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# A geological investigation of the Walvis Ridge Area, based on the interpretation of hydroacoustic data

An article by *Andreas Prokoph**

Aseismic ridges are among the most impressive topographic features on the bottom of the world's oceans. They can be thousands of kilometres 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. Both, in terms of age, and geographical and tectonic definition, the Walvis Ridge is one of the best documented aseismic ridges on Earth. 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. 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.

multi-beam echo-sounder | sub-bottom profiler | backscatter | mantle plumes | continental break-up
aseismic ridges | flood basalts | denudation

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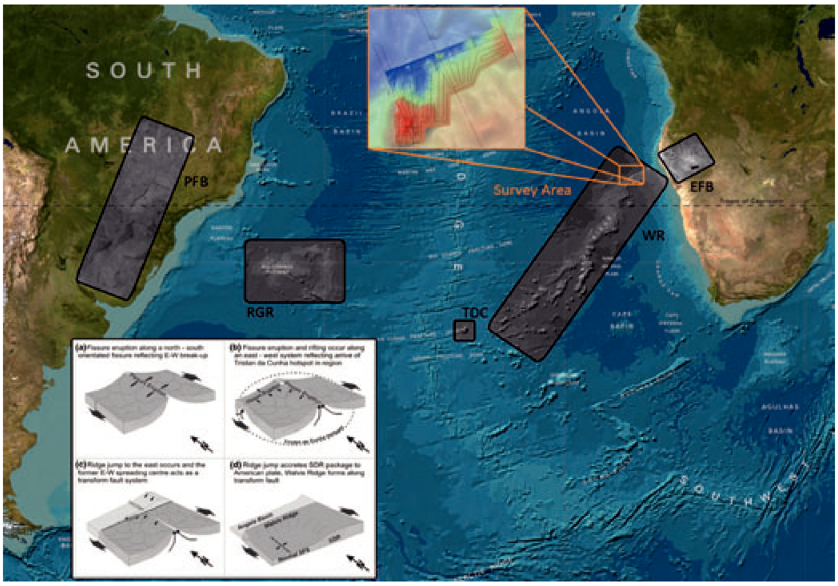
## Introduction

Continental break-up is closely related to the question, which are the driving forces behind processes related to such an incisive geological event. Intraplate rises, including aseismic ridges and submarine plateaus are associated with the breakup of continental plates. It is commonly suggested, that the formation of such large structural units is provided by a mechanism based on the interaction between deep-sourced stationary mantle plumes and moving lithospheric plates.

Around the head of a plume the upper mantle temperatures are strongly increased. After weakening of the continental crust by horizontal extension resulting high temperatures cause extensive volcanism, forming flood basalts on the continents, and in some cases also in the newly formed oceanic basins. Following this theory, in the ideal case flood basalts are deposited on the continents before break-up. After begin of the drifting stage with formation of oceanic crust between the continents, the mantle plume should create an aseismic ridge due to his continuing activity. The aseismic ridge will mark the plume position through space and time. However, such a clear relationship between volcanism on the continents and the adjacent ocean basins is rarely observed on a global scale (Artamonov et al. 2006). One of the best examples on Earth for such a relationship are the Etendeka basalts in Namibia, Africa, the Paraná basalts in South America and the Rio Grande Rise trending southeast from the South American margin, just as the Walvis Ridge offshore Namibia.



Between November 2010 and January 2011, during the Expeditions MSM 17/1 and 17/2 the German research vessel »Maria S. Merian« carried out surveys on the northwestern side of the Walvis Ridge, Southeast Atlantic Ocean, providing high resolution bathymetric data, backscatter images and sub-bottom profiles (Fig. 1). 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.

## System Setup

For the investigations the following components were equipped, interfaced and integrated: The used multi-beam system was a Kongsberg Simrad EM 120, a deep-water echo-sounder designed to perform seabed mapping to full ocean depth. Basic components of the system are two linear transducer arrays with separate units for transmitting and receiving signals. The nominal sonar frequency is 12 kHz with an angular coverage sector of up to 150° and 191 beams per ping.

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* This article is based on his Master Thesis and »High Resolution Bathymetric Survey on the NW Slope of Walvis Ridge, Offshore Namibia« written by Prof. Dr. Jan H. Behrmann, Alexey Shulgin and Andreas Prokoph.

Furthermore, the research vessel »Maria S. Merian« is equipped with the sediment profiler Parasound DS P-70, manufactured by Atlas Hydrographic. With the Atlas Parasound the water column and seabed structure from 10 m to full ocean depth can be directly explored. It is able to penetrate the seabed more than 200 m and samples data with up to 50 kHz frequency. The Parasound utilises the parametric effect to generate very low frequencies with a range of 0.5 to 6 kHz.

The data for heave, roll and pitch compensation was provided by the Kongsberg SeaTex Seapath 200 system. The Seapath 200 provides real-time heading, attitude and position information by blending the characteristics of sensor-based inertial navigation and continuous GPS position. Motion data obtained from the system's inertial measurement unit and precise position data from two, fixed baseline GPS carrier-phase receivers are integrated in a Kalman Filter within the processing unit.

## Background of the Walvis Ridge Area

The formation of the Walvis Ridge is suggested to be related to movement of the African Plate above the Tristan da Cunha hot spot and the break-up of Gondwana. It is assumed, that the Tristan da Cunha plume initiated the separation of Africa and South America, in the late Jurassic, early Cretaceous. The lithospheric plates, moving over the plume, produced flood basalts, forming the Walvis Ridge and the Rio Grande Plateau (Gladczenko et al. 1998). The existence of continental flood basalts on the African Continent (the Etendeka flood basalts) and on the American Continent (the Parana flood basalts) underlay this hypothesis.

Mantle plumes are vertical flows of material that originate at a great depth in the mantle and reach the Earth's surface. It is assumed, that mantle plumes are responsible for intraplate magmatism. It is suggested, that the plumes are stationary and that the plumes function for very long periods (Artamonov et al. 2006). Mantle plumes are supposed to be one reason for continental breakup, or at least assist the breakup of continental crust. The head of the plume forms a hot spot beneath the lithosphere, melting the lower surface of the crust. This leads to volcanism and the formation of flood basalts. The result is a volcanic chain, with flood basalts at the former position of the plume, respective to the lithosphere (Fig. 2). Flood basalts are the result of volcanic eruption or series of eruptions that coats large stretches of land or ocean floor with basalt lava. Flood basalts consist of basaltic lava with very low viscosity. The lava erupts out of fissures on the ocean floor, forming thin lava sheets. If the lava flow lasts for a longer period, the sheets can produce huge lava plateaus, called flood basalts.

## Geological Interpretation

The area under investigation has a dimension of about 100 km from southwest to northeast and of 25 km to 60 km from the southern to the northern end. It covers the NW of the Walvis Ridge between 18,5° S to 19,5° S and 9,5° W to 11° W. The depth ranges from less than 1000 m in the southwestern edge of the area to more than 4.000 m around 19° S and 10° E.

Fig. 3 marks the most prominent features of the survey area. In the north-western end of the area, a striking structure can be recognised: The Freiburg seamount. This plateau-shaped seamount has an extension from north to south of about 10 km, the maximum elevation in reference to the basalt plateau is around 650 m. One of the most dominant topographic features is the 60 km long escarpment, representing the northern boundary of the high plateau. The escarpment is very steep, almost vertical in some segments and up to 250 m high. Adjacent to the escarpment a mountainous landscape with weakly to strongly dissected slopes can be found. The elevation differences in this area range up to 2.500 m. Near the eastern end of the surveyed area there is a 10 km long southeast trending valley that has a tributary structure joining from the northeast. Its origin may be a paleo-drainage system, transecting the ridge from north to south. Morphological details in the eastern embayment fossil stream systems that extend for about 10 km from the escarpment to the abyssal plain at 3.400 m below sea level. The valleys are 200 m to 400 m wide and up to 50 m deep. The southern boundary of the surveyed area is located about 1.700 m beneath sea level. The very smooth topography there is due to sedimentary overburden quickly thickening southward.

Fig. 4 shows a detailed southward view towards the northern escarpment and the foothills beneath. The most prominent features are two

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Fig. 1 (left): Area under investigation and magmatic features related to the opening of the South Atlantic Ocean: Parana flood basalts (PFB), Rio Grande Rise (RGR), Walvis Ridge (WR), Tristan da Cunha (TDC), and Etendeka flood basalts (EFB)

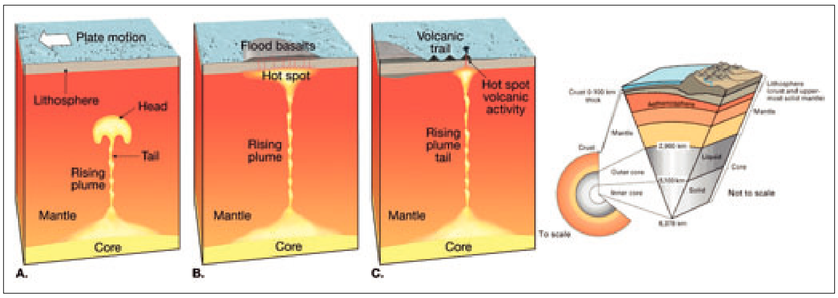

Fig. 2: Formation of mantle plumes

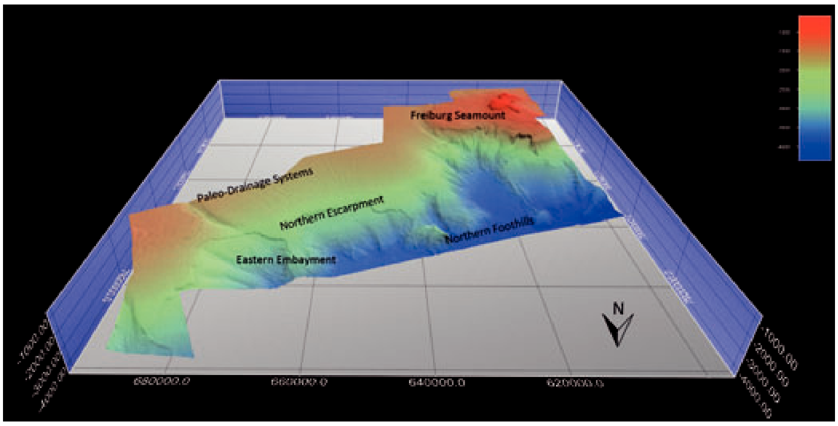

Fig. 3: Overview of the bathymetric survey area and locations of the most dominant geological structures

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crest-shaped embayments that represent clear denudational features. 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, as can be seen in the case of the smaller of the two embayments. There are numerous valleys up to about 10 km long, decorating most of the slope northward of the escarpment. Some have tributaries in the upstream section, making a fluvial origin likely.

The structure of the tabular Freiburg Seamount (Fig. 5) offers some insights in the magmatic history of Walvis Ridge, and the later subsidence. At the northern and eastern sides of the table mountain stacked sequences of flood basalt can be found. The shape of the seamount gives some evidence for denudation processes that occur only on land. The central summit areas show oblique cuts of the flows by two planar features, probably originated by coastal erosion. These wave abrasion platforms occur when waves break on cliff faces and slowly erode it. As the sea pounds rock and sediment against the escarpment, it also uses the scree from other wave actions to batter and break off pieces of rock from higher up the cliff, which can be used for this same wave action and abrasion. A possible explanation is that these abrasion platforms formed when the mountain had subsided below sea level.

The mountains in the area of the foothill-section lack the appearance of tabular mountains, as seen further upslope. This indicates that they are composed of more homogeneously erodible basement rock of the Walvis Ridge, and are not series of stacked lava flows.

At the eastern end of the survey area, north of the escarpment, we can find a large embayment. Above the embayment we find the basaltic high plane, followed by the northern escarpment. The seafloor beneath is smooth. Fig. 6 shows a cross section of the northern escarpment at the western end of the embayment. The profile is about 7,5 km long and the escarpment has an elevation of 200 m at this point. The Parasound data of the cross section shows some interesting details. In contrast to the escarpment further west we can find sedimentary structures in this area. Furthermore the seafloor allows a higher acoustic penetration, in contrary to the flood basalts found in the other areas, for example near the Freiburg seamount. The sub-bottom data reveals sediment layers up to 100 m below the seafloor. For that we assume a composition of basement rock of this section. At this point of the surveyed area, the escarpment marks the change of the basaltic high plateau to the foothill section made of basement rock. In this area we can find evidence for erosive processes, like gullies and fan deposition.

Further southwest, and approaching the crestal area of Walvis Ridge, there is smooth topography. Here, fine-grained marine deposits overlie the ridge, with thickness of the sediment column rapidly increasing southward. The seafloor, however, is not completely structureless, a network of kilometre-long irregular furrows that are trending north-south can be found in this area (Fig. 7). A cross section with thirty times vertical exaggeration shows dune-like structures 500 m to 1 km wide and approximately 10 to 30 m high. The sediment thickness is about 50 m, with clear cut layers in the valleys between the structures, indicating increased deposition of marine deposits (Behrmann et al. 2011). It is difficult to interpret the features 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. This may mainly concern Antarctic Intermediate Water gently flowing northward across the Walvis Ridge (Talley 1996). It is this current, which may have aided to prevent deposition of fine-grained biogenic sediment on the north

Fig. 4: The escarpment below the Freiburg seamount

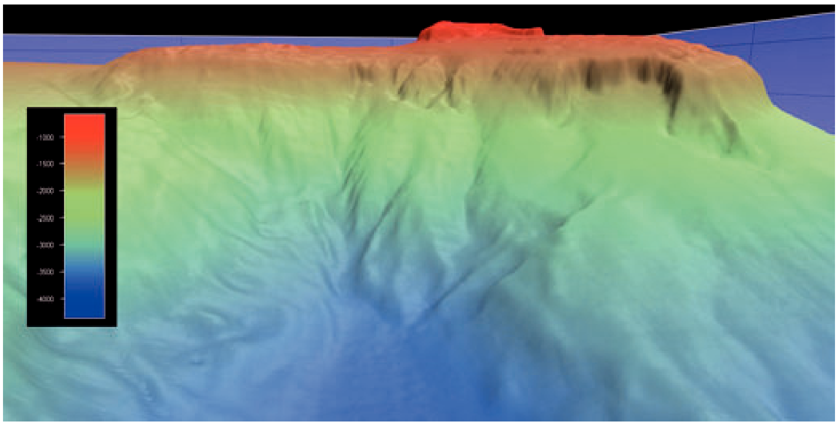
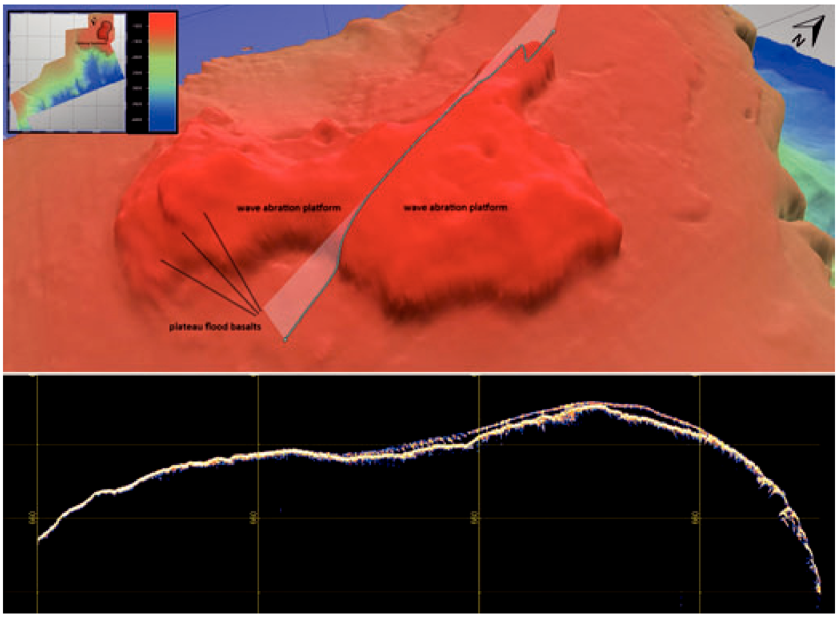


Fig. 5: Detailed view of the Freiburg seamount, showing plateau flood basalts and wave abrasion platforms



side of Walvis Ridge from the Upper Cretaceous onward.

## Results and conclusion

The main purpose of the geological interpretation was to find out whether the surveyed area of the Walvis Ridge was formed by erosion on land or by processes when the region subsided below sea level. Maybe the most interesting question concerns the age of the discovered submarine mountainscape. Although not located in the immediate vicinity, a number of drill sites were cored by the Deep Sea Drilling Program (DSDP) (Bolli et al. 1978; Hay et al. 1984). The stratigraphic records give some important insights into the onset of marine sedimentation in the southern Angola Basin and on Walvis Ridge. A site on the south-eastern 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. One site drilled on top of an isolated basement high on the north side of Walvis Ridge about 80 km seaward of the surveyed area in 2.248 m of water, yielded cores of Upper Aptian limestone at 715 m depth, about 35 m above seismically inferred basement. This means that this drill site has recorded at least 3.000 m of post-Aptian subsidence. Another core, located on the crest of Walvis Ridge, terminated in Eocene limestones at 1.081 m below seafloor, without penetrating basement rocks. For that, the maximum stratigraphic ages of the marine sediments constrain the subsidence of Walvis Ridge below sea level in this area 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 to 134 million years ago (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 drill hole data correspond well with the present depth of base levels for the fluvial systems mapped, which are around 3.000 to 3.500 m below sea level (Behrmann et al. 2011).

The analysis of the acquired data revealed clear evidence for morphological structures formed by aerial processes. Structures showing on-land erosion can be found especially near the Freiburg Seamount and the Northern Escarpment. Some evidence for erosion below sea level can be found in the eastern part of the area under investigation, near the crestal area of the ridge or some features in the eastern embayment, where it is not possible to decide over the on-land or submarine origin of the erosive features, at least without further evidence.

This study shows that geological interpretation based on hydroacoustic data is possible. While not offering a full tectonic interpretation, it can be concluded that the record of geomorphic processes revealed by high-resolution bathymetric imaging may contribute important information regarding the formation of the Walvis Ridge and its tectonic history. Of course this information must be combined with the results of the refraction and reflection seismic studies. The geophysical datasets are processed and analysed at the AWI in Bremerhaven. The results will be combined with the data used for this contribution – bathymetry, backscatter and sub-bottom. It will be interesting if the outcomes of the seismic interpretation fit to the evaluation of the hydroacoustic datasets. ☐

Fig. 6: DEM and sub-bottom data of the eastern embayment with a cross section intersecting the escarpment

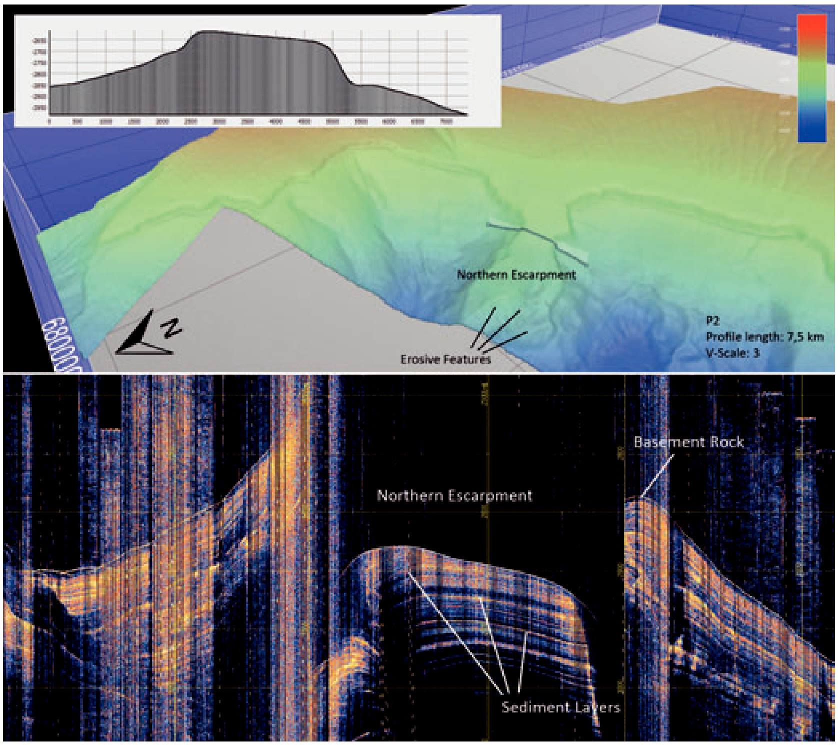


Fig. 7: Sediment structures on the high plane of the Walvis Ridge. The dune-like structures are approximately 20 to 30 m high. The Parasound profile reveals some evidence for sedimentation in the valleys between