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Agulhas Plateau, SW Indian Ocean: New Evidence for Excessive Volcanism

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Abstract. A new set of seismic reflection and refraction lines has been interpreted regarding the basement and crustal structure of the southern Agulhas Plateau. A large number of extrusion centres were identified. Lava flows dip away from those extrusion centres and form subparallel-stratified sequences. We interpret those extrusion centres as the result of excessive volcanism in course of the separation of the southern Agulhas Plateau from the Maud Rise. Since the sedimentary layers appear to be little affected by the volcanism, that episode obviously ceased before onset of sedimentation in Late Cretaceous times. We have not found evidence for continental fragments within overthickened, predominantly oceanic crust. We therefore propose that the Agulhas Plateau belongs to the world-wide suite of Large Igneous Provinces (LIP) of predominantly oceanic origin.

Introduction and Data Acquisition

The Agulhas Plateau is located about 500 km southeast of the Cape of Good Hope in the southwestern-most Indian Ocean (Fig. 1). It rises up to 2500 m above the surrounding seafloor. The Agulhas Plateau is one of the key structures within the reconstructions of the break-up of Gondwana. The knowledge of its crustal structure and paleo-position would provide further constraints for the processes and movements involved in Gondwana's break-up but both are still under debate. Strong indications for a continental origin were found (LaBrecque and Hayes, 1979; Martin and Hartnady, 1986; Ben-Avraham et al., 1995). This hypothesis states that the Agulhas Plateau formed one structural unit together with the Falkland Plateau and Maud Rise prior to the opening of the South Atlantic. ODP drilling at the Northeast Georgia Rise, however, led to the suggestion of an equivalent evolution of the Northeast Georgia Rise and the Agulhas Plateau, and thus an oceanic origin of the Agulhas Plateau (Kristoffersen and LaBrecque, 1991). An attempt to solve the puzzle of the evolution of the plateau by seismic investigations and geological sampling was already made by Barrett (1977), Tucholke and Carpenter (1977), and Allen and Tucholke (1981). Although those seismic data give valuable information, both penetration and resolution are not sufficient to provide a clear picture on the structural and sedimentary development of the Agulhas Plateau.

In December 1997/January 1998, the Alfred-Wegener-Institut (AWI) gathered six high-resolution seismic reflection lines (1550 km total length) on the southern Agulhas Plateau (Fig. 1). Two GI-guns™ generated seismic signals with frequencies up to 250 Hz. The data were received with a 96-channel streamer (2400 m long). All seismic reflection data have been processed up to migration.

Two in-line seismic refraction/wide-angle reflection profiles (AWI-98200 and AWI-98300) were shot coincident to the reflection lines AWI-98017 and AWI-98018, using a 60-l airgun as source and 7 and 6 ocean-bottom hydrophone systems (type GEOMAR-OBH) as receivers for each profile, respectively (Fig. 1). OBH systems from a total of 9 deployment locations recorded data useful for subsequent seismic phase analysis and velocity-depth modeling.

Discussion and Results

The seismic reflection data show a distinct, up to 1200 m thick sedimentary unit (2000 m/s conversion velocity) which overlies the basement of the plateau (Fig. 2). The sedimentary layers are well stratified (Fig. 2). The deepest reflection detectable within the sedimentary unit is very smooth with strong amplitudes and good continuation (Fig. 2, CDPs 5800-8200 and 9800-11400). We correlate this reflector with the top of the acoustic basement of Tucholke et al. (1981). They were able to core this reflector where it crops out at the western flank and high up on the plateau and identified it as a surface of unconformity. The minimum age of the reflector was found to be Maastrichtian, and at least 25 my of the older sedimentary record was missing (Tucholke et al., 1981). Our data reveal this reflector to be an erosional surface. The underlying reflections, which we identify originating from basement, terminate against this Late Cretaceous reflector (Fig. 2, CDPs 6400-7600 and 9800-11000) thus documenting strong erosion (Emery and Myers, 1996). Only locally in basement depressions we can identify layers up to 100 m thick between reflector Maastrichtian and the top of the basement (Fig. 2, CDPs 7600-8200 and 11000-11400).

The basement itself appears hummocky with an erosional top (Fig. 2, e.g. CDPs 3400-4000 and 5200-6000). Several relative basement highs can be observed with flow-like reflections on each side dipping away from the highs (EC in Fig. 2). The reflections can be followed for several kilometres, some are up to 15 km long. The reflections overlap and are superposed to form subparallel-stratified sequences. In this they resemble lava flows associated with flood basalt volcanic fields (Reading, 1996). Interval velocities provide further indications for a volcanic and not a sedimentary nature of the

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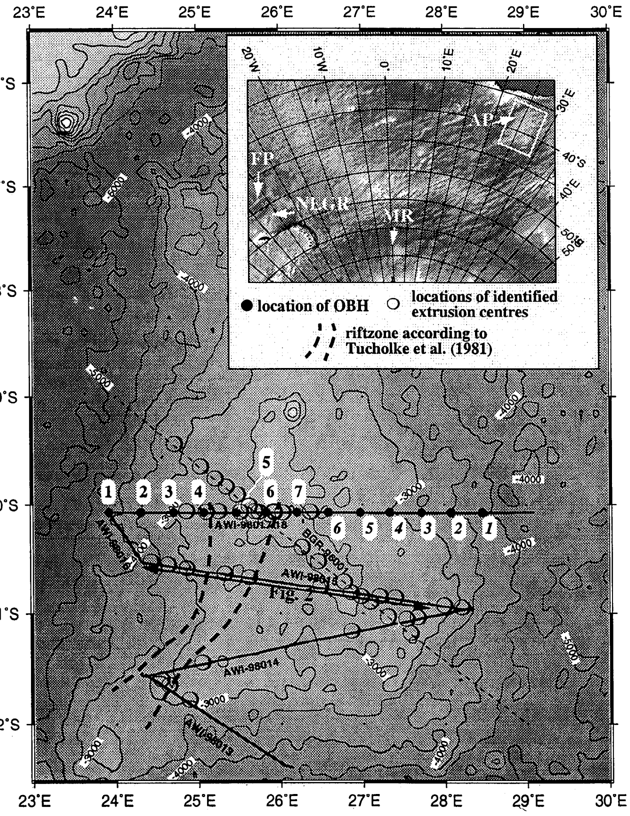

Figure 1. Bathymetric map of the Agulhas Plateau showing the location of the seismic reflection lines. Parallel to lines AWI-98017 and AWI-98018 the seismic refraction lines AWI-98200 and AWI-98300 were shot. The big dots show the locations of the oceanbottom hydrophones (OBH). The white circles represent the locations of the observed extrusion centres. The riftzone according to Tucholke et al. (1981) is also displayed. Furthermore, the location of line BGR-96001 is given. The insert map shows the location of the Agulhas Plateau relative to South Africa. Bathymetry is satellite derived from Sandwell and Smith (1997). AP= Agulhas Plateau, MR= Maud Rise, NEGR= Northeast Georgia Rise, FP= Falkland Plateau.

dipping basement reflections. Values of 3800 m/s up 5000 m/s were deduced from the reflection data for those reflections whereas the sedimentary record above only exhibits velocity values of 3000 m/s and lower. This is in agreement with velocity information derived from our refraction data. Similar reflections have been observed and identified as seaward dipping reflections on a traverse across the southern Agulhas Plateau by Hinz (1996). He suggests the emplacement of an enormous volcanic sequence during the Cretaceous magnetic quiet period prior to magnetic anomaly 34 as the source of those seaward dipping reflections (Hinz, 1996).

We now interpret the relative basement highs as extrusion centres. The flow-like reflections, thus, represent volcanic flows. At least 43 of those extrusion centres have been observed along AWI and BGR profiles (Fig. 1). The sedimentary layers appear to be little affected by the volcanism. According to this, the southern Agulhas Plateau was overprinted by extensive volcanism prior to the onset of sedimentation.

The origin and Cretaceous evolution of the Agulhas Plateau are still under debate. Three theories are mainly discussed. Tucholke et al. (1981) report rugged basement on the northeastern Agulhas Plateau and suggest it was caused by oceanic spreading at a triple junction around magnetic anomaly 34. The southern plateau they claim to be underlain by continental crust. But within the otherwise smooth basement of the southern plateau they observed a SSW striking zone of rough basement flanked by major normal faults. Tucholke et al. (1981) interpret this as an axis of crustal extension or basaltic intrusion as the result of ridge jumps of the triple junction from the northern plateau to the southwestern edge thus forming the irregular crust. By 80 my, the triple junction migrated southwest of the Agulhas Plateau (Tucholke et al., 1981).

The extrusion centres are not restricted to the riftzone proposed by Tucholke et al. (1981) but are distributed randomly across the southern Agulhas Plateau (Figs. 1 and 2). There is no dominant trend that indicates a ridge or spreading axis and major faults were not found either (Fig. 2). The only faults recognized are located on line AWI-98015 immediately west of the plateau's summit (Fig. 2, west of CDP 5000) and on line AWI-98013 in waterdepths greater than 3700 m and are probably related to cooling of the lava flows. The fault displacements are no larger than 100 m which is in contrast to Tucholke et al. (1981) who observe large normal faults with offsets of several hundreds of metres.

In contrast to Tucholke et al. (1981), Martin and Hartnady (1986) infer in their reconstruction of the Gondwana break-up that the northern plateau was not the location of a triple junction. Instead, they suggest excessive volcanism and find no evidence for a spreading axis on the plateau. This is supported by Hinz (1996) who observes at least two units of dipping sub-basement reflections and links those to effusive volcanism in the Late Cretaceous (anomaly 34).

Seismic data (e.g. LAZ96-100 and BGR96-016) from the Maud Rise, a plateau-like feature off Dronning Maud Land/Antarctica of continental origin and discussed conjugate margin of the Agulhas Plateau (Martin and Hartnady, 1986), clearly show wedges of seaward dipping reflections (Hinz, 1996). They form a 100 km wide zone with individual reflections which are up to 20 km long. This strongly resembles the observations on the southern Agulhas Plateau. Further evidence for late Cretaceous volcanism on the Maud Rise was produced by ODP leg 113. At Site 690 basaltic basement which represents alkalic volcanism, generally associated with the building of oceanic islands, was recovered (Shipboard Party, 1988). Thus supports our interpretation of the basement highs on the Agulhas Plateau to be extrusion centres which were created during a phase of excessive volcanism while the Agulhas Plateau and the Maud Rise separated about 90 my ago.

In opposition to Tucholke et al. (1981) and Martin and Hartnady (1986), whose theories are based upon the hypothesis that the Agulhas Plateau formed one structural unit together with the Falkland Plateau and the Maud Rise prior to the opening of the South Atlantic, Kristoffersen and LaBrecque (1991) argue that the basement structure of the Agulhas Plateau points to an origin at the same spreading centre as the Northeast Georgia Rise. The Northeast Georgia Rise is underlain by oceanic crust (Ciesielski, Kristoffersen et al., 1991). Thus, they conclude that the Agulhas Plateau is not a continental fragment.

The OBH refraction/wide-angle reflection records (Fig. 1) show coherent energy from refracted phases up to 120 km offset from some OBH locations. Apparent velocities from 5 to

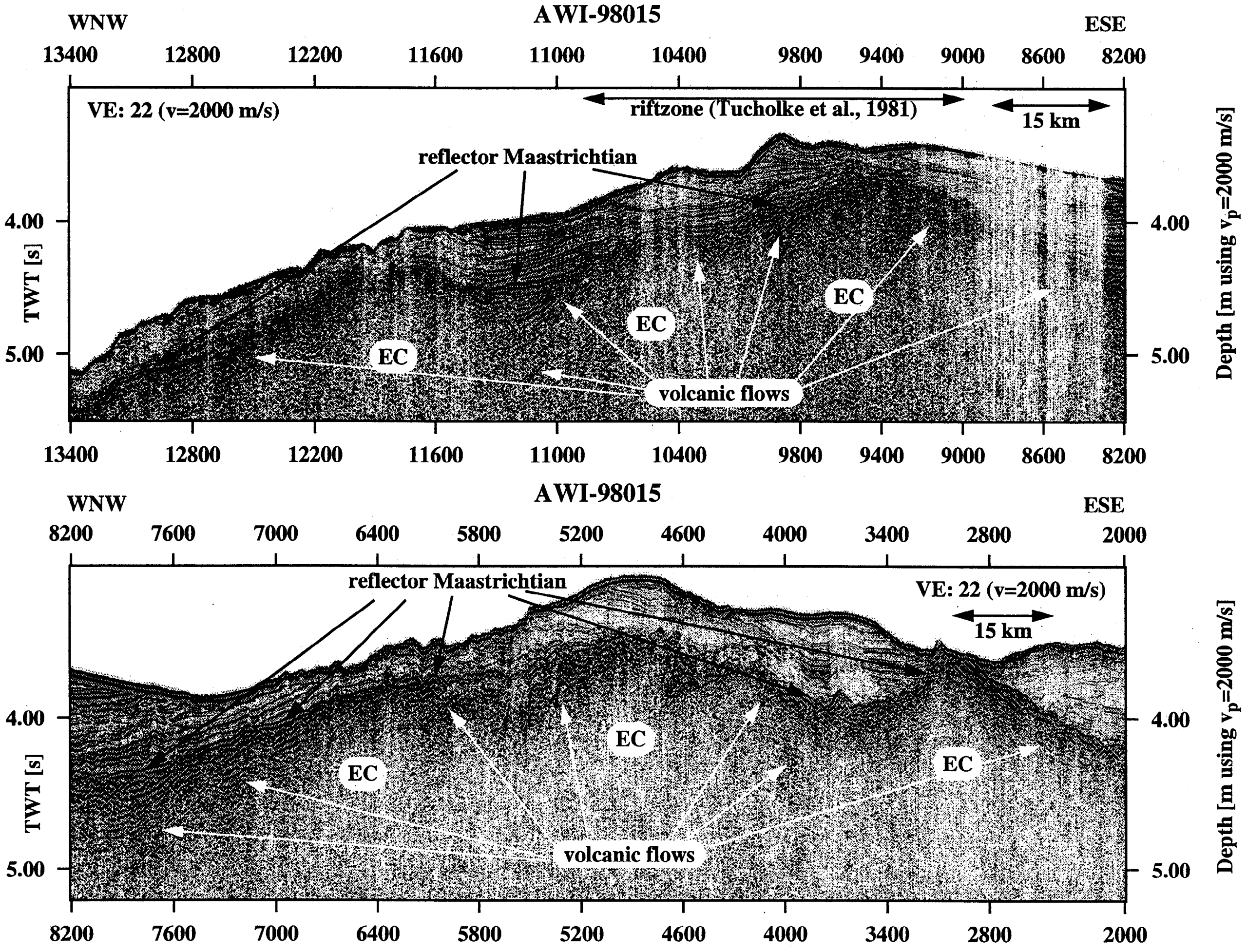

Figure 2. Seismic reflection line AWI-98015. The data were bandpass-filtered (20-220 Hz), and an AGC window of 300 ms length was applied for display. The right-hand depth scale was converted from traveltimes using a velocity of 2000 m/s.Note the strong volcanic flows and reflector Maastrichtian. EC = extrusion centre.

7.6 km/s are observed for the first P-wave arrivals from the crust on all records, and an upper mantle refraction phase (Pn) of 8.1 to 8.2 km/s can be identified in two records. All records contain clearly identifiable Moho reflections (PmP phases) but no indications for mid- or lower crustal reflection phases. We derived a two-dimensional model of the velocity-depth distribution (Fig. 3) using a travel-time inversion routine by Zelt and Smith (1992). The data were initially modeled by forward ray-tracing. Subsequently, the model parameters were adjusted by a damped least-square inversion scheme. Data processing and modeling details are discussed in a separate publication (Gohl et al., in preparation).

The P-wave velocity-depth model along the OBH east-west transect AWI-98200/98300 (Fig. 3) shows high velocities between 7.0 and 7.6 km/s for the lower 50-70% of the central plateau's crust. Maximum crustal thickness is 24-25 km. There is a strong correlation with similar velocity distributions of other oceanic plateaux of predominantly oceanic affinity, such as the Ontong Java Plateau (Miura et al., 1996). The velocities in the lower crust of the Agulhas Plateau are even higher than those for the northern Kerguelen Plateau (Charvis et al., 1995). The evidence for high velocities throughout the mid and lower crust of the Agulhas Plateau lets us suggest that at least the central part of the plateau is of oceanic origin.

The seismic velocity model is in strong contrast to implications from quartzo-feldspathic rock samples dredged from the western part of the southern Agulhas Plateau (Allen and Tucholke, 1981) which show a petrological composition similar to that of rocks from the Falkland Plateau, South Africa and Antarctica. However, we cannot exclude the possibility that small fragments of continental crust have remained attached to the westernmost Agulhas Plateau after separation from the Falkland Plateau.

Conclusions

The Agulhas Plateau is one of the key structures within the reconstructions of the break-up of Gondwana with its crustal structure and paleo-position still under debate. A new set of seismic reflection and refraction lines has been interpreted to shed more light on the Late Cretaceous development of the southern Agulhas Plateau. We have found new evidence for interpreting the southern Agulhas Plateau as of predominantly oceanic origin. Continental micro-fragments might be part of the western plateau which started to move from its attachment to the Falkland Plateau towards its present position at about 108-105 my (anomaly M0). Excessive volcanism that led to the formation of the northern oceanic Agulhas Plateau around

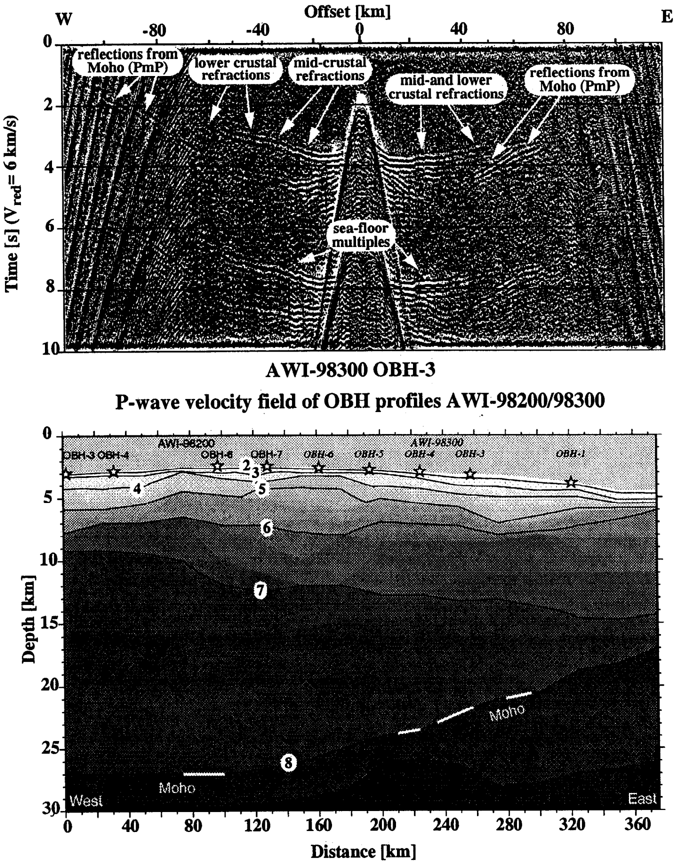

Figure 3. Seismic section recorded at OBH-3 (top) and P-wave velocity distribution field (bottom)derived from OBH data across the centre of the Agulhas Plateau. The seismic data were bandpass-filtered (3-17 Hz), an AGC window of 1s was applied and the data were reduced dor display (vred= 6 km/s). Note the clear PmP phases.The model shows velocities of well above 7 km/s for the lower 50-70 % of the crust, suggesting an oceanic origin. Note that a high-velocity ridge in the upper crust at 75 km coincides with an area identified as an extrusion centre in the seismic reflection data. The white lines on the 8 km/s isoline represent reflections from the Moho.

90 my (Martin and Hartnady, 1986; Ben-Avraham et al., 1995) caused the wedges of seaward dipping reflections on the western and central plateau (Hinz, 1996). Strong volcanism was again initiated at a later stage in the area of the southern Agulhas Plateau. A large number of extrusion centres formed on the southern Agulhas Plateau, documenting the overprinting of the already overthickened oceanic crust. During this period the plateau was near sea-level, and subaerial and/or shallow submarine erosion strongly affected the sediments and led to the formation of the strong smooth reflection of Maastrichtian age directly overlying the basement. Subsidence then set in while sedimentation continued. The high velocities in the middle and lower crust and the evidence for major extrusion centres across the Agulhas Plateau are indicative for voluminous emplacement of predominantly mafic extrusive and intrusive rocks, the defining characteristics of Large Igneous Provinces (LIP).

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