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High Resolution Bathymetric Survey on the NW Slope of Walvis Ridge, Offshore Namibia

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Abstract

Expedition 17/1 of the German research vessel R/V MARIA S. MERIAN, carried out geophysical surveys and experiments between November and December 2010 in the area around Walvis Ridge, Southeast Atlantic Ocean. Among the data collected, a high-resolution bathymetric dataset aquired on the northwestern slope of the ridge offers some important preliminary insights into the tectonic evolution of the ridge and the adjoining lower continental slopes and ocean basin. The NE-SW trending Walvis Ridge has a trapezoid shape and is likely built up by thick sequences of plateau basalts, with top of basement rocks inclined to the south. Sediments are almost absent on the NW side of the ridge, preserving a fascinating mountainscape formed early in the tectonic history, most probably on-land. This interpretation is supported by clear denudational features, like steep cliffs up to 150 m high, and deeply incised valleys, defining paleo-drainages. Isolated, flat-topped guyots seaward of the ocean-continent boundary attest to a later history of wave abrasion and progressive subsidence of Walvis Ridge.

Key words

Multibeam bathymetry, Walvis Ridge, Atlantic Ocean, denudation, plateau basalt

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Hochauflösende bathymetrische Vermessungen auf dem NW-Abhang des Walfischrückens seewärts von Namibia

Kurzfassung

Expedition 17/1 des deutschen Forschungsschiffs FS MARIA S. MERIAN war im November und Dezember 2010 geophysikalischen Experimenten im Gebiet des Walfischrückens im südöstlichen Atlantischen Ozean gewidmet. Zu den gesammelten Daten gehört eine hoch auflösende bathymetrische Kartierung des Meeresbodens am nordwestlichen Abhang des Rückens. Die Karte liefert einige wichtige, vorläufige Einblicke in die tektonische Entwicklung des Rückens, sowie die angrenzenden unteren Kontinentalabhänge und ozeanischen Becken. Der NE-SW verlaufende Walfischrücken hat die Form eines Trapezoids und wird wahrscheinlich von mächtigen Abfolgen von Plateaubasalten aufgebaut. Die Oberkante des basaltischen Grundgebirges ist nach Süden gekippt. Die Nordwestflanke des Rückens ist im Wesentlichen frei von überlagernden Sedimenten und zeigt eine faszinierende Gebirgslandschaft, die früh in der tektonischen Geschichte, wahrscheinlich an Land gebildet worden ist. Diese Interpretation wird durch eindeutige Denudationsstrukturen gestützt, wie zum Beispiel Steilabbrüche mit bis zu 150 m Höhe, aber auch tief eingeschnittene Täler, die Paläo-Drainagesysteme anzeigen. Isolierte Guyots seewärts des Ozean-Kontinentübergangs bezeugen eine spätere Phase der Abrasion durch Wellen im Flachwasser und eine darauf folgende weitere Subsidenz des Walfischrückens.

Stichwörter

Multibeam, Bathymetrie, Walfischrücken, Atlantischer Ozean, Denudation, Plateaubasalt

1. Introduction

Aseismic ridges (e.g. DAVIS & LISTER 1974) are among the most impressive topographic features on the bottom of the World´s oceans. They can be thousands of kilometers long, and in most cases owe their existence to excessively intense seafloor volcanism, typically above hot spots. Sometimes they form parts of so-called "large igneous provinces" related to the activity of mantle plumes (e.g. COFFIN & ELDHOLM 1994).

Both, in terms of age, and geographical and tectonic definition, the Walvis Ridge (e.g. O´CONNOR & DUNCAN 1990) is one of the best documented aseismic ridges on Earth. It has been used to prove the validity of the hot spot model, and helped to define the hot spot reference frame of global plate motion. Regionally it can be used to track the kinematics and dynamics of the opening of the South Atlantic Ocean basin. There is a compelling geographical and plate kinematic link to two large Cretaceous-aged volcanic provinces on land on both sides of the Atlantic Ocean: the Etendeka basalts in Namibia/Africa, and the Paraná Basalts in South America (e.g. PEATE 1997). This indicates that anomalous magmatism in the Cretaceous beneath the southwestern African and southeastern South American continents predated crustal break and the opening of the South Atlantic, at least to some extent. The fact that the Walvis Ridge is a permanent topographic feature protruding far into the Southeast Atlantic makes it likely that its near-shore parts have an earlier history of formation on land, and subsided thermally to the present depth below sea level. The objective of this contribution is to provide a descriptive account of a high resolution bathymetric survey carried out during Expedition 17/1 of the German research vessel R/V MARIA S. MERIAN, between November and December 2010 on the northwest side of Walvis Ridge, Southeast Atlantic Ocean. This part of the ridge is practically devoid of sediments, offering the chance to study basement rock topography and landforms, and learn about possible origins of this part of Walvis Ridge.

2. Geological setting and evolution

Western Gondwana ruptured in the Late Jurassic and Early Cretaceous when the South Atlantic Ocean opened from south to north. The South Atlantic passive margins resulting from the rifting process can be grouped into three provinces, based on crustal structure and bathymetric expression:

(1) The segment covering Walvis Ridge (Fig. 1), offshore northern Namibia and its symmetric counterpart defining the Florianopolis Basement High and Rio Grande Rise offshore southern Brazil. Here magmatism was voluminous, forming the ridges themselves, and resulting in a substantial crustal root, probably generated by magmatic underplating. Further landward, the part of the margin floored by continental crust is also dominated by magmatism, with the basalts of the Etendeka Plateau as a surface expression. In contrast to the margin segments further south and north, the offshore part of the Walvis Ridge has retained its topographic expession as a complex, probably segmented aseismic ridge, suggesting that syn-rift, and possibly post-rift magmatic addition to the crust has left a permanent isostatic signal. However, it may also be that tectonic mechanisms made a major contribution to the formation of anomalous crustal structure.

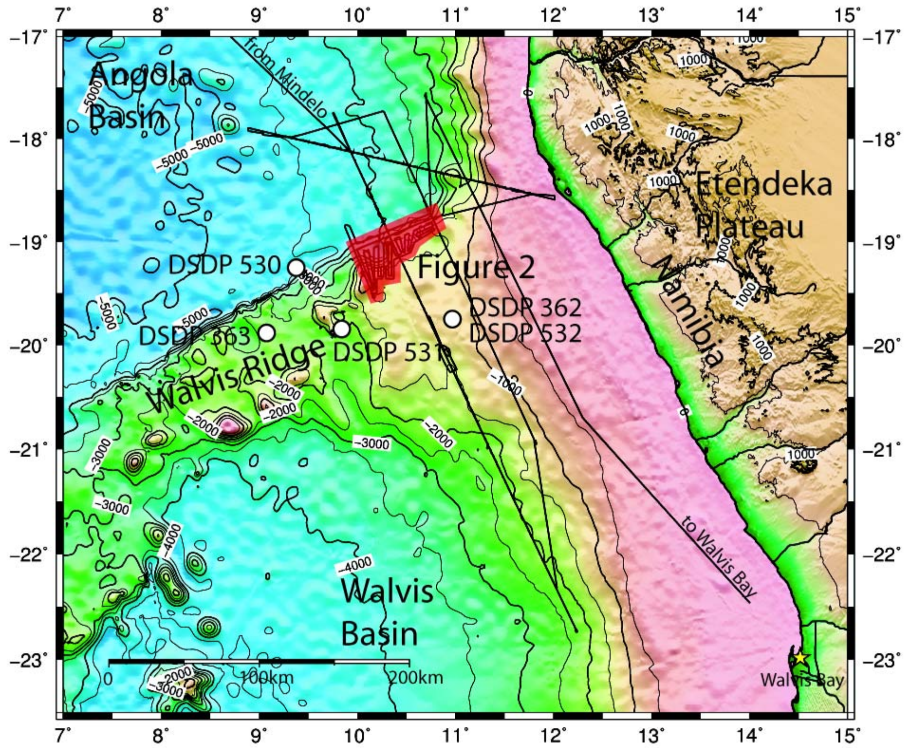

Fig. 1: Overview map of the southeast Atlantic Ocean seaward of the northern Namibian coast. Shown are the ship track of R/V MARIA S. MERIAN Expedition MSM 17/1, the area of the bathymetric survey (red box), and the locations of DSDP drillholes.

Abb. 1: *Übersichtskarte des südöstlichen Atlantischen Ozeans seewärts der Küste von Nordnamibia. Gezeigt werden die Fahrtroute von FS MARIA S. MERIAN auf der Expedition MSM 17/1, das Gebiet der bathymetrischen Vermessung (roter Kasten) und die Positionen von DSDP-Bohrungen.*

(2) South of Walvis Ridge (the Walvis Basin, Fig. 1), the structure of the passive margin has been imaged by commercial seismic data (e.g. GLADCZENKO et al. 1998, BAUER et al. 2000). In addition, there are a number of amphibious refraction seismic experiments (BAUER et al. 2000). The magmatic contributions may be derived from high-velocity lower crustal bodies at the ocean-continent transition. Such high velocity bodies are also known from other volcanic passive margins (e.g. TALWANI & ABREU 2000) and were interpreted as mafic intrusions emplaced late in the rifting process.

(3) North of Walvis Ridge the margin offshore Congo and Angola also experienced volcanism during breakup, but syn-rift and early post-rift evolution was dominated by formation of Aptian salt, shallow water carbonates and clastic sediments. A poorly understood but characteristic feature here are deep sag basins, probably floored by rifted continental crust (e.g. CONTRUCCI et al. 2004, HOPPER et al. 2007). The absence of major faults within these sediment accumulations indicates that most subsidence

occurred after extension of the continental basement had ceased. Observed margin subsidence is not consistent with simple conductive cooling. Instead, tectonic attenuation of the lower crust and subjacent lithospheric mantle must have continued after the end of brittle extension in the shallow basement directly beneath the sag basins. This process involves large strains (e.g. NAGEL & BUCK 2004), leads to mantle exhumation in basins deep below sea level (e.g. LAVIER & MANATSCHAL 2006), and is an elegant way for nature to achieve crustal break at magma-poor continental margins.

3. Method of bathymetric survey

We have used the Simrad EM120 swathmapping bathymetry system installed aboard R/V MARIA S. MERIAN. This is a multibeam echosounder with 191 beams, providing accurate bathymetric mapping up to water depths higher than 11000 m. This system is composed of two transducer arrays fixed on the hull of the ship, which send successive frequency coded acoustic signals (11.25 to 12.6 kHz). Data acquisition is based on successive emission-reception cycles of this signal. The emission beam is 150° wide across track, and 2° along track direction. The reception is obtained from 191 overlapping beams, with widths of 2° across track and 20° along it. The beam spacing can be defined as equidistant or equiangular, and the maximum seafloor coverage fixed or not. The echoes from the intersection area (2° by 2°) between transmission and reception patterns produce a signal from which depth and reflectivity are extracted.

For depth measurements, 191 isolated depth values are obtained perpendicular to the track for each signal. Using the 2-way-travel-time and the beam angle known for each beam, and taking into account the ray bending due to refraction in the water column by acoustic velocity variations, depth is estimated for each beam. A combination of phase (for the central beams) and amplitude (lateral beams) is used to provide measurement accuracy practically independent of the beam pointing angle. The raw depth data were then to be processed to obtain depth-contour maps. In the first step, the data are merged with navigation files to compute their geographic position, and the depth values are plotted on a regular grid to obtain the digital terrain models (DTM). In the last stage, the grid is interpolated, and finally smoothed to obtain a better graphic representation.

The EM120 was used continuously during the seismic experiments (BEHRMANN 2011) as well as during the transits and seafloor mapping phases. Bathymetric data were processed routinely onboard during the survey, using the NEPTUNE software from Simrad, available on board. Subsequently, the data collected during the cruise were cleaned of outlier readings, and merged with the global bathymetry datasets. Then the maps shown in the results section (see Figs. 2-10) below were generated.

4. Results

The area surveyed is shown in red in Figure 1. It covers the NW slope of Walvis Ridge in a segment approximately 60 km long along strike, and between 20 and 50 km wide. Spacing of individual tracks was chosen to achieve optimum coverage while minimizing gaps and areas of overlap. Reflection seismic profiles shot during the expedition (BEHRMANN 2011), and parasound records revealed that the area is practically devoid of a substantial cover by marine sediments.

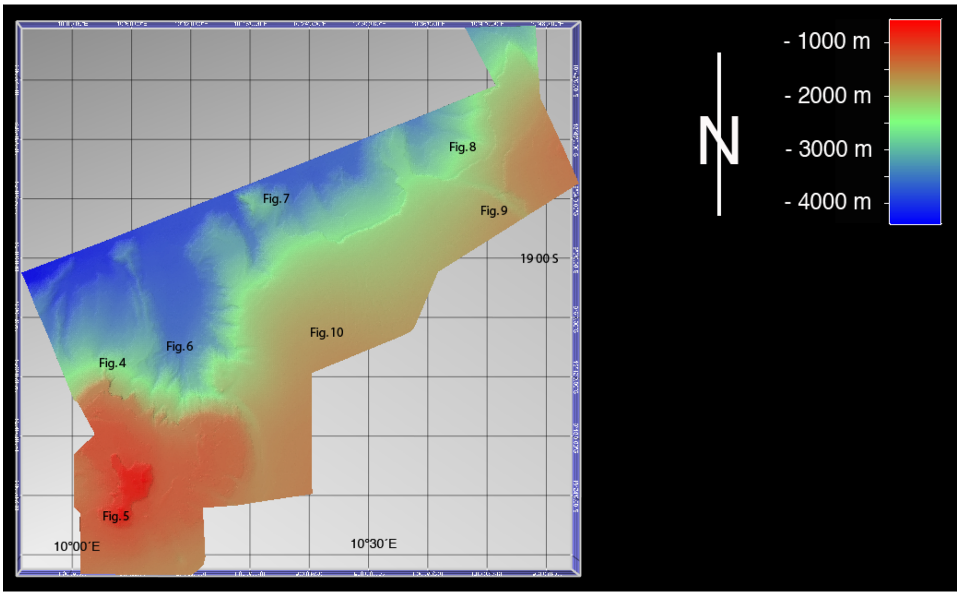

Fig. 2: Map view of the bathymetric survey area. North is on top side, illumination from NW. Depth is color-coded. Numbers indicate the figures showing the detailed features of the seafloor described in the text.

Abb. 2: *Das bathymetrisch vermessene Gebiet im Kartenbild. Norden ist im Bild oben und die Beleuchtung kommt aus NW. Die Farbkodierung zeigt die Tiefe des Meeresbodens unter dem Meeresspiegel an. Die Zahlen geben die ungefähre Lage der Detailabbildungen des Meeresbodens an, die im Text beschrieben werden.*

Figure 2 gives a bird´s eye view of the surveyed area, with depths in meters below sea level (mbsl) colour-coded. Ocean floor depths range from less than 1000 mbsl in the SW edge of the area to more than 4000 mbsl around 19°00´ S and 10°00´ E. The most prominent topographic feature in Fig. 2, even better seen in the oblique view of the area from the north (Fig. 3), is a 60 km long escarpment (termed Northern Escarpment in Fig. 3), forming the northern boundary of a high plateau. The Northern Escarpment is very steep, in places almost vertical, and up to 250 m high. Most likely it is made up of plateau basalts of the kind that are found on the Etendeka Plateau. It shows several large, amphitheatre-shaped embayments with intervening north-pointing ridges. In the northeastern corner of the area the escarpment is at about 2500 mbsl. It rises to about 2000 mbsl in the centre, and about 1600 mbsl in the far west. The plateau defining the table mountain at about 10°33´ E (Fig. 3) shows that there is a gentle northward tilt of the high plateau. The two eastern embayments of the escarpment show long straight segments, without major incision by valleys. This changes further westward where the escarpment is dissected by numerous short valleys. These seem to be tributary structures to several south-closing valleys flooring at 3300 to 4000 mbsl. The submarine landscape north of the escarpment is mountaineous, with weakly (in the east) to strongly (in the west) dissected slopes. We here adopt the term Northern Foot-

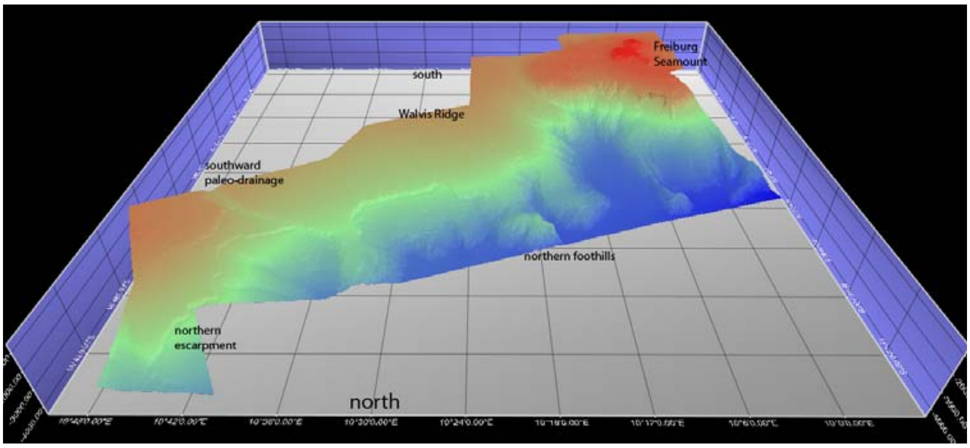

Fig. 3: Oblique view of the surveyed area from the northwest; Illumination from NW; color coding for depth of seafloor is as in Fig. 2. See text for description.
Abb. 3: *Schrägansicht des vermessenen Gebietes aus NW. Beleuchtung aus NW; die Farbkodierung ist wie in Fig. 2.*

hills for this area, although elevation differences up to 2500 m suggests that this is a relief more akin to that found in high mountain ranges on land. As described above the axial area of the Walvis Ridge (Fig. 3) is a high plain. On this plain a striking feature near the western end of the surveyed area is a plateau-shaped seamount more than 10 km long in N-S direction, with maximum elevation as high as about 650 mbsl. Unnamed so far, we adopt the name Freiburg Seamount for this structure (shown in close-up view in Fig. 5). Near the eastern end of the surveyed area there is a 10 km long SE trending valley that has a tributary structure joining it from the NE. This geometry suggests that it once formed part of a southward paleo-drainage system transecting the crestal area of Walvis Ridge (Figs. 2, 3). The southern boundary of the surveyed area is located in about 1700 m of water. The very smooth topography there is due to sedimentary overburden quickly thickening southward.

Figure 4 shows a detailed southward view towards the Northern Escarpment and the Northern Foothills. The most prominent features are two crest-shaped embayments (1) that represent clear denudational features. The western one is about four kilometres across. The escarpment here is about 250 m high, and the average slope angle is about 70°. The eastern one (1) is much smaller, but has similarily steep slopes. Questions arise regarding the origin of such embayments. Catastrophic landsliding is an unlikely possibility, as no coarse debris and large slide blocks are seen on the downward slopes, which are inclined about 10° northward. Therefore, subaereal denudation seems the more likely possibility, with deposition of finer-grained detritus on the slopes, or downstream sediment transport in valleys (2), as can be seen in the case of the smaller of the two embayments. There are numerous valleys up to about 10 km long, like the two examples (2), decorating most of the slope northward of the escarpment. Some have tributaries in the upstream section, making a fluvial origin likely.

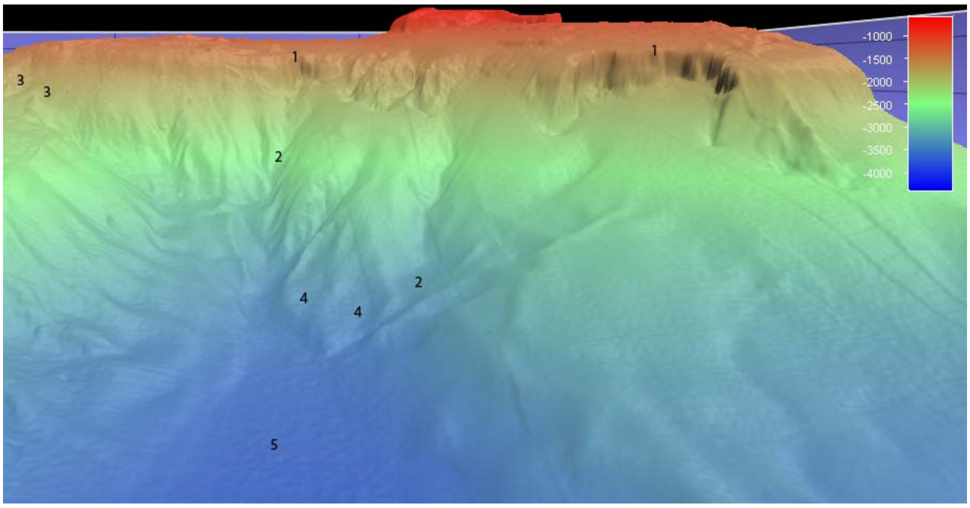

Fig. 4: Close-up oblique view from the North of the Northern Escarpment at the western end of the surveyed area. Field of view approximately 35 km wide. Illumination from NW, three times vertical exaggeration. Shown are (1) amphitheatre-shaped erosive scars of plateau basalt sequences, (2) fluvial systems defining northward paleo-drainages, (3) probable cinder cones of volcanic origin, (4) areas of suspected slope failure, and (5) paleo-flood plain at approximately 3500 m water depth. See text.

Abb. 4: *Schrägansicht des Northern Escarpment am Westende des Untersuchungsgebietes von Norden. Das Blickfeld ist etwa 35 km breit. Beleuchtung von NW, dreifache Überhöhung. Sichtbar sind (1) erosive Steilabhänge von Plateaubasalten in der Form von Amphitheatern, (2) Flusssysteme, die nordwärts gerichtete Paläo-Entwässerung anzeigen, (3) Schlackenkegel wahrscheinlich vulkanischen Ursprungs, (4) Gebiete mit möglichen Hangrutschungen und (5) eine Paläo-Überflutungsebene in etwa 3500 m Wassertiefe. Siehe Text für weitere Beschreibung.*

At the locations marked with (3) in Fig. 4 there are two axially symmetric cones about 100 m high. We interpret these as volcanic structures, possibly cinder cones, which must have formed after the plateau had formed and after southward retreat driven by denudation. The rocks underneath the plateau basalts forming the escarpment are much more erodible along valleys, and in places show evidence for slope failure (marked by 4 in Fig. 4, and shown in detail in Fig. 6). The area of suspected slope failure is tongue-shaped, with a weakly defined headwall scarp at 2900 mbsl (see profile on the right of Figure 6) above a 7-10° slope about 4 km long, soling out in a floodplain (5 in Fig. 4) at 3500 mbsl. The structure is about 50-100 m high in cross section (see profile in the upper part of Figure 6). The toe of the structure appears to be erosively undercut by two paleo-rivers coming from the higher ground to the north (marked 2 in Fig. 4).

The structure of the tabular Freiburg Seamount is interesting, as it offers some insights in the magmatic history of Walvis Ridge, and the later subsidence. On the northern and eastern sides the close-up view of the seamount from the northeast (Fig. 5) shows cliffs built up by a stacked sequence of what are most probably plateau basalt flows. The shape of the mountain gives clear evidence for denudation processes that occurred on-land. In the northern and in the central summit areas, flows are obliquely cut by two planar features. We interpret these planes as wave abrasion platforms, which were formed when the mountain had subsided to just below sea level.

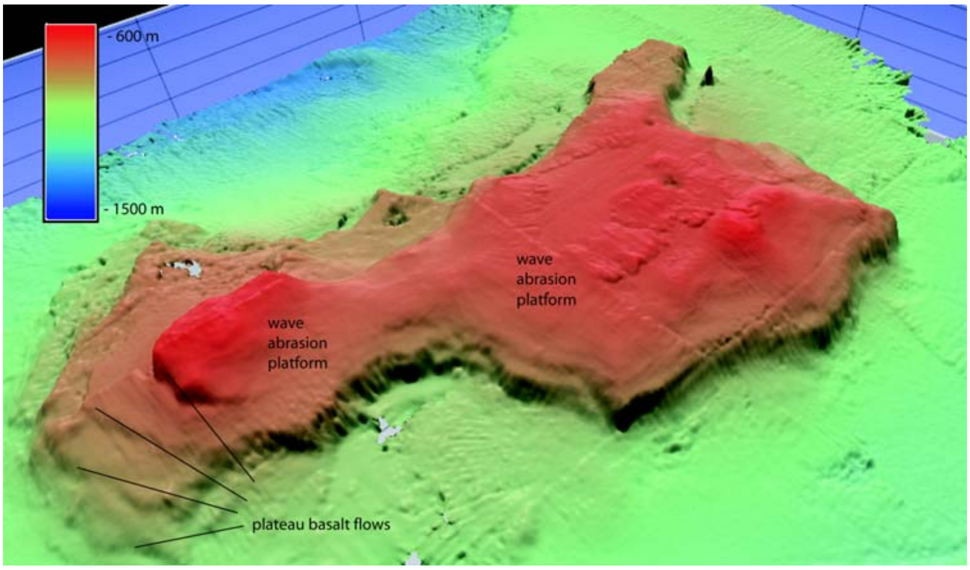

Fig. 5: Oblique view of Freiburg Seamount from SE. Field of view approximately 12 km wide. Illumination from NW, three times vertical exaggeration. See text.
Abb. 5: *Schrägansicht des Freiburg Seamount von SE. Das Blickfeld ist etwa 12 km breit. Beleuchtung von NW, dreifache Überhöhung. Siehe Text für weitere Beschreibung.*

As noted above, the mountains in the area of the Northern Foothills lack the appearance of tabular mountains, as seen further upslope. This indicates that they are composed of more homogeneously erodible basement rocks of the Walvis Ridge, and are not series of stacked lava flows. The mountain shown in Fig. 7 has some characteristic landforms for the foothills zone. Elevations above the surrounding lowlands are up to 800 m. Slope angles are up to 50°, and the shapes of the northern, western and eastern slopes are typically concave. On the steep western slope, the mountain in Fig. 7 shows some erosive gullies (eg), and some evidence for alluvial fan (af) deposition on the lower slope. The base of the mountain is near to 4000 mbsl. Without further evidence is not possible to decide over the on-land or submarine origin of the erosive features, and therefore a fluvial base level at this depth (almost 4000 mbsl) remains uncertain.

Morphological details in the eastern large embayment of the North Escarpment can be seen in Fig. 8, and three cross sections (A-B, C-D, E-F) are shown in Fig. 9. As mentioned above the escarpment itself is not strongly dissected, and is about 100-150 m high, with slope angles of about 45° (Fig. 9, section A-B). The seafloor immediately beneath is smooth, and is inclined 10° or less. In the eastern edge of the embayment there is a fossil stream system with tributaries that extends WNW for about 10 km from near the escarpment to the plain at 3400 mbsl. In cross section (Fig. 9, section C-D) it can be seen that the valleys are about 200-400 m wide and about 50 m deep. Beside what could be paleo-streams there are small terraces that may have been created by fluvial processes. South of the escarpment another fossil bifurcated fluvial catchment can be seen that once was part of a southward drainage system. The main valley is an open structure almost a kilometre wide (Fig. 9, section E-F). SE of the stream junction the valley seems to continue in a small canyon with a meandering shape.

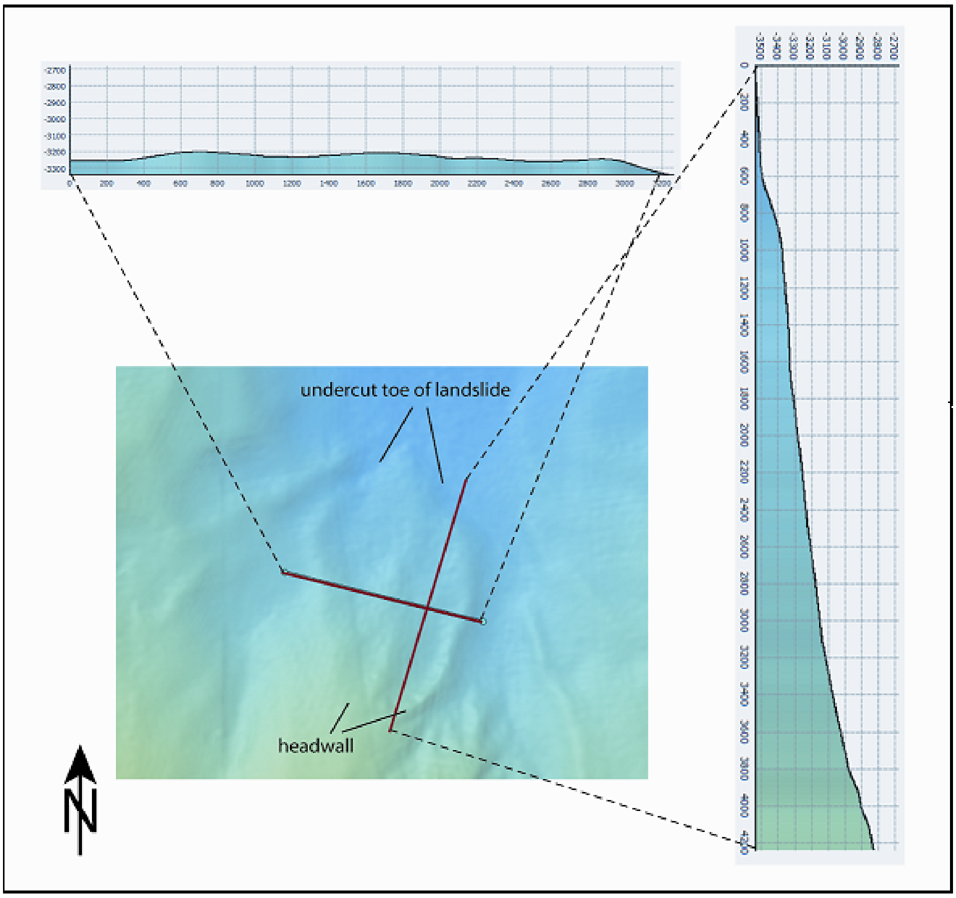

Fig. 6: Map view and two cross sections of an area with suspected slope failure. For location see Fig. 2.
Abb. 6: *Kartenansicht mit zwei Profilen eines Gebiets mit vermuteter Hangrutschung. Zur Lage siehe Fig. 2.*

Further southwest, and approaching the crestal area of Walvis Ridge, there is smooth topography. Here the ridge is overlain by fine-grained marine deposits, with thickness of the sediment column rapidly increasing southward. The seafloor, however, is not completely structureless. The close-up view from the north (Fig. 10) shows a network of kilometre-long irregular furrows that are trending north-south. A cross section (inset in Fig. 10) with ten times vertical exaggeration shows dune-like structures 0.5 –1 km wide and approximately 20-30 m high. It is difficult to interpret them with respect to their exact origin. However, they seem to occur in an area that is a structural low, and therefore a current conduit for water mass exchange across Walvis Ridge to and from the Angola Basin. At the depth of seafloor measured this may mainly concern Antarctic Intermediate Water (AAIW, see Talley 1996) gently flowing northward across Walvis Ridge. It is this current, which may have aided to prevent deposition of fine-grained biogenic sediment on the north side of Walvis Ridge from the Upper Cretaceous onward.

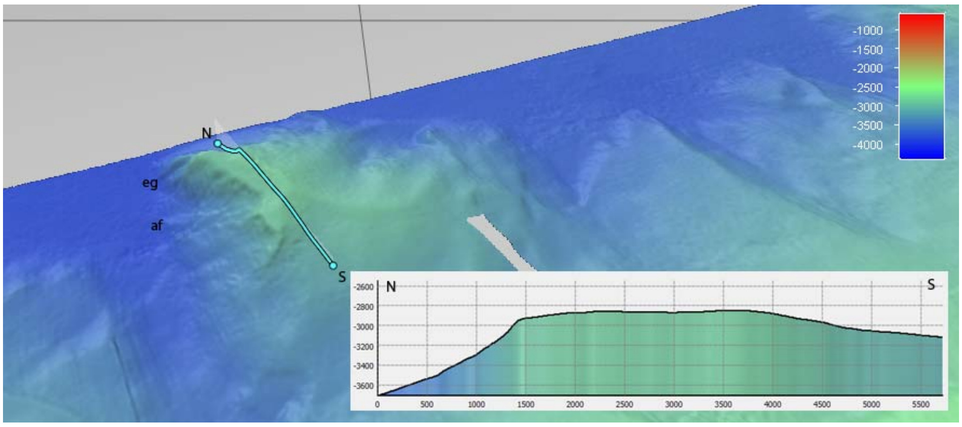

Fig. 7: Oblique view from SSW on part of the foothills north of the central segment of the North Escarpment. NNW-SSE cross section shows structure without vertical exaggeration; eg = erosional gullies, af = alluvial fan.

Abb. 7: *Schrägansicht von SSW auf die Vorbergzone im Zentralbereich des North Escarpment. Das NNW-SSW orientierte Profil zeigt die Struktur ohne Überhöhung; eg = Erosionstälchen, af = Alluvialfächer.*

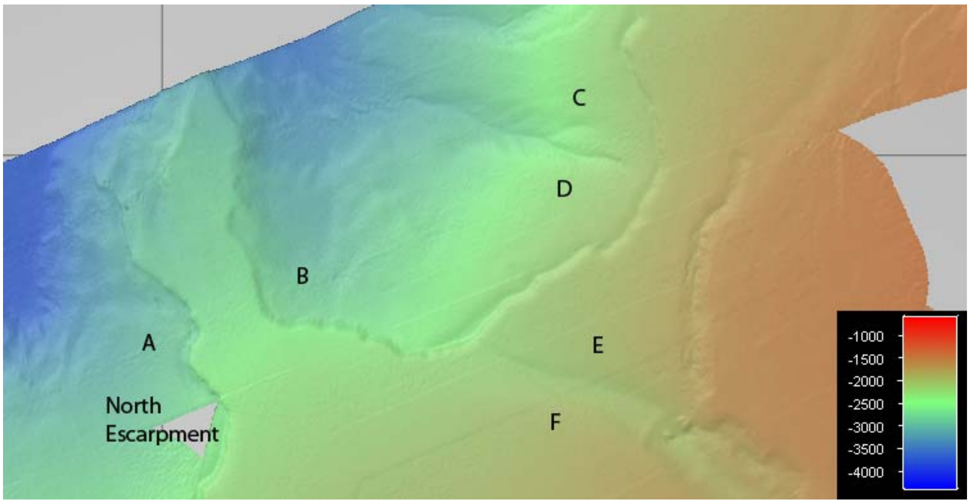

Fig. 8: Map view of the eastern part of the North Escarpment area. Letters A-F mark the end points of the three cross sections shown in Fig. 9.

Abb. 8: *Kartenansicht der Umgebung des östlichen Teils des North Escarpment. Die Buchstaben A-F sind die Endpunkte der drei Profile in Fig. 9.*

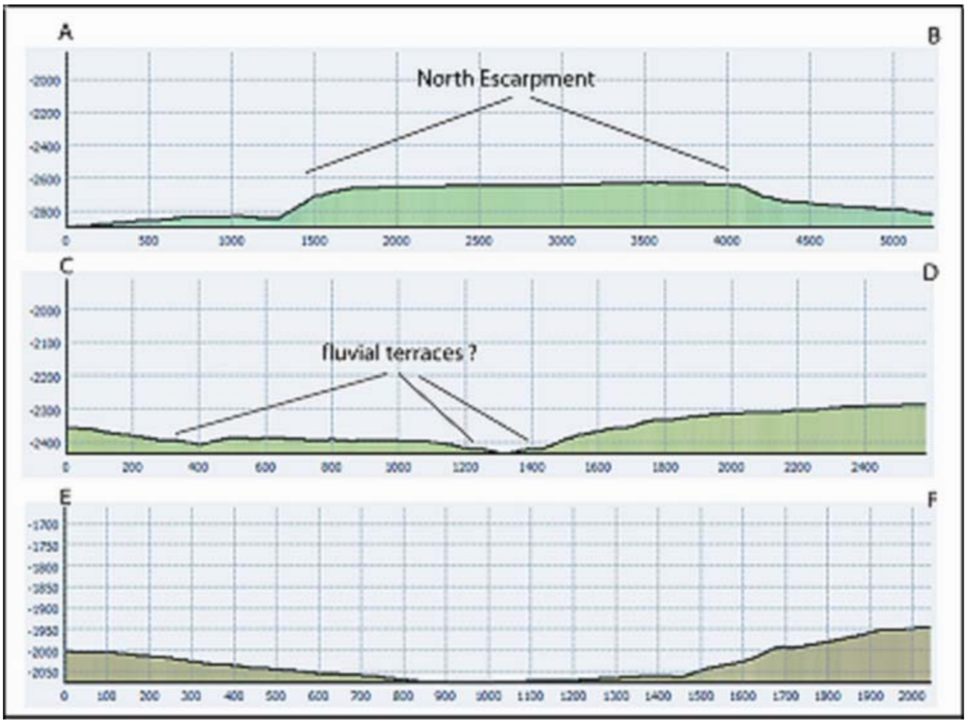

Fig. 9: Sections across the North Escarpment (A-B) and two paleo-drainage systems (C-D, E-F). See text.

Abb. 9: *Profile über das North Escarpment (A-B) und zwei Paläo-Entwässerungssysteme (C-D, E-F). Siehe Text für weitere Beschreibung.*

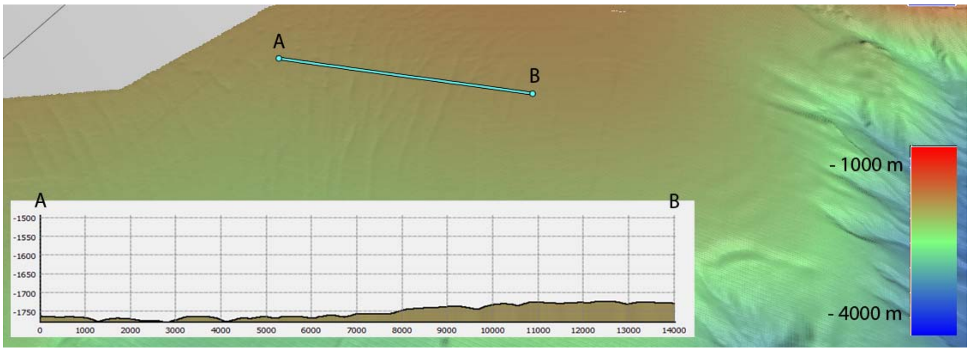

Fig. 10: Close-up view of the crestal area of Walvis Ridge at the southern border of the surveyed area. Cross section A-B has ten times vertical exaggeration to show the dune-like sediment structures discussed in the text.

Abb. 10: *Nahaufnahme der Schulter des Walfischrückens am Südrand des Untersuchungsgebietes. Profil A-B ist zehnfach überhöht, um die dünenartigen Strukturen hervorzuheben, die im Text beschrieben sind.*

5. Interpretative remarks and conclusion

Maybe the most interesting question concerns the age of the discovered submarine mountainscape. Although not located in the immediate vicinity, a number of drillsites (locations shown in Fig. 1) were cored during Legs 40 (Bolli, Ryan et al. 1978) and 75 (Hay, Sibuet et al., 1984) of the Deep Sea Drilling Program (DSDP). The stratigraphic records give some important insights into the onset of marine sedimentation in the southern Angola Basin and on Walvis Ridge. Site 530 on the SE corner of the Angola Basin intersected 1100 m of sediments above oceanic basalt. The oldest marine sediment is Late Albian in age (> 99 million years), attesting to the fact that oceanic basin evolution immediately north of Walvis Ridge had commenced at this time. Site 363, drilled on top of an isolated basement high on the north side of Walvis Ridge about 80 km seaward of the surveyed area in 2248 m of water, yielded cores of Upper Aptian limestone at 715 m depth, about 35 m above seismically inferred basement. This means that Site 363 has recorded at least 3000 m of post-Aptian subsidence. Site 362, located on the crest of Walvis Ridge, terminated in Eocene limestones at 1081 m below sea floor, without penetrating basement rocks. The maximum stratigraphic ages of the marine sediments, especially at Site 363, constrain the subsidence of Walvis Ridge below sea level at this site to somewhat older than 112 million years. If we suppose that the plateau basalts mapped in this study were formed synchronously to the Paraná-Etendeka flood basalts at about 129-134 Ma (see Peate 1997), then a time bracket of 17 million years must have been sufficient to create about three kilometres of relief on land, plus approximately three kilometres of subsidence after landscape creation. These estimates from the DSDP drillhole data correspond well with the present depth of base levels for the fluvial systems mapped (Figs. 2 and 3 for overview), which are around 3000-3500 mbsl.

While not offering a full tectonic interpretation here, we conclude by stating that the record of geomorphologic processes revealed by high-resolution bathymetric imaging may contribute important information regarding the formation of Walvis Ridge and its tectonic history. This information must be later combined with the anticipated results of the refraction and reflection seismic studies under way.

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