PALAEOCEANOGRAPHIC INTERPRETATION OF A SEISMIC PROFILE FROM THE SOUTHERN MOZAMBIQUE RIDGE, SOUTHWESTERN INDIAN OCEAN

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ABSTRACT
Seismic reflection data from the southern Mozambique Ridge, Southwestern Indian Ocean, show indications for a modification in the oceanic circulation system during the Neogene. Major reorganisations in the Indian Ocean circulation system accompanying the closure of the Indonesian Gateway led to the onset of current controlled sedimentation in the vicinity of the Mozambique Ridge at ~14 Ma. The modifications in water mass properties and path are documented in changes in reflection characteristics in the Mozambique Ridge area. Correlating these with identified changes of the Nd isotope evolution in deep water masses the general present day large scale circulation in the southern Indian Ocean is suggested to have prevailed for the last 9 Ma. References should not be included in abstracts.

Introduction

The exchange of water masses between the Indian and South Atlantic Oceans has a crucial influence on the global thermohaline circulation and thus also the general climate (Wunsch, 2002). In this context the seafloor topography of this gateway and its magmatic-tectonic development play an important role. Seafloor elevations such as the Agulhas Plateau and the Mozambique Ridge constitute barriers for both deep and bottom water masses. Current systems and environmental conditions as well as their modifications are archived in sedimentary structures and packages offshore South Africa. The evolution of the ocean circulation system on million year time scales still remains unclear with only pieces of the puzzle slowly being resolved. Uenzelmann-Neben and Huhn (2009) have identified a record of current activity similar to today's circulation pattern on the southern South African continental margin extending into the Neogene. For the Transkei Basin, Southeastern South African continental margin, a reorganisation at 15 Ma and again at 3 Ma was observed (Schlüter and Uenzelmann-Neben, 2008b). Here, we present seismic data from the southern Mozambique Ridge to gather more local information on modifications of the circulation system. In the absence of a direct tie to well or drill core information, analyses of ferro-manganese nodules and crusts from Heuer (2009) are used to provide a record of oceanic circulation and weathering inputs using radiogenic isotopes of Nd, Pb, and Hf over the past 20 Ma.

Geological and Oceanographic Background

The gateway south of South Africa evolved during the break-up of Gondwana between 170 Ma and 160 Ma with the formation of a shallow basin between the Mozambique Basin and the Rijser-Larsen Sea (Lawver et al., 1992; Storey et al., 2001; Jokat et al., 2003), and the creation of oceanic crust in the Natal Valley started at ~130 Ma (Goodlad et al., 1982). A deep water passage between the Indian and South Atlantic Oceans was created after the separation of the Falkland Plateau from Africa at 110 to 100 Ma (König and Jokat, 2006).

The origin of the Mozambique Ridge is still under heavy debate. A partitioning of the ridge into a northern oceanic and a southern continental part is favoured by Ben Avraham et al. (1995). A continental provenance is suggested by Tucholke et al. (1981), Raillard and Mougenot (1990), Mougenot et al. (1991), and Hartnady et al. (1992). New seismic refraction data is interpreted as strong evidence for a LIP origin of the southern Mozambique Ridge (Gohl et al., 2011) and is supported by a recent magnetic survey (König and Jokat, 2010).

doi:10.2113/gssajg.114.3-4.449

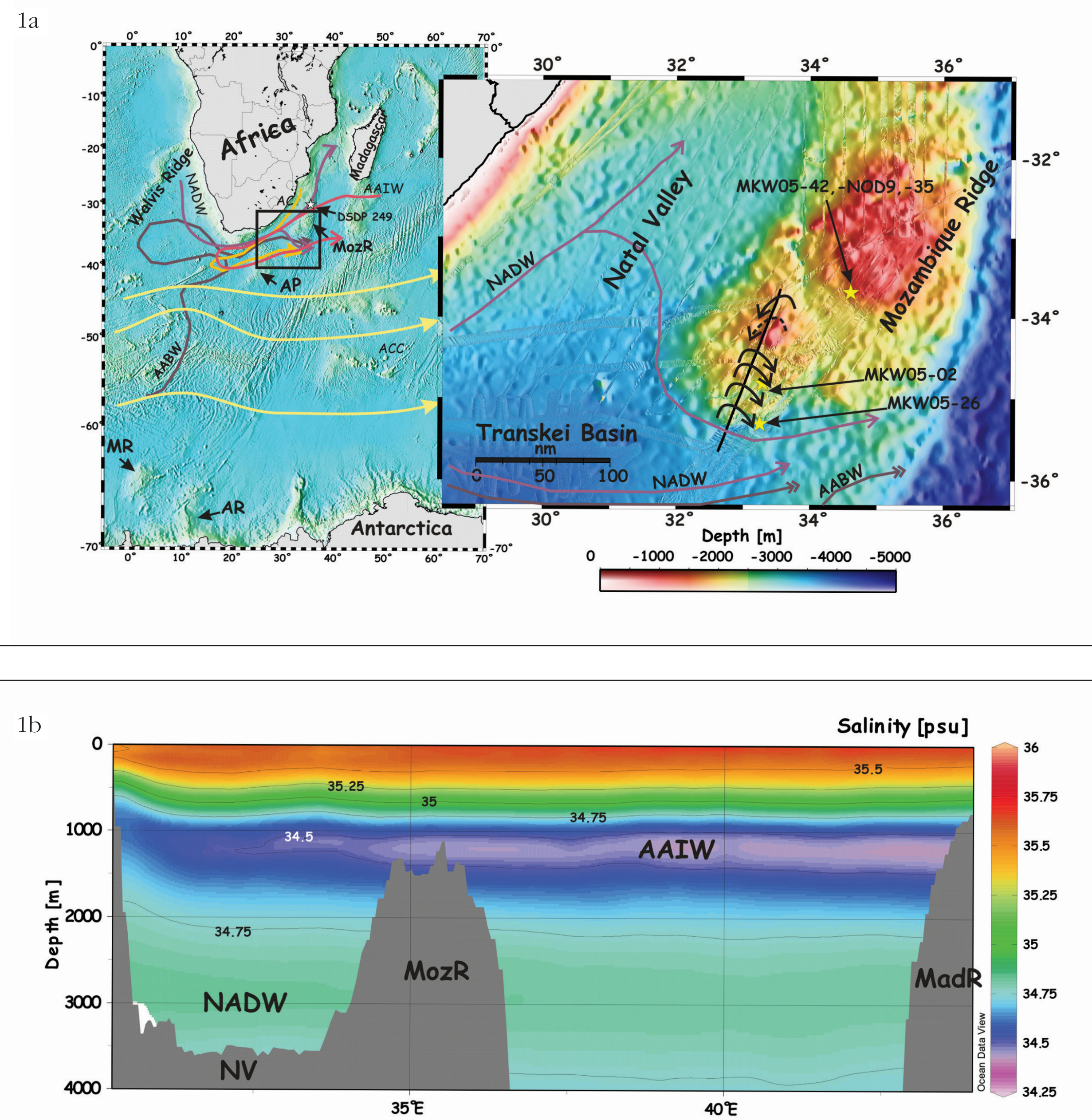

Figure 1. *(**a**) Bathymetric map from the southwest Indian Ocean (Smith and Sandwell, 1997; Uenzelmann-Neben, 2005; Jokat, 2006). The locations of the seismic profile (black line) and dredges (yellow stars) are shown in the blown-up part. The index map shows the general paths of the water masses active in the South African gateway. AABW= Antarctic Bottom Water, AAIW= Antarctic Intermediate Water, AC= Agulhas Current, ACC= Antarctic Circumpolar Current, AP= Agulhas Plateau, AR= Astrid Ridge, MR= Maud Rise, MozR= Mozambique Ridge, NADW= North Atlantic Deep Water. (**b**) Salinity profile across the southern Indian Ocean at 33º S (Schlitzer, 2010). AAIW= Antarctic Intermediate Water, NADW= North Atlantic Deep Water, MadR= Madagascar Ridge, MozR= Mozambique Ridge, NV= Natal Valley.*

As a LIP the Mozambique Ridge will have presented an obstacle for water mass exchange until it was positioned deep enough due to thermal subsidence. A restricted circulation within the evolving gateway south of South Africa even during the Late Cretaceous has been identified by Schlüter and Uenzelmann-Neben (2008a). They observed ‘bright spots’ in seismic reflection data from the Transkei Basin southwest of the Mozambique Ridge and interpret those as indications for black shales, which have been deposited between 85 Ma and 80 Ma.

First indications for an open circulation around southern Africa are found in hiati due to sea level high stand or erosion (Tucholke and Carpenter, 1977; Tucholke and Embley, 1984) as well as via sediment drifts (Uenzelmann-Neben, 2001; Uenzelmann-Neben,

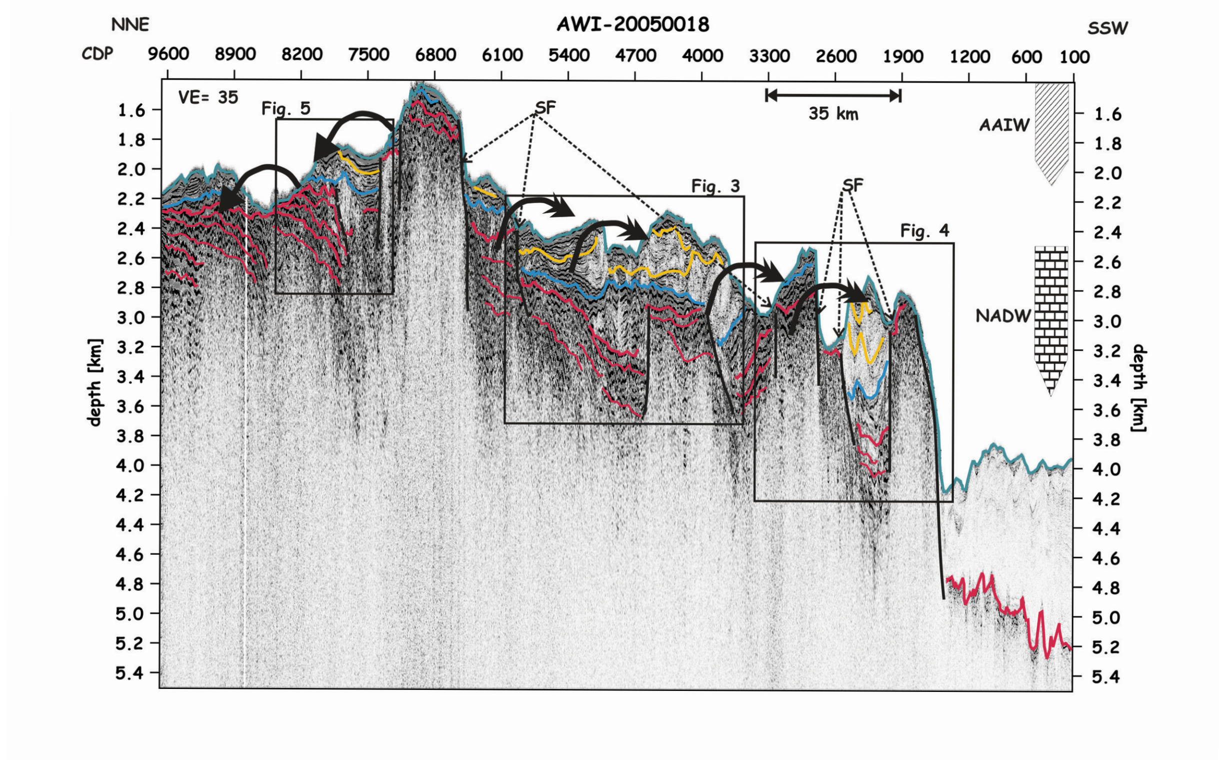

Figure 2. *Profile AWI-20050018 across the southern Mozambique Ridge. For location see Figure 1. The red lines mark the uppermost basement reflections, the blue lines mark the top of unit S1, and the yellow lines mark unit S1. The black arrows show the suspected overflow of AAIW (single arrow head) and NADW (double arrow head). The shaded bars on the right show the activity levels of present day AAIW and NADW (Lutjeharms, 2006). SF= secondary faults.*

2002). These indications pointed towards the activity of a proto-Antarctic Bottomwater (AABW) already in Oligocene times (Uenzelmann-Neben et al., 2007). Distinct modifications of the oceanic circulation could be identified for 15 Ma (strengthening of proto-AABW) and the Miocene/Pliocene boundary (deflection of AABW to the south by increased flow of North Atlantic Deep Water NADW) (Schlüter and Uenzelmann-Neben, 2008b).

Today, the South African gateway is characterised by a number of water masses (Figure 1). Part of AABW produced in the Weddell Sea flows eastwards: (a) through the Agulhas Passage, and (b) across the southern margin of the Agulhas Plateau into the Transkei Basin (Tucholke and Embley, 1984). This water mass then moves on into the Mozambique Basin (Read and Pollard, 1999).

NADW flows through the Agulhas Passage into the Transkei Basin and onwards into (a) the Natal Valley, and (b) the Indian Ocean (Van Aken et al., 2004) (Figure 1). Recent observations have shown NADW to overflow the Mozambique Ridge in water depths >2500 m (Lutjeharms, 2006).

Antarctic Intermediate Water (AAIW) originates from surface water around Antarctica. From there it flows northward into the Indian Ocean where it extends to water depths of up to 1500 m (Lutjeharms, 2006) (Figure 1). After recirculation through the Indian Ocean, AAIW flows westwards along the Agulhas Bank (You et al., 2003) and turns eastwards again in a retroflection at the south-western tip of South Africa to flow across the Agulhas Plateau into the Indian Ocean (Lutjeharms, 1996).

The Agulhas Current is the western boundary current of the Indian Ocean It extends to water depths greater than 2000 m and has a mean transport of 108 m^3/s (Lutjeharms, 1996; De Ruijter et al., 1999). Southwest of Africa the Agulhas Current turns abruptly eastward in a tight retroflection loop and becomes known as the Agulhas Return Current. This current flows eastwards to the Agulhas Plateau where it forms a major northward loop around the plateau (Lutjeharms, 1996; De Ruijter et al., 1999).

Data Acquisition and Analysis

This study is based on seismic reflection data gathered at the southern Mozambique Ridge (Figure 1a) (Uenzelmann-Neben, 2005). The seismic reflection data were collected using a three GI-gun cluster as source and a 2.4 km long digital streamer system with 180 channels to record the data. A sample rate of 1 ms guaranteed a theoretical vertical resolution of 4 m.

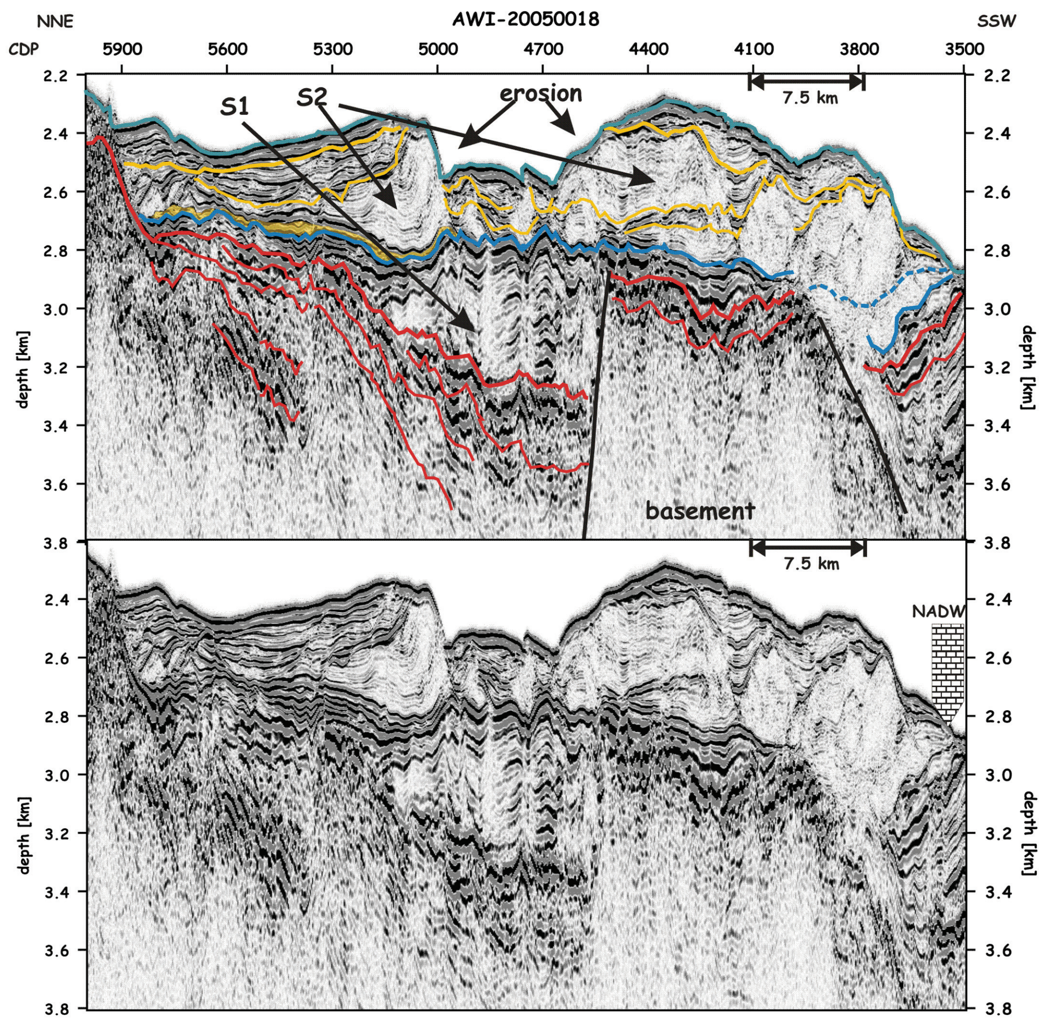

Figure 3. *Central part of profile AWI-20050018. The shaded bar on the right shows the depth range of present day NADW (Lutjeharms, 2006).*

Processing of the data comprised geometry definition using the ship's navigation, and Common Depth Point (CDP) sorting with a CDP spacing of 25 m. A precise velocity analysis (every 50 CDPs) was carried out and used for spherical divergence and normal moveout corrections. After stacking, migration was carried out both in the time and depth domain (Omega-X migration, (Yilmaz, 2001). The stacking velocities, which were converted into interval velocities using Dix's formula, were used to set up the velocity field used for the migration process and the imbedded conversion from time to depth. Filtering or gain modules were applied to the data only for on-screen analysis. The seismic velocities have not been interpreted in terms of lithology but only been used for processing. Interpretation of the seismic data is based on reflection characteristics and their changes. Unfortunately, the seismic data set comprises only one line, hence the interpretation concerning 3-D structures has to be regarded with caution.

Ferro-manganese crusts and one nodule from the three dredge sites (Figure 1a) have been analysed with respect to variations in radiogenic isotope composition (Nd, Hf, Pb) (Jokat, 2006; Heuer, 2009). Ages and growth rates were derived from $^{10}Be/^{9}Be$ chronology, and the results are used as information on modifications in oceanic circulation. For particulars of sample preparation and the analytical methods as well as the detailed interpretation of the radiogenic isotopic data we refer to Heuer (2009).

Observations

Three seismic units can be distinguished based on reflection characteristics. The lower most unit shows low frequency reflections and the penetration of this unit is low. The top of the unit is characterised by short, inclined reflections. They can be followed for 20 to 35 km and form subparallel stratified wedges, which overlap in places (Figure 2, CDPs 7800 to 9600, red reflections). The unit's top in general appears hummocky, and we interpret this reflection as the top of basement. Faults with a displacement of up to 700 m cut through both basement and the overlying sedimentary units. A step-down in basement of 2 km is observed in the south (Figure 2, CDPs 1200 to 1900) and defines the boundary from the Mozambique Ridge to the Transkei Basin.

The lower sedimentary unit shows continuous reflections of strong amplitude and lower frequency (Figure 3, e.g. CDPs 3900 to 5300). This unit S1 drapes the morphology of the basement, and its top appears to be affected by erosion. Unit S1 is 20 to 500 m thick. The younger sedimentary unit S2 is characterised by the alteration of transparent bodies with continuous reflections of moderate to weak amplitude (Figure 3, e.g. CDPs 5000 to 5600). Several discontinuities within this unit as well as erosional truncation, onlap and toplap termination are observed. Internal reflections are

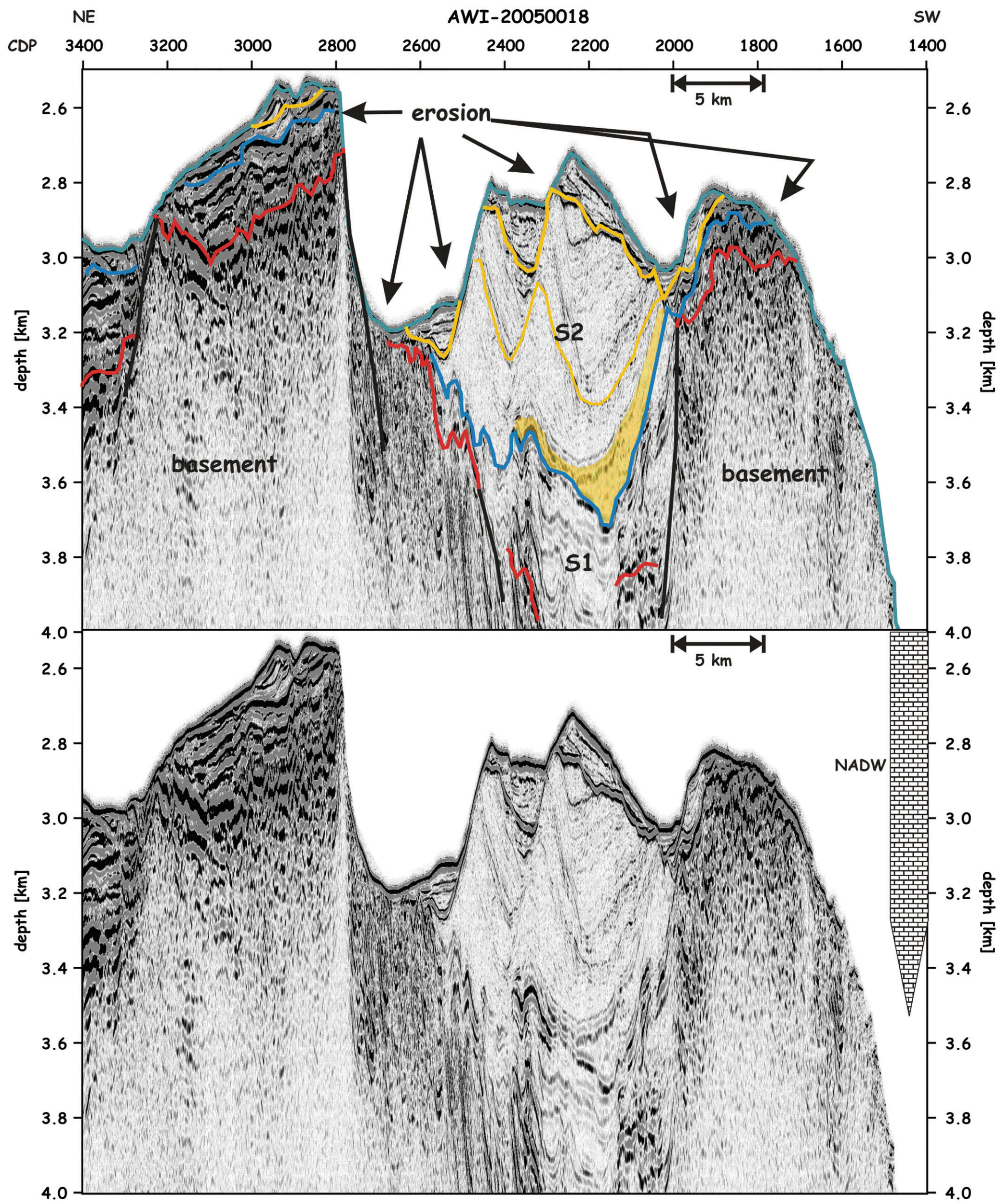

Figure 4. *Southern part of profile AWI-2005001. The shaded bar on the right shows the activity level of NADW (Lutjeharms, 2006).*

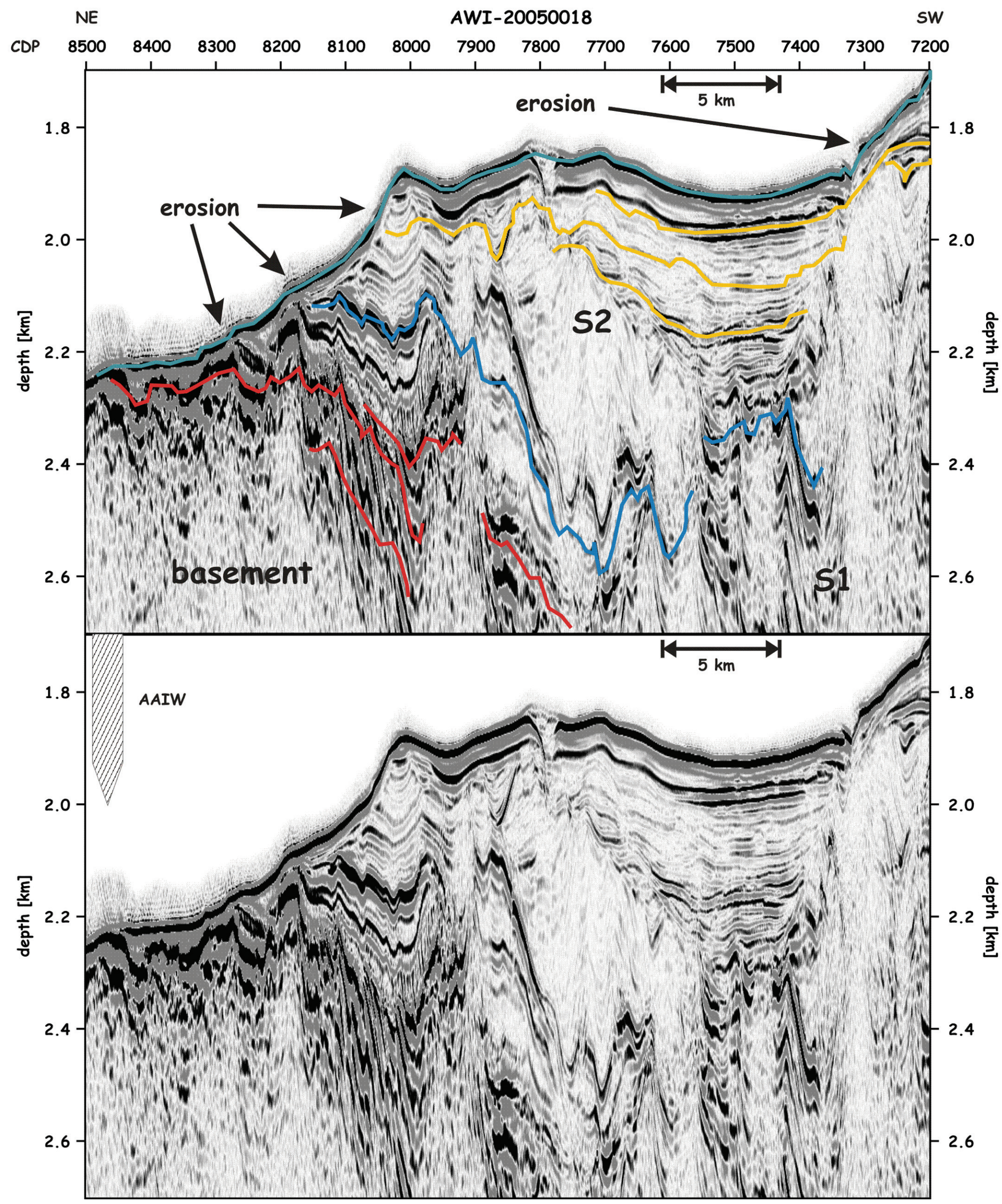

Figure 5. *Northern part of profile AWI-20050018. The shaded bar on the right shows the activity level of AAIW (Lutjeharms, 2006).*

terminated abruptly. Both erosional truncation and toplap are reflector terminations that represent sediment bypass or erosion. Erosional truncation is more extreme than toplap implying physical development of erosional relief (Emery and Myers, 1996). These characteristics correspond to those reported for the shaping of sedimentary sequences by oceanic currents (Faugères and Stow, 1993; Stow et al., 2002; Uenzelmann-Neben et al., 2007).

Mass transport deposits (mtd) show similar reflection characteristics (Laberg and Vorren, 1995; Laberg and Vorren, 2000; Ó Cofaigh et al., 2004). Still, the source of the mtds remains a problem since the southern Mozambique Ridge represents a topographic high (2800 to 1500 m water depth, Figure 1) while the surrounding basins are up to 4000 m deep. Mass transport deposits originating in the north would be hindered by the even shallower central Mozambique Ridge and thus would not reach our area of investigation. We thus exclude mtds as an interpretation of the observed reflection characteristics.

The sedimentary column covering the basement is not uniform and ranges from 20 m to 1100 m in thickness. Strong erosion of the sedimentary units is observed (Figures 2 and 3, e.g. CDPs 4400 to 5200), and in several places the whole sedimentary column is missing (Figures 2, 4, CDPs 2550 to 2650, and 5, CDPs 8300 to 8600). In addition to the one set of faults, which has been covered by unit S1 (Figures. 2, 3, e.g. CDP 4700, and 5, e.g. CDP 7800), a second set of faults affecting both basement and sedimentary units can be identified (Figure 2, e.g. CDPs 1900, 2500, 4000, 5900, 6400, 7100, and 7300). This points towards a syn-sedimentary phase of tectonism on the southern Mozambique Ridge.

Discussion

Geological nature of seismic units

Two seismic units overlie basement and are separated by a distinct unconformity (Figure 2, blue horizon). The older unit S1 fills the basement topography, which is strongly affected by faulting. Gohl et al. (2011) suggest that the Mozambique Ridge was formed at the same magmatic province as the Astrid Ridge. Faulting then occurred during the separation of the Mozambique Ridge from the Astrid Ridge shortly after 120 Ma. Seismic unit S1 would hence comprise sediments of Early Cretaceous age.

DSDP Leg 25 Site 249 was drilled on the northern Mozambique Ridge and recovered the complete sedimentary column down to basement (Shipboard Scientific Party, 1974) (Figure 1). Even though this site is located about 180 nm (~330 km) to the north of our seismic profile and thus a direct tie of the seismic data with the geological information is not possible, drilling results provide general information on the nature of discontinuities observed in the sedimentary column and the processes, which shaped the sequences in general. At Site 249 the sedimentary column with 408 m is quite thin. Three lithological units were recovered (Shipboard Scientific Party, 1974). The oldest unit III comprises silty claystone and volcanic siltstone of Early Cretaceous (Neocomian-Aptian) age. The seismic image of lithological unit III at Site 249 appears to be similar to the seismic image of our unit S1: well stratified with low frequency reflections of strong amplitude (Shipboard Scientific Party, 1974, their Figures 3 and 8). Lithological unit III also drapes the basement topography. The top of this unit is formed by a very clear reflector (Shipboard Scientific Party, 1974). Based on these reflection characteristics we correlate our seismic unit S1 with lithological unit III of Site 249. This supports the assumed age deduced from the time of formation of the Mozambique Ridge. The top reflector of unit S1 is thus interpreted to represent the 14 my hiatus (Cenomanian-Campanian) identified at Site 249 (Shipboard Scientific Party, 1974).

Lithological unit II drilled at Site 249 is of Campanian to Maastrichtian age (Late Cretaceous), it shows a variable thickness and thins out towards the basement highs (Shipboard Scientific Party, 1974). This unit also shows low frequency reflections. It is topped by a 40 my hiatus (Maastrichtian-middle Miocene) as a result of erosion (Shipboard Scientific Party, 1974). We cannot with certainty identify a seismic unit in our data definitely correlating with lithological unit II. The lower 100 m of our seismic unit S2 in places shows lower frequencies and stronger amplitude reflections (Figure 4, CDPs 2000 to 2400, shaded in yellow). We hence interpret this lower part of seismic unit S2 to represent the Late Cretaceous sedimentary rocks drilled at Site 249.

At Site 249 the 40 my hiatus is overlain by foram-rich nanno ooze of Miocene to Quaternary age (lithological unit I, (Shipboard Scientific Party, 1974). High sedimentation rates (14 m/my) indicate high plankton production. The seismic image of lithological unit I is of more transparent nature with a few internal reflections of moderate to weak amplitude (Shipboard Scientific Party, 1974). This strongly resembles the seismic characteristics of the major part of our seismic unit S2 (Figure 3, CDPs 3800 to 5300). We thus suggest seismic unit S2 to consist of pelagic sediment of Miocene to Quaternary age.

The reflection characteristics change significantly from seismic unit S1 to S2 (Figures 2, 3, 4, and 5). Instead of low frequency reflections unit S2 shows internal discontinuities and distinct changes in reflection pattern ranging from transparent to subparallel internal reflections. Truncation and down/onlap terminations at the seafloor and at the discontinuities are observed (e.g. Figure 3, CDPs 4400-5100). According to Faugères and Stow (1993) and Stow et al. (2002) these reflection characteristics are representative for sedimentary units shaped by oceanic currents. The discontinuities are interpreted to correspond to significant changes in oceanic current flow pattern, links to ice sheet formation or periods of major growth of Antarctic ice. Both physical and chemical properties of the water masses are changed by those hydrological events thus modifying the biological productivity as well (Faugères and Stow, 1993; Stow et al., 2002; Scher and Martin, 2004). This interpretation of a strong current influence having commenced with the deposition and being documented in both deposition and shaping of unit S2 demonstrates the erosive nature of the 40 my hiatus (Maastrichtian-middle Miocene) (Shipboard Scientific Party, 1974).

Paleogene and Neogene development

Leclaire (1974) suggested the South Equatorial Current (SEC) to have been responsible for strong winnowing of sediment during both the Paleogene and the Neogene. He infers that a western prolongation of the Pacific SEC through the Indonesian gateway into the Indian Ocean during the Eocene and Oligocene was deflected southward by India to east Madagascar and the southeast African coast. This current would then have had the same erosive effect as the present Indian Ocean SEC, which is a vertical circulation pattern over the Mozambique Ridge and Basin (Leclaire, 1974). The 40 my hiatus forming the top of seismic unit S1, which covers the Paleogene, is interpreted to be the result of this circulation pattern.

Middle Miocene (15/14 Ma) – onset of current controlled sedimentation

Following our correlation of seismic unit S2 with lithological unit I of Site 249 the onset of current controlled sedimentation commenced at ~15 Ma. Schlüter and Uenzelmann-Neben (2008b) suggest a major reorganisation of the circulation system in the South African gateway to have occurred at 15 Ma. They interpret an increased inflow of Proto-AABW into the Transkei Basin and the Natal Valley due to a cooling event in Antarctica (Zachos et al., 2001; Shevenell et al., 2008). This then led to a northward deflection of NADW (Schlüter and Uenzelmann-Neben, 2008b).

The northwards movement of Australia and simultaneously the southward motion of the Sunda Block commencing at 14 Ma have been reported to lead to major adjustment of the Indian Ocean circulation system (Kuhnt et al., 2004; Gourlan et al., 2008). On the basis of neodymium (Nd) isotope analyses of past seawater extracted from pelagic sediments it has been suggested that the Miocene Indian Ocean Equatorial Jet (MIOJet) was established at this time, a strong westward setting current (Gourlan et al., 2008). The MIOJet is supposed to have strengthened and modified the properties of the surface currents and deeper circulation in the southern Indian Ocean, e.g. the Agulhas Current, as well. This then led to both erosion (top reflector unit S1) and the onset of current controlled sedimentation (unit S2). The strength of the MIOJet increased from 14 Ma to 9 Ma and then remained relatively stable until 4 Ma (Gourlan et al., 2008).

The Nd isotope composition of deep water masses is controlled by continental weathering inputs in their source areas (cf. Frank, 2002). Due to an oceanic Nd residence time of between 400 and 2000 years in the open ocean, water masses preserve their isotopic signature over large distances. The dissolved Nd isotope composition in the open ocean only changes as a function of water mass mixing and can thus serve as a quasi-conservative tracer of water mass mixing. Past bottom water Nd isotope compositions are recorded in authigenic phases of marine sediments or chemical sediments, such as ferromanganese crusts (cf. Frank, 2002) and have been used for reconstructions of the past deep water circulation system in the Southern Ocean on different time scales (e.g. (Frank et al., 2002; Piotrowski et al., 2005). Comparison of Nd isotope records in the North Atlantic with those from the Southern Ocean has suggested that the overall strength of NADW export to the Southern Ocean has continuously decreased over the past 3 Ma (Frank et al., 2002).

Nd isotope analyses of ferromanganese crusts dredged at different water depths on the southern Mozambique Ridge show indistinguishable values for the period prior to about 9 Ma (Heuer, 2009). Since 9 Ma the signatures of water masses from water depths < 2500 m have been significantly more radiogenic in their Nd isotope signatures than at locations from deeper water depths. These Nd isotope compositions have been interpreted to represent the difference between AAIW or a precursor of it (more radiogenic signatures at shallow depths) and NADW (less radiogenic signatures, deeper water depths) suggesting that the general water mass structure at the Mozambique Ridge (Figure 1b, Lutjeharms, 2006) has prevailed since 9 million years ago (Heuer, 2009). The change from seismic unit S1 to S2 thus is interpreted to document the onset of the MIOJet and its increase between 14 Ma and 9 Ma, which appears to be reflected in the homogenous Nd isotope compositions through the entire water column recorded by the ferromanganese crusts at the southern Mozambique Ridge for this period of time.

Pliocene (4 Ma) – Quaternary development

At 4 Ma the MIOJet decreased as a result of the final closure of the Indonesian gateway (Gourlan et al., 2008). The predominant trade winds resulting from the MIOJet were replaced by the seasonal East Asian Monsoon system (Kuhnt et al., 2004; Gourlan et al., 2008). A trend towards more radiogenic Nd isotope values over the past 4 to 5 million years at all water depths suggests an overall decreasing influence of NADW at the southern Mozambique Ridge over this period of time or a strongly modified NADW (Heuer, 2009). We do not see direct evidence for a decrease in the MIOJet at 4 Ma in the geophysical data but at this time a large scale reorganisation of the global current system occurred. It is controversial, however, whether this ultimately led to intensification of NADW after the closure of the Isthmus of Panama (Lear et al., 2003; Schneider and Schmittner, 2006) or, as previously proposed, an overall weakening of the NADW export into the Southern Ocean since about 3 to 4 Ma (Raymo et al., 1990; Frank et al., 2002). The weakening of the MIOJet may thus only have been a consequence of a globally less intensive thermohaline circulation. The effect of the modification of this deep water mass may have been more severe in the water depth range of the Mozambique Ridge with NADW possibly being shifted southward into the Agulhas Passage and also into the Transkei Basin (Schlüter and Uenzelmann-Neben, 2008b).

The seismic data show evidence for on-going current controlled sedimentation in the form of erosion and sediment drift formation (Figures 2 to 5). This indicates that, depending on water depth, both AAIW and NADW have had a strong influence on the sedimentary deposits on the southern Mozambique Ridge during the Pliocene (see arrows in Figure 2). Schlüter and Uenzelmann-Neben (2008b) also suggested an increased activity of NADW for the Pliocene, which supports our observation and is consistent with less radiogenic Nd isotope compositions for this period of time also pointing to an increased influence of NADW. Combining the seismic and geochemical information (Heuer, 2009) we suggest a modification of both the water mass itself and of its intensity of flow during the past 4 my. More geological samples are needed to test this hypothesis.

Conclusions

Analysing new seismic reflection data from the southern Mozambique Ridge, we identified two seismic units overlying basement, which show distinct differences in reflection characteristics and are separated by a prominent unconformity. The correlation with results from DSDP Leg 25 Site 249 allowed an assignment of an Early Cretaceous age to the lower seismic unit S1 and a Miocene to Quaternary age to the upper seismic unit S2. The unconformity separating the two units is interpreted to represent a hiatus, which has been identified to have lasted 40 Ma at Site 249. We further suggest that seismic unit S2 documents the onset of current controlled sedimentation. This modification in deposition is inferred to be the result of major reorganisations in the Indian Ocean circulation system accompanying the closure of the Indonesian gateway. Water masses active in the southern Indian Ocean were modified in path and physical/chemical properties, which in addition to the change in reflection characteristics are documented in changes of the Nd isotope evolution of deep water masses in the vicinity of the southern Mozambique Ridge (Heuer, 2009). These records suggest that the large scale present patterns of water masses and ocean circulation in the southern Indian Ocean have prevailed since about 9 Ma. On-going erosion on the southern Mozambique Ridge in the activity levels of both AAIW and NADW is observed.

Acknowledgements

This work is based on data and samples gathered during FS Sonne cruises SO-182 and SO-183 under contracts 03G0182A and 03G0183A. We further acknowledge grant No SUA 07/007 from the German International Bureau. Warren Kretzinger gratefully acknowledges support of bursaries initially through the Inkaba yeAfrika project and from the South African National Antarctic Programme. We thank Prof. Dr. John Compton for his helpful comments during the review process. This is AWI publication No awi-n19375 and Inkaba yeAfrica publication number 51.

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Editorial handling: R.B. Trumbull