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Orbital forced cyclicity of reflector strength in the seismic records of the Cape Basin

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[1] A well-pronounced succession of continuous high-amplitude reflectors characterises the upper acoustic units off Southwest Africa as revealed in our seismostratigraphic study. We performed spectral analyses over age-transformed seismic traces. The results suggest a temporal regularity in the variation of reflector strength according to Milankovitch cycles since the early Pliocene. Periods of 100 kyr/cycle between 0–2 Ma correspond to eccentricity modulations. From 2–3 Ma, shorter periods close to obliquity cycles prevail, whereas in even older units periodicity increases again to 100 kyr/cycle. We propose the cyclicity of high-amplitude reflectors is caused by orbitally driven climate variations, which modulate the sedimentary properties and with it the seismic reflectivity. **Citation:** Weigelt, E., and G. Uenzelmann-Neben (2007), Orbital forced cyclicity of reflector strength in the seismic records of the Cape Basin, *Geophys. Res. Lett.*, *34*, L01702, doi:10.1029/2006GL028376.

1. Introduction

[2] Numerous studies demonstrate cyclicity in depositional sequences and relate them to changes in sedimentary composition due to orbital controlled climate variations [e.g., *Imbrie et al.*, 1984; *Gorgas et al.*, 2001, and references within]. These observations provide a basis for tuning and improving age models of sedimentary sections [e.g., *Christensen and Maslin*, 2001; *Westerhold et al.*, 2005]. However, all such studies are restricted to drill sites locations. Seismic surveys in contrast offer a comparatively simple way to image sedimentary structures over much larger ranges. With an integrated study of borehole and seismic data we aim at a seismostratigraphic model to test the impact of climate changes on the seismic reflection pattern.

[3] The Cape Basin represents an ideal site to study climate influences on sedimentation at a fine scale because of its high sedimentation rates, which occur due to the influence of the Benguela Current Upwelling System. The depositional structures were shaped by the interaction of climate, oceanic currents and sea level fluctuations, which left an imprint on the physical properties of the marine sediments. Therewith density and P-wave velocity are affected, which are the parameters controlling seismic reflectivity. The amplitudes of generated reflectors are higher with stronger and more abrupt changes in density and/or P-wave velocity of succesive layers.The seismic section in the Cape Basin reveals a well-pronounced sequence of high-amplitude reflectors characterizing the upper seismic units. Using spectral analyses we examine the periodicity in the variations of reflector strength. In particular, we aim to quantify Milankovitch cyclicity in the reflection seismic records.

2. Material and Methods

[4] The base of our study is a combination of reflection seismic lines and drill site records from six ODP Leg 175 sites (Figure 1). Drill site data recovered a mainly continuous organic-rich sedimentary section, intermediate between hemipelagic mud and pelagic ooze. With a maximum depth of 600 mbsf (site 1085), the logs offer an excellent record of the productivity history of the last 15 myr (since middle Miocene) [*Wefer et al.*, 1998].

[5] Seismic data image a well-pronounced reflection pattern of more than 2 s twt (two-way traveltime) thickness, which corresponds to a penetration depth of more than 1 km below sea floor. Dating and areal tracing of reflectors was achieved by converting drill site data from the depth domain into the two-way traveltime by sonic logs calculated from P-wave velocities measured at the drilling sites, which imply a depth resolution of 10 m (Figure 2) [*Weigelt and Uenzelmann-Neben*, 2004].

[6] For dating, we rely on the interpolated age model of *Berger et al.* [2002], which is derived from nannofossil stratigraphy and paleomagnetic reversals. This model provides a table of ages assigned to a depth scale (mbsf) in 10-meter steps. Errors of age assignment are of the magnitude 0.01 myr [*Berger et al.*, 2002]. We resampled our sonic log into the same depth steps and simply pasted it to the age-depth table of *Berger et al.* [2002], achieving a table of depth (mbsf), twt (ms) and age (Ma). Based on this biostratigraphic age model the seismic sample rate of 1 ms twt represents a temporal resolution of 6–20 kyr depending on the sedimentation rate at the sites (Table 1). Concerning the constraints for signal analysis (Nyquist-frequency) this sample resolution is not sufficient to identify precession cycles (19 and/or 23 kyr). Obliquity cycles (41 kyr) and the much longer eccentricity cycles (100 and 400 kyr), however, should be observable in the seismic data set.

[7] To test any regularity in the succession of high-amplitude reflectors (HARS) we performed spectral analyses computed with the software package of *Schulz and Stattegger* [1997] (Figure 3). Prior to the analyses, single seismic traces close to the location of the drilling sites were converted from two-way traveltime domain (ms) into age domain (kyr). For each site, the maximum possible data point window length was chosen to cover all main orbital cycles, and especially to resolve the shortest period contained in the data (Table 1). To detect a possible shift of dominant periods with time (e.g. as for the Mid-Pleistocene revolution) we computed spectra for time slices of 1 myr length. Site 1082 data is used as an example (Figure 4).

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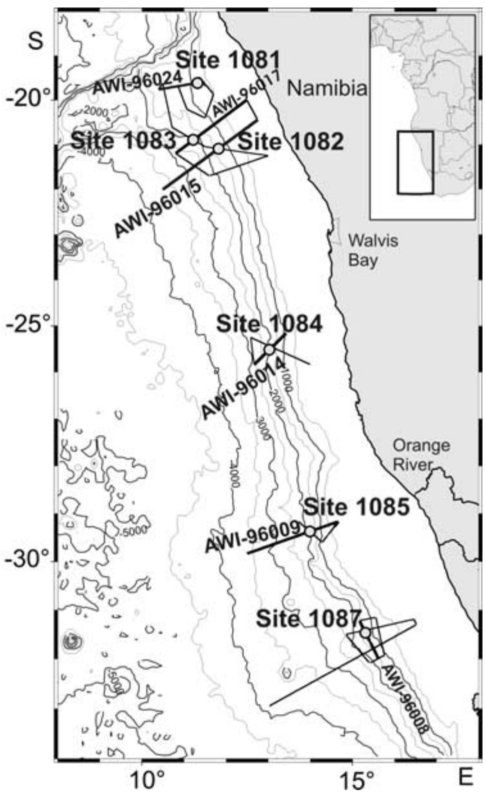

Figure 1. Bathymetric map of the southern Cape Basin showing the locations of the seismic reflection lines [*Bleil and Shipboard Scientific Party*, 1996] and ODP Leg 175 sites 1081–1087 [*Wefer et al.*, 1998]. Annotated lines are focused in this contribution.

[8] Furthermore, we performed a spectral analysis on the density records and compared it to the spectra of the seismic traces, as shown for example with records at site 1082 (Figure 4). For this purpose we established a density log composed of discrete GRA bulk density and log density (HLDT) over the whole drilling depth of 580 mbsf, and sampled it in twt. To remove the trend of increasing density with depth, we applied a median-filter with a length of 26 twt-samples (=200 kyr). This filtered record was subtracted from the unfiltered log. Finally, the spectral analysis was performed on this residual density record with the same parameters as for the seismic traces.

[9] Several tests were performed to exclude the periodicity of HARS being an artifact of the sampling rate of seismic traces. In one, we calculated the spectra of records in the traveltime domain (ms) and in the age domain (kyr) for timeslices with great differences in sedimentation rates. As supposed the spectral power of the data against the traveltime scale do not show a pronounced maxima, whereas the spectra of age-dated time slices show maxima around the 100 kyr period. In another test, the correspondance of HARS to periodical density variations emphasizes the natural origin of the cyclicity of strong reflectors.

3. Results

[10] Our study of age-transformed seismic traces shows regularity in the succession of HARS since the Early Pliocene (since ~4.2 Ma) that can be related to orbital modulations. However, regional differences are evident on the spectra over seismic lines through the Cape Basin (Figure 3).

[11] For the northern and middle Cape Basin where the upper seismic units are characterized by a sequence of undisturbed, continuous reflectors we can provide evidence for the cyclicity of HARS. Close to the Walvis Ridge at site 1081 the spectrum over the amplitude of seismic traces shows a strong maximum at a period of 200 kyr, and a weaker one at 100 kyr (Figure 3, curve a). In the northern Cape Basin at sites 1082 and 1083 power maxima dominate clearly at periods of 100 kyr, corresponding to eccentricity modulations (Figure 3, curves b and c). For the middle Cape Basin, power maxima occur at 100 kyr/cycles as well as at shorter periods between 40 and 80 kyr corresponding to obliquity cycles (Figure 3, curve d).

[12] In contrast, for the southern Cape Basin we observe no distinct cyclicity of reflectors throughout the last 15 myr (Figure 3, curves e, f, and g). Here, in general, the seismic reflection pattern is much more irregular. The amplitude, frequency, and sequence of reflectors are much lower. Additionally, the deposition sequence seems to be disturbed by faults and mass movements as indicated in numerous slump scarps recorded on the seismic lines. Therefore, a further interpretation seems inappropriate.

[13] Some more detailed investigations were performed on site 1082 data, because it supplies the longest record in age concomitant with a high temporal resolution of reflector depth (Table 1). To test a possible shift of dominant periods with age, we calculated spectra over time slices (Figure 4) and a wavelet spectrum. The computations emphasize the strong spectral power at a period around 100 kyr/cycle,

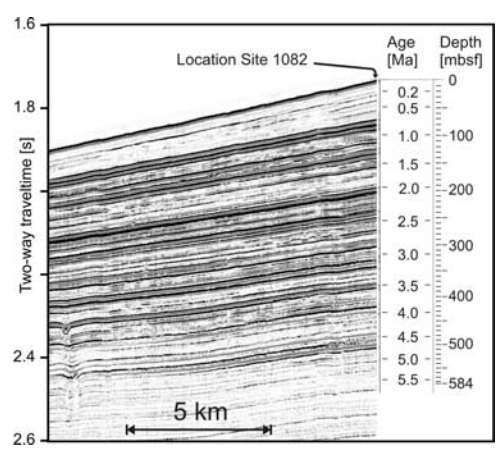

Figure 2. Section of reflection seismic line AWI-96015 close to ODP Leg 175 site 1082 (see location in Figure 1) and a curve of the combined eccentricity and obliquity cycles. The assignment of the depth scale in meters below sea floor (mbsf) was achieved by converting drill site data from depth domain into two-way traveltime domain by applying sonic logs. The dates of the ages (Ma) are adopted from the interpolated age model of *Berger et al.* [2002] and aligned to the seismic records via the depth scale. An apparently regular sequence of continuous high-amplitude reflectors is well pronounced for the last 4.5 Ma. In contrast, in older layers only fragments of low-amplitude reflectors prevail.

Table 1. Parameters for Spectral Analyses

Site	Age Range, Ma	Number of twt Samples	Resolution, kyr/sample	Bandwidth, 1/myr	Minimum Period, kyr	Maximum Period, myr	Average Sedimentation Rate, cm/kyr
1081	0–4.2	337	12	0.77	25	1.4	6
1082	0–4.4	604	7.3	0.77	15	1.5	11
1083	0–2.6	255	10.2	0.13	21	0.9	7.5
1084	0–3.4	663	5.1	0.99	10	1.1	15
1085	2–7	342	14.6	0.67	29	1.7	6
1085	6.5–13.8	262	27.8	0.46	56	2.5	5
1087	0–10.6	549	19.3	0.32	38	3.5	4.4

especially for the last 2 myr corresponding to eccentricity. Between 2 and 3 Ma, a shift to shorter periods of about 42 kyr/cycle, similar to obliquity cycles, is evident. From 3 to 4.4 Ma periods of 100 kyr/cycle predominate again. Before 4.4 Ma a clear periodicity is no longer evident. At this time, we also observe a striking change of reflection amplitudes (Figure 2). At this interface, a change from high-amplitude reflectors above to underlying low-amplitude reflectors has been interpreted in terms of a reorganisation of the deposition regime (E. Weigelt and G. Uenzelmann-Neben, Early Pliocene basic change of deposition style in the Cape Basin as derived from seismostratigraphy submitted to *GSA Bulletin*, 2006).

[14] In a further step, we analysed the variations of density and P-wave velocity of the sediments, since these parameters control the impedance and reflection coefficients (reflectivity). The tests showed that the influence of density changes exceeds the impact of velocity changes on the reflectivity. Thus, we restricted the calculation of the power spectra to density variations. The results correlate well with the cyclicity of HARS (Figure 4). Several high-density spikes in the records of sites 1081, 1082 and 1084 are related to dolomite layers [*Wefer et al.*, 1998]. These density peaks generate broad band noise in spectral power and likely are responsible for the portion of the longer periods around 200 kyr/cycle in the spectra of these sites.

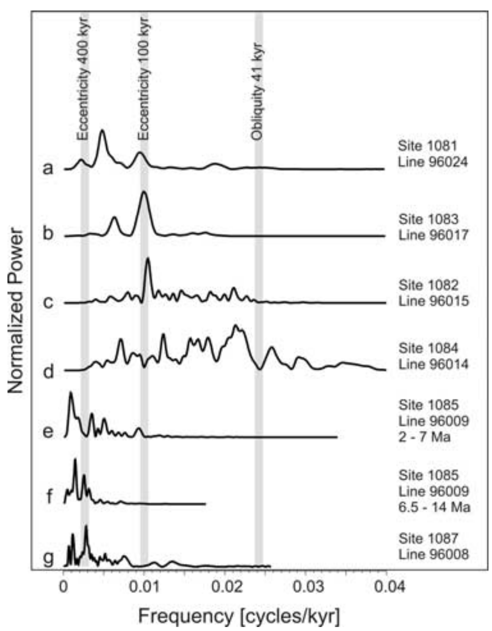

Figure 3. Power spectra of seismic traces in the age domain computed with the program of *Schulz and Stattegger* [1997]. Plots are, from north to south, close to: site 1081 (curve a), site 1083 (curve b), site 1082 (curve c), site 1084 (curve d), site 1085 (curves e and f), and site 1087 (curve g). Grey bars mark the main orbital periods (at 41, 100 and 400 kyr/cycle). The bandwidths for the windows are adapted individually for each trace to resolve the shortest periods contained in the data (Table 1). Spectral estimates are smoothed by an oversampling factor of 4.

4. Discussion

[15] Analyses of the seismic reflection pattern revealed a cyclic variability in the amplitude of reflectors, especially around periods of 100 kyr/cycle in the NCB. As a reason for the regularity of HARS we suggest climate variations due to orbital forcing. These climate changes represent cyclic thresholds at which sediment composition drastically changes [e.g., *Gorgas et al.*, 2001, and references therein], leading also to a variation in density and P-wave velocity of the deposits. These two parameters generate impedance contrasts, which in turn affect the strength of reflection

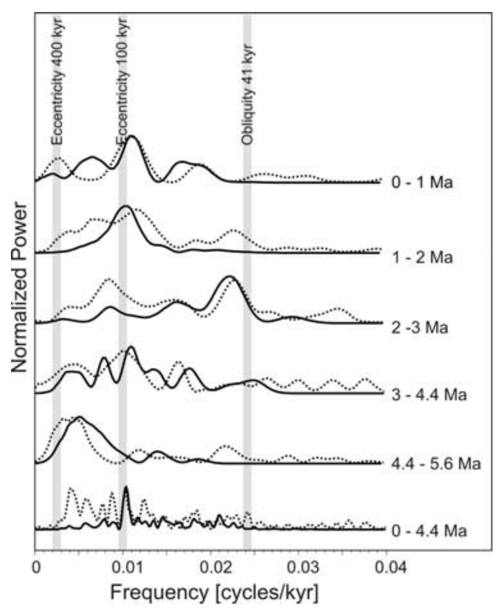

Figure 4. Spectra over time intervals of 1 myr length of seismic traces (solid line) and density variations (dotted line) for site 1082 data. Grey bars mark the main orbital periods (at 41, 100 and 400 kyr/cycle). The bandwidth for the window is 300 kyr. Spectral estimates are smoothed by an oversampling factor of 4. Prior to spectral analyses, the density records were rid of spikes and the increasing trend with depth was removed.

coefficients. In addition to this our study reveals a good correlation between density variations and the strength of reflection amplitudes (Figure 4), raising the question of which climate-controlled processes cause such modulations.

[16] *Westerhold et al.* [2005] showed a correlation of magnetic susceptibility with eccentricity cycles at site 1085, which they related to increased input of more iron-rich terrigenous material during glacials. However, the variation in iron concentration is too low to lead to density changes strong enough to generate a pronounced reflection.

[17] Another parameter with a strong impact on density is the clay content in the sediments, due to its low porosity. The clay content is dependent on the amount of terrestrial sediments, which is higher during interglacials because of enhanced river input [*Diester-Haass et al.*, 1992]. Unfortunately, grain size analyses exist only for site 1085 [*Diester-Haass et al.*, 2001], which we excluded from our investigations (see above).

[18] Numerous studies [*Gorgas et al.*, 2001, and references within] show that variations in orbital forcing influence local changes in bioproductivity and upwelling vigour. So, the abundance of larger foraminifers relative to fine-grained nannofossil ooze is linked to bioproductivity and dissolution [*Meyers*, 1992]. *Gorgas et al.* [2001] also revealed Milankovitch cyclicity in the form of density variations in the sediments at sites 1081, 1082 and 1084. They suspect that variation in the abundance of large foraminifers (calcareous microfossils) strongly influences the preservation of porosity and, in turn, affects the variability in density at the sites. Their power spectra of density cyclicity show that the presence of main Milankovitch cycles varies with age. For sites 1081 and 1084, we calculated power spectra of HARS over the whole length and time range of logs, which might explain the more scattered frequency maxima in our analyses. Also, intermittend frequencies may result from noise effects induced by strong density variations [*Gorgas et al.*, 2001]. For site 1082 however, we performed cycles analyses in time slices and found quite similar maxima in our spectra of HARS and in the spectral energy of density logs. Concordantly, eccentricity cycles prevail since 1.5 Ma, and before 2.6 Ma, whereas obliquity cycles are more amplified between 2 and 2.6 Ma. Since our results are in good agreement with the study of *Gorgas et al.* [2001] we consider climate driven biodiversity to generate density variations, which in turn control the reflection amplitudes.

5. Conclusion

[19] Our study shows that Milankovitch cyclicity can be detected in reflection seismic records in the form of a regular succession of HARS in time. As a cause we propose climate variations modulating the sedimentary composition and, with it, the seismic reflectivity. The computed spectra over the age of strong amplitude reflectors indicate dominating periods. Especially for the undisturbed sequences close to sites 1082, 1083 and 1084 we observe variations in reflector strength corresponding to eccentricity and obliquity modulations over the last 4.4 Ma. In the southern Cape Basin, however, we cannot observe such a distinct cyclicity of reflectors. In this region, a much lower sedimentation rate probably prevents the resolution of a fine scale reflector sequence.

[20] We suggest therefore that the cyclicity of strong amplitude reflectors might represent a tool for dating seismic records in areas where no drill site data are available, but where deposition was continuous, undisturbed and of a reasonably high rate.

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