Geophys. J. Int. (2005) **161,** 325–333 doi: 10.1111/j.1365-246X.2005.02578.x

Cenozoic bottom current sedimentation in the Cape basin, South Atlantic

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Accepted 2004 December 23. Received 2004 November 26; in original form 2003 April 8

SUMMARY

The Agulhas Ridge, which rises up to 2.5 km over the ocean floor of the adjacent Cape and Agulhas basins, located along the Falkland-Agulhas fracture zone, acts as a barrier for northward flowing deep-water masses, deflecting them along the bathymetric contours of the Agulhas Ridge. Seismic data recorded over the Agulhas Ridge shows that the sediments transported by these deep-water currents accumulate in contourite drifts. Several hundred metres of sediments have accumulated since the onset of intrusion of Antarctic Bottom Water (AABW) derived water masses into the basins of the South Atlantic. An erosional surface in early Oligocene sediments appears to mark a prominent change in the sedimentation pattern. Up to this event, strong and varying currents formed a rapidly accumulating sheet of sediments subdivided into units with significant seismic impedance contrasts and thus strong reflections in the seismic image of these sediments. After the early Oligocene erosional event, a stable unidirectional bottom current was established, with sedimentation of mainly muddy material, leading to the formation of a more than 200-km-long, approximately 30-km-wide elongate contourite drift. A period of non-deposition during the middle Miocene is followed by an increase of well-defined seismostratigraphic units, most pronounced for sediments of Quaternary age. This suggests that build-up of the drift structure generally continued, with alternating episodes of erosion and sedimentation in response to glacial cycles.

Key words: Agulhas Ridge, Leg 177, Ocean Drilling Program, reflection seismology, sedimentation, South Atlantic.

GJI Seismology

1 INTRODUCTION

During the Cenozoic, starting at the end of the Eocene, a process of cooling started in the Southern Ocean (Berger & Wefer 1996). A crucial step was the opening of several gateways between the oceans of the world as the continents, which were formed after the Gondwana breakup, drifted apart and established a ring of cold water around the Antarctic continent causing thermal insulation in the Oligocene (Lawver & Gahagan 1998). This eventually led to the production of cold bottom water at high latitudes, which subsequently was injected into the southern Atlantic ocean. Northward flowing branches of Circumpolar Deep Water (CDW) enter the Agulhas Basin but further northward flow is blocked by the Agulhas Ridge, which separates the Agulhas Basin from the Cape Basin southwest of the coast of South Africa (Reid 1989). Through the passage near the South African coast it enters the Cape Basin as a bottom current and follows a southwestward direction along the contours of the Agulhas Ridge (Tucholke & Embley 1984). The northward extent and the flow intensity of water masses with Antarctic origin into the basins of the Atlantic ocean shows variations over time, especially in response to Northern Hemisphere glaciation cycles (Turneau & Ledbetter 1989). Sediments transported by the CDW are deposited parallel to the Agulhas Ridge in the form of contourite drifts. The structure of these drifts in the Cape Basin can be used as an indicator of palaeocurrent activity.

In order to reveal the internal structure of these drift deposits and, hence, the evolution of the CDW in response to the climatic events of the Cenozoic, several multichannel seismic profiles were obtained across the northern flank of the Agulhas Ridge and southern part of the Cape Basin and are interpreted here in terms of deep-water geostrophic flow from the Southern Ocean. The acquisition of seismic data is required to reveal and classify large-scale structures based on morphology and facies of deep sea sediment bodies.

The interpretation of the seismic profiles opens the opportunity to trace drift structures over a wide area in an oceanic basin.

2 REGIONAL SETTING

After the Early Cretaceous breakup of Gondwana, the continents of Africa and South America drifted apart, thereby opening the South Atlantic ocean along the Falkland-Agulhas fracture zone. Along this fracture zone, the Agulhas Ridge formed during the Late Cretaceous (Ben-Avraham *et al.* 1997). The Agulhas Ridge rises to 2 km below the sea surface, with the adjacent oceanic basins being over 5 km deep. It extends for more than 1100 km from the Agulhas Rift, a spreading centre abandoned 61.2 Ma (Marks & Stock 2001), extending from the northeast at 40°S, 15°E (LaBrecque & Hayes 1979) to the northern end of the Meteor Rise at 45°S, 4°E. The Agulhas Ridge separates the Cape Basin to the north from the Agulhas Basin to the south and, as a result of its topography, blocks the exchange of water masses between these two basins.

After separation of Antarctica from its surrounding continents, a circumpolar current developed, which caused thermal insulation of the Antarctic continent (Barker & Burrell 1977; Kennett 1977; Lawver & Gahagan 1998). This eventually led to the onset of Antarctic glaciation in the Oligocene and marked the beginning of the production of Antarctic Bottom Water (AABW) (Mackensen & Ehrmann 1992; Zachos *et al.* 1994), originating mainly in the Weddell Sea area.

In the present-day situation, as AABW flows northwards, it mixes with the warmer North Atlantic Deep Water (NADW) forming circumpolar water (CPW). In the Southern Ocean, the CPW splits into an upper and a lower branch, vertically separated by a tongue of NADW (Mantyla & Reid 1983; Orsi *et al.* 1999). CDW, the lower branch, cannot cross the Agulhas Ridge, but enters the Cape Basin through a passage between the African coast and the northeastern part of the Agulhas Ridge as a bottom current (Tucholke & Embley 1984). Previous studies indicate that the Cape Basin was already swept by a proto-AABW bottom current during the Oligocene (Tucholke & Embley 1984; Sykes *et al.* 1998).

3 INTER-OCEAN WATER EXCHANGE THROUGH THE TASMANIAN GATEWAY AND DRAKE PASSAGE

The Eocene–Oligocene boundary marks a fundamental modification of the ocean circulation with the opening of the Tasmanian gateway. Ocean Drilling Program (ODP) Leg 189 drilling at the South Tasman Rise (Exon *et al.* 2001) shows that this gateway opened in the late Eocene for shallow water and during the earliest Oligocene for deep water. The opening of the Tasmanian gateway permitted the interchange of deep water between the southern Indian and Pacific oceans that enabled the onset of at least a partial Antarctic Circumpolar Current (ACC). Increased current strength led to widespread hiatuses in the Oligocene sections of Leg 189.

In the wider region of Leg 189, there exists a regional hiatus near New Zealand known as the Marshall paraconformity (Carter & Landis 1972; Fulthorpe *et al.* 1996; Carter *et al.* 1999), which coincides with the initiation of the Deep Western Boundary Current (DWBC; Carter *et al.* 1999). Like the CDW of the South Atlantic, the DWBC is a product of mixing dense waters around Antarctica with deep water from the Atlantic and Indian oceans, under the influence of wind-driven ACC.

Data from Leg 177, Site 1090 shows an increased supply of detrital matter with affinities to oceanic crust derived from rifting west of site 1090 after ∼33 Ma and suggests the existence of a circumpolar flow for at least surface waters (Gersonde *et al.* 2002). However, Scotia Sea reconstructions preclude deep-water flow at this time, and show that deep-water pathways between the Pacific and Atlantic oceans have developed within the time frame of 22–17 Ma (Barker 2001). By this time, the Tasmanian gateway was already fully open and the way was cleared for a full circumpolar current leading to the thermal isolation of Antarctica.

4 CONTOURITES

Contourites are defined as sediment bodies deposited or reworked by the sustained flow of thermohaline driven, geostrophic, deep-water bottom currents (Heezen *et al.* 1966; Faugères & Stow 1993). As a result of morphological constraints, these currents often follow bathymetric contours in deep sea basins. Sediments are transported and redistributed over distances of thousands of kilometres (McCave 1986). In this way, sediments originating in the Antarctic region can be transported into the basins of the Atlantic Ocean. Downslope turbidity currents form another important source of sediment input to bottom currents. Apart from being a major source of sediment influx in the oceanic basins, bottom currents can be strong enough to scour the seafloor and create widespread erosional surfaces. The eroded particles add to the sediments already in suspension.

Several types of contourite morphologies are known in ocean basins (Faugères *et al.* 1999, give an overview and a classification). On the largest scale, there are contourite sheets, formed when bottom currents become trapped in a basin and sedimentation takes the form of building wide sheets, either abyssal sheets, distant from the basin boundaries, or slope sheets at a basin margin. The variation in geometry is very slight and the internal layers are often seismically transparent. A second frequent type of contourite deposit is the elongate mounded drift, with length much greater than width and a distinctly mounded topography. These drifts are typically deposited parallel or subparallel to slopes. The base of such a drift is often an erosional surface developed after extensive previous erosion by bottom currents. Such erosional surfaces often appear on seismic sections as outstanding and discordant reflectors and then form the basis of new contourite drifts.

Seismostratigraphic units of contourite sediments often show an upward convex lenticular shape (Faugères *et al.* 1999). In some cases, an asymmetry is observed in contourites. This is the result of a preferential deposition of sediments on one side of the current under the influence of the Coriolis force (McCave & Tucholke 1986; Faugères *et al.* 1999), leading to deflection of suspended material to the left-hand side of the current on the Southern Hemisphere and to the right-hand side on the Northern Hemisphere.

5 OBTAINING AN IMAGE FROM SEISMIC DATA AND SEDIMENT CORES

Eight profiles of seismic data with a total length of approximately 2000 km were collected over the Agulhas Ridge, extending into the Agulhas and Cape Basins, during a seismic survey carried out by the Alfred Wegener Institute for Polar and Marine Research (Uenzelmann-Neben 1998; Fig. 1). An energy source of two GI^{TM} guns was used to record 8 s of data with a 96 channel streamer.

Physical properties data from ODP Leg 177 were used to establish the link between the image of sediment bodies obtained from the seismic data and the geological information obtained from recovered sediments during this drilling campaign in the Agulhas Ridge area. Drilling of Leg 177 took place at a total of seven locations, three of which (Sites 1088, 1089 and 1090) are in the vicinity of the Agulhas Ridge (Gersonde *et al.* 1999). Core samples were dated based on their fossil contents and examined for several of their physical and chemical properties. Among the physical properties measured in core samples were density and seismic *P*-wave velocity. The density was measured with the gamma ray porosity evaluator (GRAPE) at a 2- or 4-cm sample interval and by moisture and density (MAD) measurements, usually once per core section (Shipboard Scientific Party 1999a). GRAPE measurements exist over a length of 233 m for site 1088, 265 m for site 1089 and 397 m for site 1090. Fig. 2 shows the density profile of site 1090 and the corresponding lithostratigraphy. The *P*-wave velocity was measured with a *P*-wave logger (PWL) at a 2- or 4-cm sample interval and with a *P*-wave Velocity

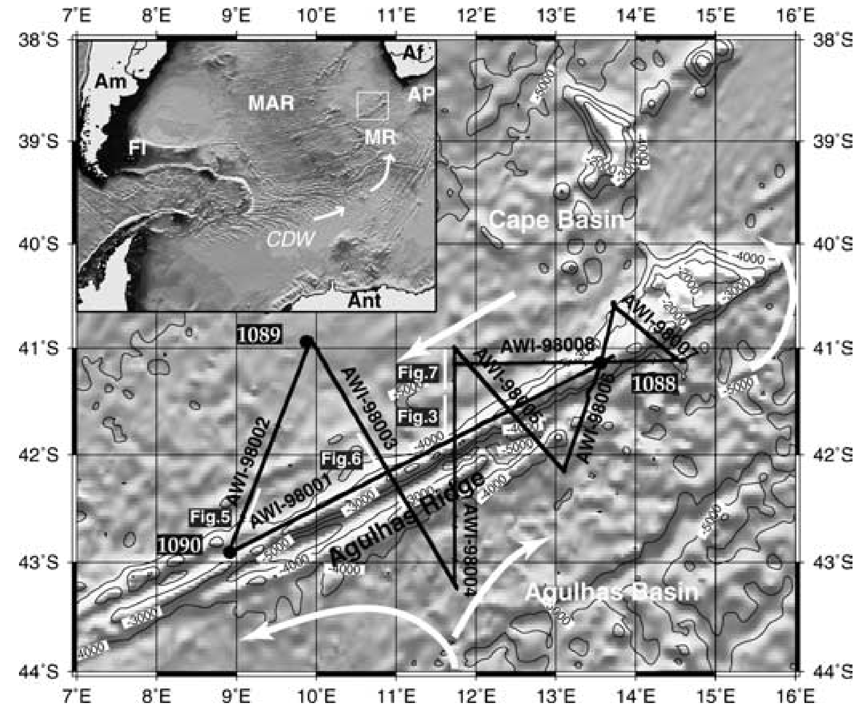

Figure 1. Bathymetry map of the Agulhas Ridge area (after Sandwell & Smith 1997) with seismic profiles AWI-98001 through AWI-98008 and drilling locations of Ocean Drilling Program (ODP) Leg 177 Sites 1088, 1089 and 1090 (big dots). Abbreviations: Af, Africa; Am, South America; AP, Agulhas Plateau; Ant, Antarctica; FI, Falkland Islands; MAR, mid-Atlantic ridge; MR, Meteor Rise; arrows denote the flow of circumpolar deep water (CDW), the present-day bottom water current (after Tucholke & Embley 1984).

Sensor 3 (PWS3) on selected core samples (Shipboard Scientific Party 1999a). PWL measurements exist over a length of 162 m for Site 1088, 215 m for Site 1089 and 236 m for Site 1090, however these measurements yielded often poor results, especially for Site 1089, and were always close to 1500 m s^{-1}, the seismic velocity of water, largely irrespective of lithology. Density and *P*-wave measurements were filtered for spurious values and then used to create a seismic impedance series, resampled to a uniformly spaced series of values along the cored sections. The reflectivity series calculated from the seismic impedances, yield synthetic seismograms after conversion from the depth domain into the traveltime domain and convolution with a seismic source signature. As the geological timescale and sediment type is known from the core samples, these synthetic seismograms serve as the link between core samples and the geological age of the reflectors in the seismic data.

6 RESULTS

The sediments at the three Leg 177 locations near the Agulhas Ridge are mainly calcareous. Site 1088 (Fig. 1) shows a nearly continuous record from middle Miocene (∼13 Ma) of nannofossil foraminifer ooze at the upper 20 m and decreasing foraminifer content in the underlying nannofossil ooze (Shipboard Scientific Party 1999b). The sediments cored at Site 1089, in the Cape Basin approximately 140 km from the Agulhas Ridge (Fig. 1), are of Pliocene and Pleistocene age and contain reworked sediments, mainly of Pliocene age, but also some with lower Miocene and upper Eocene/Oligocene faunas (Shipboard Scientific Party 1999c). The cores show that the amount of nannofossil ooze and diatom mud fluctuates, where the latter is somewhat more abundant. The southwestern part of the Agulhas Ridge, at Site 1090, where the oldest sediments, down to middle Eocene were recovered (Shipboard Scientific Party 1999c), also consists of a predominantly calcareous composition, although the carbonate content is lower than at Site 1088, also on top of the Agulhas Ridge, but further to the northeast.

Seismic sections in the Cape Basin show two distinct series of reflections. The seismic image of the sediments below reflector O, at approximately 6600 ms, e.g. in Figs 3, 5 and 6, is more or less uniform without a distinctly mounded morphology over the seismic sections in the Cape Basin. The correlation between the seismic data and synthetic seismograms constructed from the physical properties measured on core samples at Site 1090 shows that reflector O corresponds to a hiatus in the early Oligocene (Fig. 2). In this set of Eocene/early Oligocene seismic units, structures can be found that are indicative of bottom current activity, as opposed to turbidity current deposits. Clearly present on profiles AWI-98002 (Fig. 5) and AWI-98004 (Fig. 3) are sediment packages shaped into lenticular units. The sediments above reflector O show different reflection characteristics in the form of separated drifts of a constrained width and a considerable relief of several hundreds of metres has been built up. In the Cape Basin, at approximately 50 km north of the Agulhas Ridge, an elongate southwest trending sediment drift 30 to 40 km wide and over 200 km long has developed parallel to the ridge, on top of reflector O. This drift can be identified on several of the seismic profiles in the Cape Basin as in Fig. 6 for profile AWI-98003 between Common Depth Point (CDP) 4600 and 6000, and in Fig. 3 for profile AWI-98004 between CDP 7350 and 7950. In contrast to the highly reflective older units, it shows a seismic image of sediments that are much more transparent.

Between reflectors O and M (Fig. 6), the sediments accumulated in units with hummocky appearance and mainly low-intensity internal seismic reflections. Data from Site 1090 shows that reflector M corresponds to an extensive hiatus dated as middle Miocene. The intensity of seismic reflectivity gradually become stronger and a

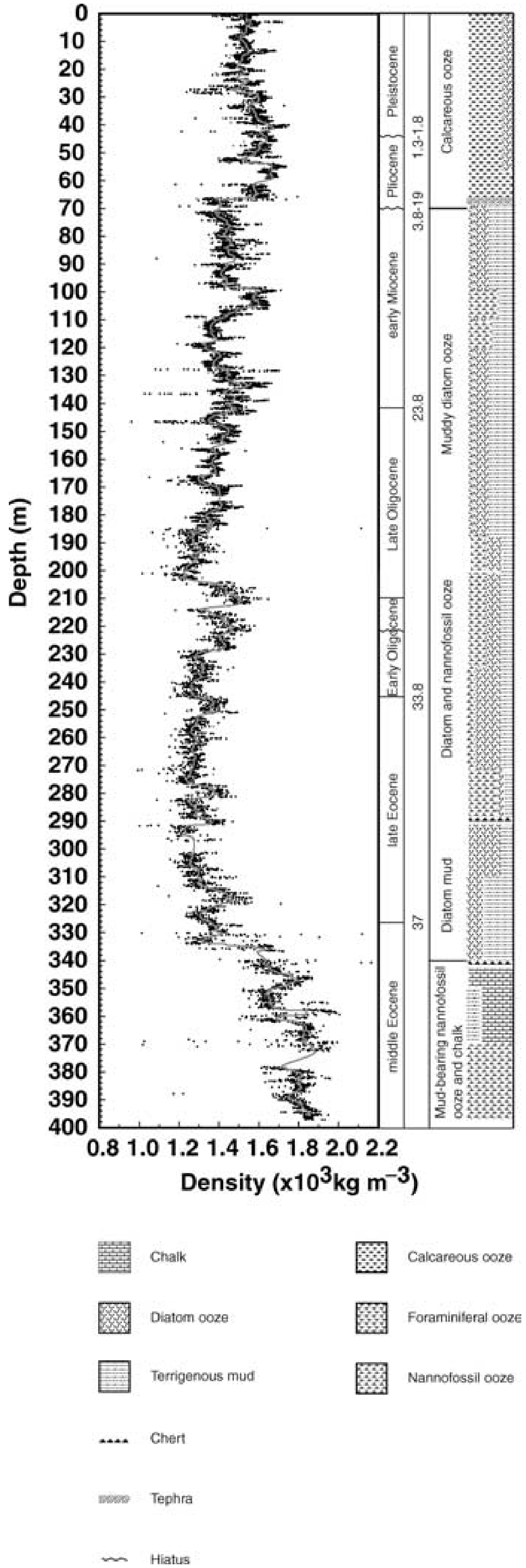

Figure 2. Correlation between density measured on cores from gamma ray porosity and lithostratigraphy (adapted from Shipboard Scientific Party 1999c) at Site 1090. A density contrast at 220 m depth correlates with a hiatus found in the biostratigraphic record of the early Oligocene.

division in well-defined layers returns for units younger than reflector M (Figs 6 and 7), though still less pronounced than for sediments below reflector O. The youngest sediments, above reflector P (Fig. 6), display sharp reflectors. Still, these reflectors tend to be parallel to deeper reflectors and sometimes even truncate the older units as in Fig. 6. Core-to-seismic correlation places this reflector at the base of the Pleistocene.

7 THE INFLUENCE OF BOTTOM CURRENT REGIME ON SEDIMENTATION

The seismic image of sediments is an expression of the seismic impedance contrast between various units, which depends on the physical properties seismic velocity and density. Because the seismic velocity in water saturated sediments, relatively close to the ocean bottom, shows little variation for different lithologies, it is the density that has most impact on the seismic impedance. Especially large are the density contrasts at hiatuses, with different lithologies at either side of the interface.

Two distinct episodes of bottom current sedimentation are observed, the first plastering the ocean bottom (Fig. 4), starting probably in the Eocene and ending in the early Oligocene with a widespread hiatus associated with an erosional event (Wildeboer Schut *et al.* 2002) at 32.8–31.3 Ma (Gersonde *et al.* 2002) and a change in sedimentation from continental to oceanic crustal sources (Gersonde *et al.* 2002). Outside of the Southern Atlantic, an environmental change by the introduction of cold deep water, has also been observed in ODP Leg 181 Sites 1123 and 1124 east of New Zealand. Here, the introduction of the DWBC is accompanied with the concurrent (∼33–27 Ma) Marshall Paraconformity (Carter & Landis 1972; Carter 1985; Fulthorpe *et al.* 1996).

A steady build-up of distinct drift structures follows the early Oligocene hiatus.

The packages within the unit below reflector O are (sub)parallel, sigmoidal (Fig. 3) or lenticular (Fig. 5) shaped. The strong seismic reflections in this unit indicate variations in current velocity. The shape of the structures indicate a contourite current type of sedimentation, as does the existence of a buried moat, on profile AWI-98003 (Fig. 6) near CDP 6000 just at the base of the Agulhas Ridge and parallel to it. Near CDP 9700 on profile AWI-98004 (Fig. 7), 75 km north of the Agulhas Ridge, a small-scale buried drift structure is found. A continuously southward migration of the crest has possibly prograded under the influence of the Coriolis force acting on a southwest setting bottom current. The top of this drift was initially associated with the erosional surface (reflector O), after approximately 100 m of sediments accumulated. Eventually it formed the basis of a continued build-up of the drift during the Miocene and reaches a total thickness of approximately 200 m. The continued build-up of this buried drift suggests that the direction of the active bottom current remained much the same during the Oligocene and Miocene.

The early Oligocene age of the Marshall Paraconformity of Leg 181 (Carter *et al.* 1999) coincides with the timing of our reflector O, which might indicate a shared response to the opening of the Tasmanian gateway. However, Leg 189 data also suggests strong regional differences in Antarctic climate during the Oligocene (Exon *et al.* 2001) indicating ocean current regimes limited to a specific region.

The low-intensity, seismically almost transparent units of which a large part of the drift structure between the reflectors O and M is composed (Figs 6 and 7), indicates a homogeneous, predominantly

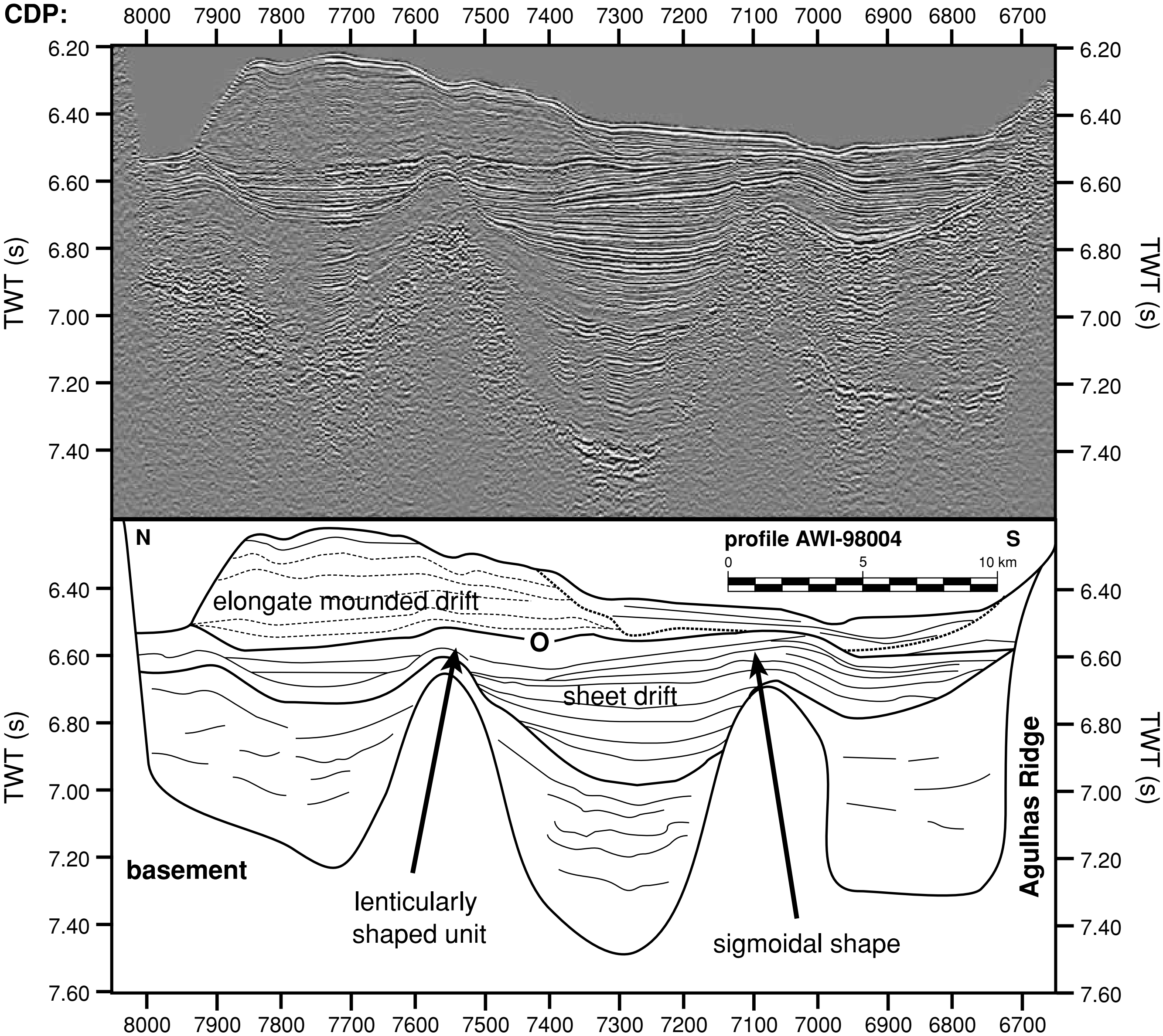

Figure 3. This section of profile AWI-98004 (position shown on Fig. 1) is located just south of the section shown in Fig. 7. The lenticular and sigmoidal shape of the seismic reflectors are indicative of sedimentation by bottom currents. The drift between CDP 7350 and 7950 above the early Oligocene hiatus O shows a very low-intensity, hummocky seismic reflectivity.

muddy composition. This is affirmed by the sediments of late Oligocene and Miocene age found in hole 1090 (Shipboard Scientific Party 1999d).

Core samples from drill Site 1089, mainly of Pleistocene age, contain older fossils. This is an indication that resedimentation by a bottom current took place. Shallow-water diatoms throughout the entire sedimentary record demonstrate a steady input of sediments originating near the African coast (Shipboard Scientific Party 1999c), which constrains the trajectory of the bottom current.

8 THE HISTORY OF CENOZOIC BOTTOM CURRENTS IN THE CAPE BASIN

Seismic images of contourite drifts often show mainly low-intensity seismic reflections, as a result of a predominantly muddy composition. The intermediate to high amplitude reflectors encountered on seismic sections often reflect a change in the sediment accumulation rate or in the composition of the sediments. Variations of the seismic structure within contourites could therefore imply variations in the larger scale circulation pattern, whereby sediments from different source regions are brought in. A different type of original sediment input or variations in biogenic production leads to lithologies with a seismic velocity and density contrast that manifests itself as a seismic reflection. Another possibility is current velocity increase, reflected in a more sandy type of sediments.

The existence of contourite sheets shows that bottom current activity existed in the Cape Basin before the timing of reflector O (early Oligocene) and transported a significant amount of sediments into the Cape Basin. Data from Site 1090 shows that the Eocene/early Oligocene units correspond with high diatom abundances and high opal percentages and variability, and were deposited at high

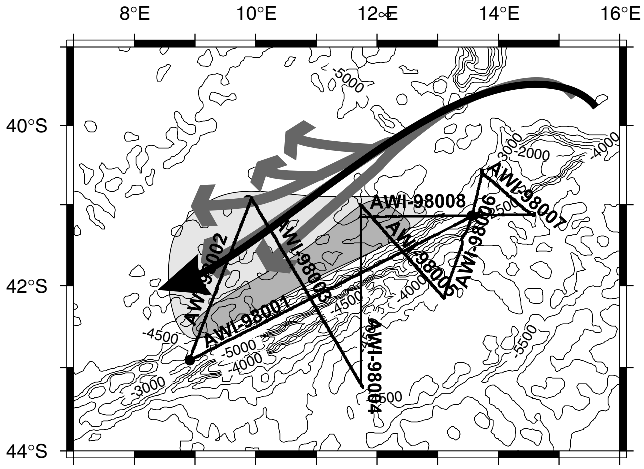

Figure 4. The light grey area shows the location of pre-early Oligocene sediments. The floor of the Cape Basin is plastered with parallel sheets of sediments of alternating composition, sedimented at a high rate by a strong current (grey arrows). An elongate mounded drift is being build on top of this erosional surface (the darker grey area) by a bottom current, which follows the bathymetric contours of the Agulhas Ridge (black arrow).

sedimentation rates (Shipboard Scientific Party 1999d). This indicates the fluctuating paths of the oceanic currents at that time, picking up materials in varying source regions.

Increased current velocity can result in large erosional surfaces, which is one of the features that are characteristic of contourites (Faugères & Stow 1993). This happened in the southern Cape Basin in the early Oligocene, after which the erosional surface became the base for large-scale drift structures. This type of large-scale drift was classified as giant elongate mounded drifts (Faugères & Stow 1993), drifts much longer than wide along a continental margin, or along the flanks of mid-ocean ridge systems.

Steady build-up of the drift structure with parallel to subparallel layers indicate that the current direction did not substantially change between the early and late Oligocene.

The bottom current flow stabilized and a steady build-up of an elongate mounded drift commenced (schematically visualized in Fig. 4). During this period, the current did not change significantly in speed or in the sediments it carried, as the seismic unit is highly transparent in contrast to the older units. Although current activity remained and in the same direction as before, there were alternating periods of stronger and weaker bottom current flow. In the middle Miocene a hiatus is found, which is probably connected to a period of non-deposition when deeper waters could no longer reach the Cape Basin as a result of the reduced production of the proto-AABW of that time (Sykes *et al.* 1998). When sedimentation continued, the seismic reflectors inside post middle Miocene units become progressively more pronounced, although still weak compared with Eocene—early Oligocene reflectors.

Quaternary sediments have been exposed to alternating periods of stronger and weaker flow, to the point where erosion could take place. These episodes are probably connected with the Pleistocene glaciation cycles. Northern Hemisphere cooling increased the input of NADW periodically, which resulted in alternating diminished and increased CDW input into the South Atlantic ocean (Turneau & Ledbetter 1989). Pleistocene hiatuses are not unique to the Cape Basin and are found on other locations of the South Atlantic ocean as well (Ledbetter & Ciesielski 1982). Site 1089, with predominantly Quaternary sediments, shows stronger variation in the relative amount of siliceous and calcareous sediments than other Leg 177 Sites with mainly older sediments do. Bioturbation, prevalent in the Pleistocene sediments of Site 1089, the scarcity of dropstones and the presence of fossilized near-coast species (Shipboard Scientific Party 1999c) indicate that a bottom current is the primary source of sediments in the Cape Basin. Furthermore, this is evidence that the CDW enters the Cape Basin near the African coast and subsequently follows a southwestward trajectory along the Agulhas Ridge.

9 CONCLUSIONS

Drift deposition as a result of bottom current activity in the Cape Basin has probably been present at least since the end of the Eocene. The character of the sedimentation however changed drastically in the early Oligocene, after the Tasmanian gateway opened for deep-water exchange between the Indian and Pacific oceans. The opening of the Tasmanian gateway resulted in the onset of an ACC and a gradual cooling of the Antarctic continent, which was further enhanced by the opening of the Drake Passage. These new gateways and the production of AABW as the Antarctic glaciation commenced, led to a change in the current regime for the Southern Atlantic. Older than early Oligocene, a series of strong seismic reflectors, often parallel to subparallel, are present on all profiles in the Cape Basin in the form of a slope plastered sheet. This indicates rapid transitions in the velocity and/or chemistry of the accumulated sediments and possibly the path followed by the bottom current. With the introduction of a steady influx of water masses associated with a proto-AABW in the Cape Basin in a similar way to the present situation, large-scale erosion took place. After settling down, the build-up of a large elongate mounded drift started parallel to the Agulhas Ridge.

As a result of its pronounced elevation over the adjacent seafloor, the Agulhas Ridge prohibits the direct northward flow of circumpolar waters (CPWs), forcing a path between the northeastern end of the Agulhas Ridge and the African coast. Once in the Cape Basin, the bottom water flows parallel to the bathymetric contours of the Agulhas Ridge. The asymmetry of a buried contourite mound is probably the result of Coriolis force deflection and is an indicator for a current following a southwestward path, similar to present-day CDW.

An elongate contourite drift of several hundred metres thickness accumulated while a steady sedimentation rate was maintained, until inflow temporarily halted in the middle Miocene. After a period of non-deposition, build-up of the drift continued. An increase in strong reflectors and an increase in layers truncated by Pleistocene layers reveal increased current velocity for younger sediments and probably a connection with glaciation cycles.

ACKNOWLEDGMENTS

We are grateful for the support of the captain and crew of R/V Petr Kottsov for their help during the expedition. Further, we would like to thank Keith Lewis for his constructive comments on this paper. The expedition was funded by the German Bundesministerium für Bildung, Forschung und Technologie under contract No. 03G0532A.

This research used data provided by the ODP. The ODP is sponsored by the US National Science Foundation (NSF) and participating countries under management of Joint Oceanographic Institutions (JOI), Inc. Funding for this research was provided by the Deutsche Forschungsgemeinschaft. This is Alfred Wegener Institute contribution AWI-N14969.

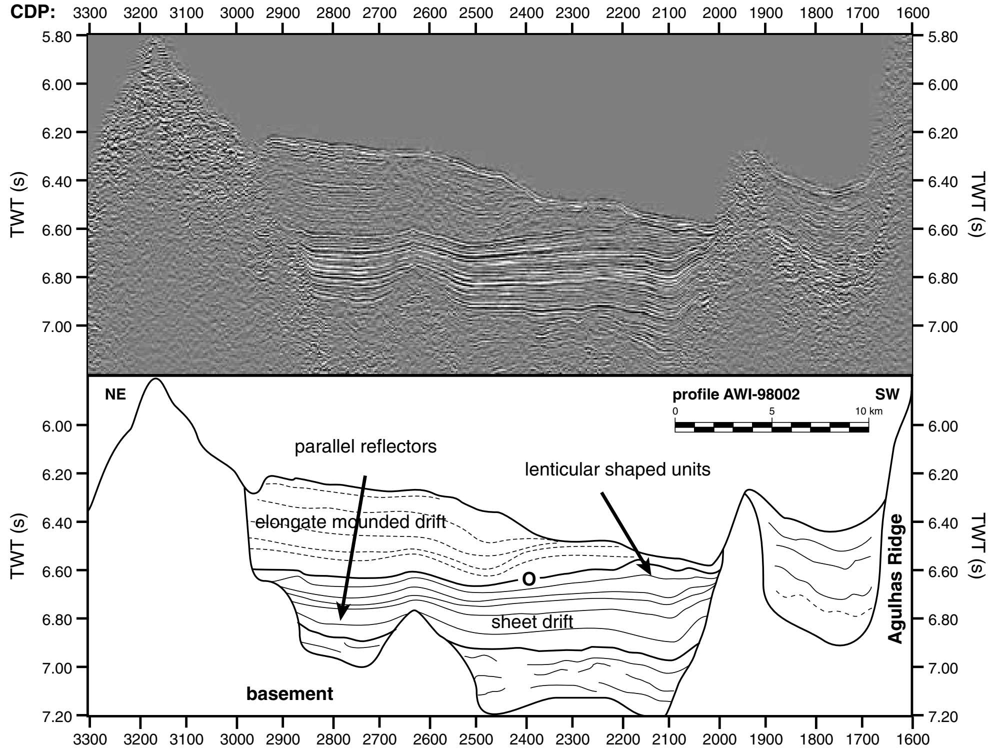

Figure 5. Profile AWI-98002, just north of the Agulhas Ridge. Seismic reflector O marks the boundary between parallel to lenticular shaped, strongly reflective pre-early Oligocene units and weakly reflective younger sediments.

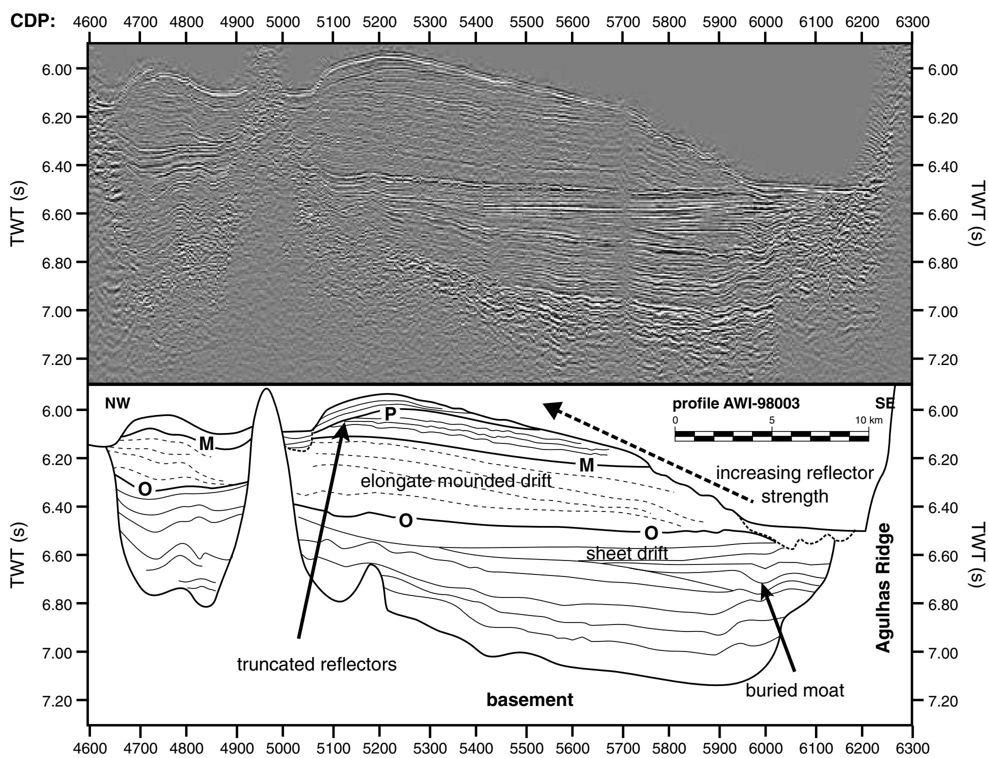

Figure 6. Profile AWI-98003 shows a stratigraphic sequence from Cretaceous basement to present. Reflector O is inferred to be early Oligocene in age and marks the top of a series of well-defined seismic reflectors. Above middle Miocene reflector M, there is a progressive increase in reflectivity. An erosional surface (P) at the base of the Pleistocene truncates Miocene units near CDP 5100.

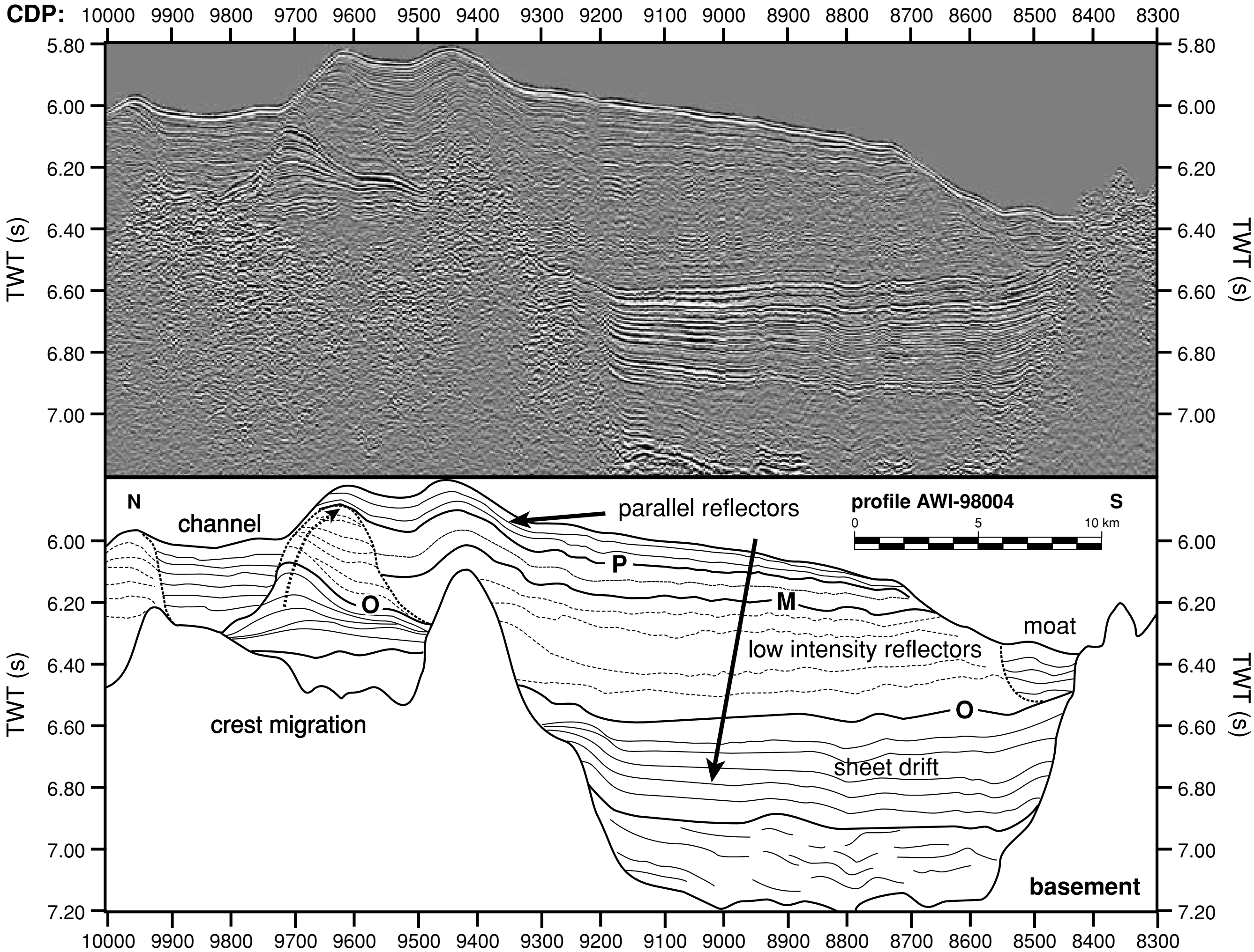

Figure 7. Seismic profile AWI-98004. A channel between CDP 9700 and 9900 has created a prograding sediment body, which shows southward migration over time. An abrupt change in the strength of seismic reflections is observed at reflector O (early Oligocene).

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