.
PF = Polar Front. SAF = SubAntarctic Front.

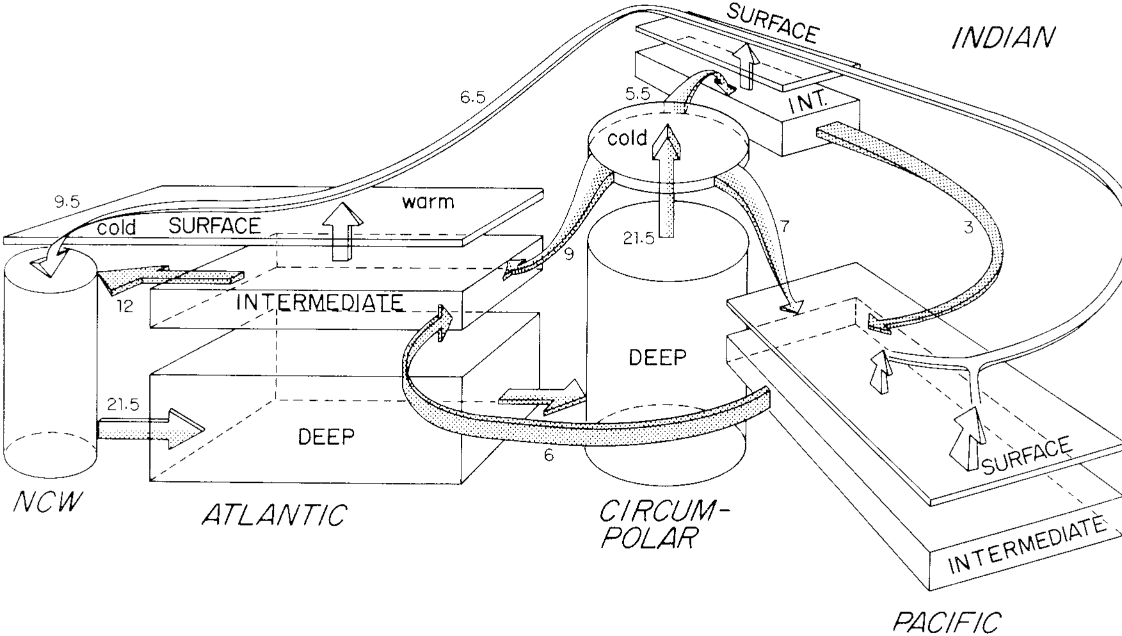

Figure 3. Schematic representation of present ocean circulation and interocean exchange. Not shown are the deep Indian and Pacific reservoirs (flux in sv, from Keir, 1988).

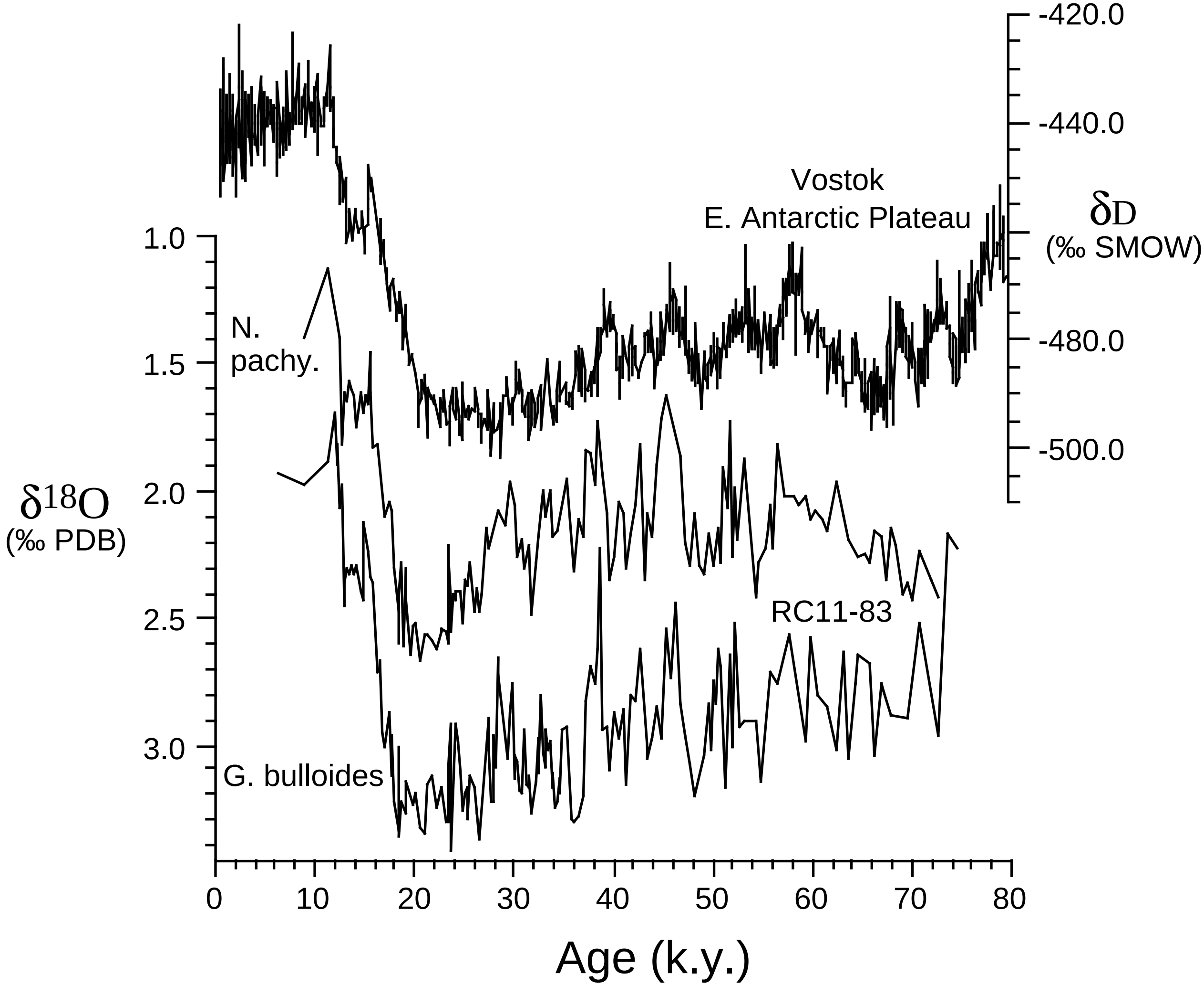

Figure 4. Oxygen isotopic record of Core RC11-83 (located near SubSAT-1C) compared with hydrogen isotopic record from Vostok ice core (Charles et al., 1996)