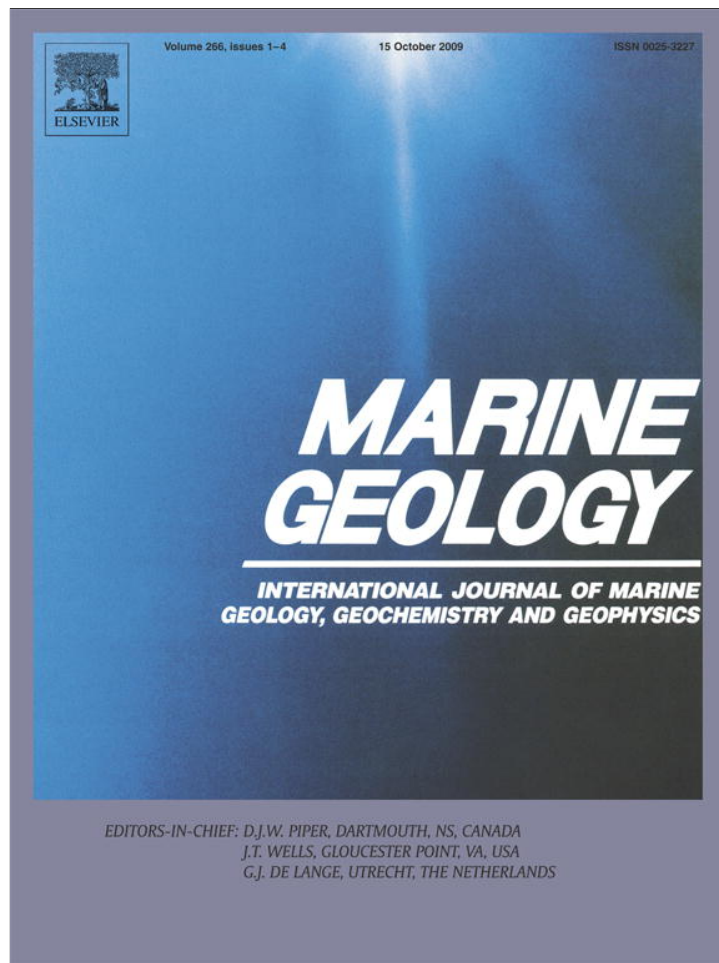


Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

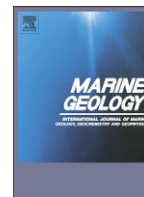
In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/copyright>



Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margeo

Terrigenous sediment export from the western margin of South Africa on glacial to interglacial cycles

John S. Compton*, James G. Wiltshire

Department of Geological Sciences, University of Cape Town, Rondebosch 7700 South Africa

ARTICLE INFO

Article history:

Received 15 April 2009

Received in revised form 26 August 2009

Accepted 30 August 2009

Available online 11 September 2009

Communicated by J.T. Wells

Keywords:

sea level

shelf export

slope

continental margin

glauconite

internal tides

ABSTRACT

Similar to many shelves globally, Pleistocene terrigenous sediment deposition on the western shelf of South Africa is strongly influenced by high-amplitude sea-level fluctuations over glacial to interglacial climate cycles. Here, variations in the glauconitic quartzose sand and terrigenous mud content of gravity cores from the western slope of South Africa are used to evaluate the dynamics of shelf sediment export over climate cycles of the last 450 kyr. Calcareous ooze on the slope contains a mean of 0.2 to 8 wt.% glauconitic quartzose sand derived from erosion of Neogene outer shelf sediments and 13 to 40 wt.% terrigenous mud sourced from the Orange River. Quartz sand content on the slope increases during glacial periods and is sharply reduced across glacial terminations and throughout interglacial highstands. Relative sea-level changes on the margin estimated from the quartz sand content on the slope are consistent with the timing, but not amplitude, of proposed eustatic sea-level records. A possible mechanism of sand erosion on the outer shelf is the vertical mixing forced by internal tides which may intensify over the shelf break as sea level is lowered during glacials. Turbidites are rare and bottom currents are generally capable of suspending mud but not sand except locally along the margin. Estimated variations in the bulk sedimentation rate and terrigenous mud mass accumulation rate on the slope suggest that export of terrigenous mud off the shelf during glacial lowstands is transported beyond the slope at intermediate and deeper water depths to the Southern Ocean.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

Continental margins comprise the critical interface between terrestrial and marine realms through which much of the sediment eroded from land must pass in its transfer to the deep sea. Transport of terrigenous sediment from the shelf to the slope is a complex function of sediment supply, hydrodynamics and morphology of the margin (Nittrouer and Wright, 1994). The dissipation of wave and tidal energy makes continental margins highly dynamic systems in which many complex physical processes are capable of resuspending and transporting sediment (Wefer et al., 2003; Nittrouer et al., 2007). During the late Pleistocene sea level has been mostly lower than today and high-amplitude (130 m) sea-level fluctuations have greatly increased the potential transfer of sediment off continental margins. However, factors other than changes in sea level can influence margin sedimentation (e.g., Sommerfield and Lee, 2004) and the flux of sediment eroded from the shelf break and the fraction of fine sediment that is transported from the shelf to the deep sea are poorly known (McCave, 2003). Sediment export from the shelf is important to understand because it can have far reaching impacts such as enhanced open ocean productivity from the lateral transport of

nutrients (Latimer and Filippelli, 2001; Lam et al., 2006; Compton et al., in press A).

The western margin of South Africa has a broad shelf with a relatively deep water (300–500 m) shelf break (Fig. 1) that underlies highly productive waters related to the Benguela Upwelling System (Shannon and Nelson, 1996). Most terrigenous sediment is delivered by the Orange River (Bremner et al., 1990) and is largely redistributed on the margin rather than accumulated in an estuary or delta (Rogers and Rau, 2006). Orange River sand is transported north along the coast to feed the Namib Desert and suspended mud is transported south to accumulate on the inner to middle shelf in a narrow ribbon of clayey silt often referred to as the mudbelt (Meadows et al., 2002; Herbert and Compton, 2007). Neogene tectonic uplift (Partridge and Maud, 2000), unusual for a passive continental margin, has resulted in limited accommodation space and a relatively thin accumulation of Pleistocene sediment on the shelf with exposure of relict Neogene sands at the shelf break (Wigley and Compton, 2006). Seismic activity on the margin is moderate with earthquakes of approximately magnitude 6 recorded in 1809 and 1969 in the Cape Town area (Theron, 1974). In the case of the narrow shelf on the eastern margin of South Africa sediment is transported by the Agulhas Current which exports nearly all of the suspended mud delivered by rivers off the shelf and exports sand along shelf structural offsets (Flemming, 1981). The lower slope of the eastern margin includes a number of quartz sand turbidites most likely triggered by earthquakes (Rau et al., 2006).

* Corresponding author. Tel.: +27 21 650 2927; fax: +27 21 650 3783.
E-mail address: john.compton@uct.ac.za (J.S. Compton).

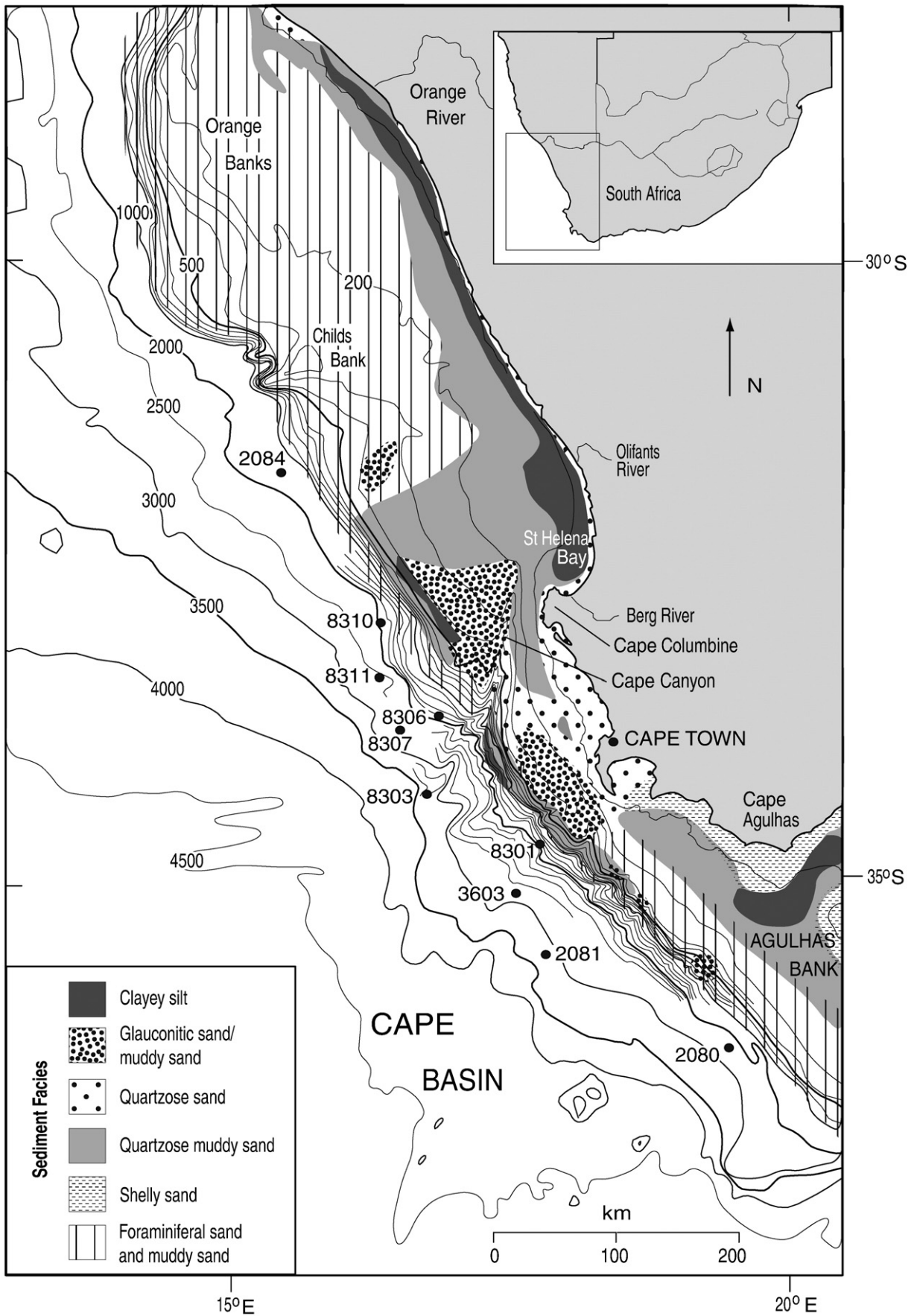


Fig. 1. Bathymetry of the western margin of South Africa in meters (Dingle et al., 1987) is shown together with core locations and the distribution of sediment facies (foraminiferal sandy mud (nannofossil ooze) extends seaward of the foraminiferal sand and muddy sand facies on the slope) (Rogers and Rau, 2006; Wigley, 2005).

In contrast, few turbidites have been observed on the western margin where the quartz sand content of the calcareous ooze on the slope is highly variable and greater during glacial than interglacial periods (Rau et al., 2002; 2006). Although interglacial mud deposits are reworked off the shelf during glacial lowstands (Compton et al., 2002), the fate of mud export off the western margin is unknown. In this paper variations in terrigenous sand and mud content of slope cores provide insights into sediment dynamics over glacial/interglacial cycles on the western margin of South Africa.

2. Methods

A total of six gravity cores recovered by the R/V *Meteor* from the continental slope in the vicinity of the Cape Canyon were analyzed (Fig. 1; Table 1). Shipboard percent reflectance (L^*) measurements were made immediately after cores were split using a Minolta CM-2002 hand-held spectrophotometer (Schneider et al., 2003). Cores were scanned for L^* data at 20 mm intervals with an image width of 850 pixels at 100 lines/cm of core length. Sediment (5 ml in volume) was sampled at 10 cm intervals on board with plastic syringes. In the lab at the University of Cape Town, the bulk sample was extruded from the syringe, dried and weighed. The bulk sediment was digested in 3% HCl acid to determine percent calcite. The acid-insoluble residue was washed through a 63 micrometer (μm) sieve to separate the non carbonate sand and mud fractions. Additional sediment (13 ml in volume) was sampled with plastic syringes at 2 cm intervals from the upper 3.5 m of core GeoB 8307-6 at the Bremen core facility. Glauconite grains were separated from quartz in the non carbonate sand fraction using a Frantz Isodynamic Magnetic Separator set to 20° pitch, 8° yaw, 0.8 A magnetic strength and near maximum vibration. Approximately 4 mg of the dominant planktonic foraminifer *Globorotalia inflata* (500–600 tests) was picked from the >250 μm size fraction for stable isotope analysis using a Finnigan Delta Plus XP mass spectrometer at UCT. Isotope data were normalized to PDB using an internal standard calibrated against NBS-19 with reproducibility better than 0.1‰ for $\delta^{18}\text{O}$.

3. Age model

An age model for the cores was developed by visual correlation of the variations in the percent reflectance (L^*) among the cores (Schneider et al., 2003) and to the L^* record of core MD96-2081 (Bertrand, 2003), which was dated along with nearby core GeoB-3603 using oxygen isotope stratigraphy (Peeters et al., 2004). The detailed results of three of the six cores analyzed are presented here on the basis of their completeness and L^* correlations (Fig. 2). The detailed results of the other three cores are presented elsewhere (Wiltshire, 2007). The $\delta^{18}\text{O}$ record of the foraminifer *Globorotalia inflata* was determined to a depth of 350 cm in core 8307 (Table 2). Although of generally low resolution, the $\delta^{18}\text{O}$ record supports the L^* correlations. For example, the glacial maxima of Marine Isotopic Stage (MIS) 2 and

MIS 6 defined in the $\delta^{18}\text{O}$ record of core 8307 correspond to the 19 ka and 130 ka L^* correlation lines, respectively (Fig. 2).

The tests (~1 mg) of the foraminifer *Globorotalia inflata* were picked from nine samples in the top 68 cm of core 8307 for Accelerator Mass Spectrometry (AMS) radiocarbon analysis (Table 3). The radiocarbon analyses were calibrated using the Fairbanks0107 calibration program (Fairbanks et al., 2005) and, in addition to the global –400 yr marine reservoir correction, includes an additional correction factor (ΔR) of –262 yr for upwelled waters on the western margin (Butzin et al., 2005). However, variations in the ΔR term are not well known and paired shell and charcoal ages from a 600 yr old coastal archaeological midden site onshore of St Helena Bay indicate a ΔR value of –150 yr (Parkington et al., 1992). Therefore, variability in ΔR may increase the uncertainty (1 σ error reported in Table 3) by as much as a factor of two.

Most radiocarbon ages are older than the modelled L^* ages. Although only whole, unaltered tests were picked for AMS radiocarbon analysis, the radiocarbon ages may be too old from the presence of reworked foraminifera, particularly during glacial lowstands (refer to Discussion below). The presence of reworked, older foraminifera is suggested by the AMS age reversal between 26 and 28 cm depth in core 8307 and an AMS age of 25 ka at 53 cm depth (Table 3) which is older than the MIS2 age of 19 ka indicated by the $\delta^{18}\text{O}$ record at 49 cm depth (Fig. 2). Because of the possibility of reworked foraminifera and for consistency among the cores, the age model of core 8307 is based only on the L^* record. The mean sedimentation rate, calculated between L^* ages, is assumed constant. Core 8306 is interpreted to have a significant hiatus in sedimentation between 50 and 70 ka (Fig. 2). Mass accumulation rates (MAR) are calculated by multiplying the mean sedimentation rate and the grams non carbonate mud/cm³ of bulk (not dried) sediment.

4. Results

Sediment recovered from the continental slope is a foraminiferal sandy mud (nannofossil ooze). Samples analyzed contain between 26 and 89 wt.% calcium carbonate (CaCO_3) with the mean (arithmetic average) CaCO_3 content of the cores ranging from 52 to 74 wt.% (Fig. 3; Table 1). The calcium carbonate is present in the sediment as nannofossil mud and sand-sized, predominantly planktonic, foraminiferal tests. Samples contain between 11 and 58 wt.% non carbonate mud with the mean non carbonate mud content of the cores ranging from 24 to 40 wt.%. Non carbonate mud and calcium carbonate are the two dominant sediment components and correlate inversely down core (Fig. 3). The non carbonate mud consists primarily of terrigenous siliciclastic grains such as clay minerals, quartz, feldspar and mica but also includes variable amounts of biogenic silica (0.1–2 wt.%) and organic matter (0.7–1.1 wt.%). Samples contain from 0.07 to 48 wt.% non carbonate sand and cores have mean non carbonate sand contents between 0.5 and 8 wt.%. The non carbonate sand fraction of samples consists of quartz and between 2.3 and 64 wt.% glauconite with cores having mean non carbonate sand glauconite contents

Table 1
Location and mean sediment composition (range in brackets) of slope cores. non carb = non carbonate (terrigenous) fraction. MD96-2080/2084 data from Rau et al. (2006) and J Rogers (unpubl. data).

Core	Lat °S	Long °E	Water depth (m)	% CaCO_3	% non carb mud	% non carb sand	% glauc in non carb sand	Slope gradient
MD96-2080	36°19'	19°28'	2488	76 (63–85)	18 (11–31)	6 (0.6–14)	4 (1.2–8.4)	3.3°
GeoB 8301-6	34°46'	17°42'	1951	52 (26–66)	40 (17–58)	8 (0.4–46)	12 (3.4–46)	3.3°
GeoB 8303-6	34°16'	16°47'	3445	63 (49–75)	36 (24–50)	1 (0.2–0.7)	9 (5.1–19)	1.3°
GeoB 8306-2	33°44'	16°51'	1923	67 (55–80)	29 (16–43)	4 (0.3–15)	11 (5.6–35)	2.0°
GeoB 8307-6	33°50'	16°32'	2671	74 (56–89)	24 (11–43)	2 (0.2–7)	18 (6.7–63)	1.5°
GeoB 8310-2	32°55'	16°23'	1994	65 (50–79)	35 (20–49)	0.6 (0.07–2.5)	14 (2.3–57)	2.5°
GeoB 8311-2	33°21'	16°19'	2534	69 (50–83)	30 (17–50)	0.5 (0.08–2.2)	17 (4.6–64)	1.9°
MD96-2084	31°45'	15°31'	1408	87 (71–95)	13 (4–30)	0.2 (0.02–1.0)	Not determined	0.7°

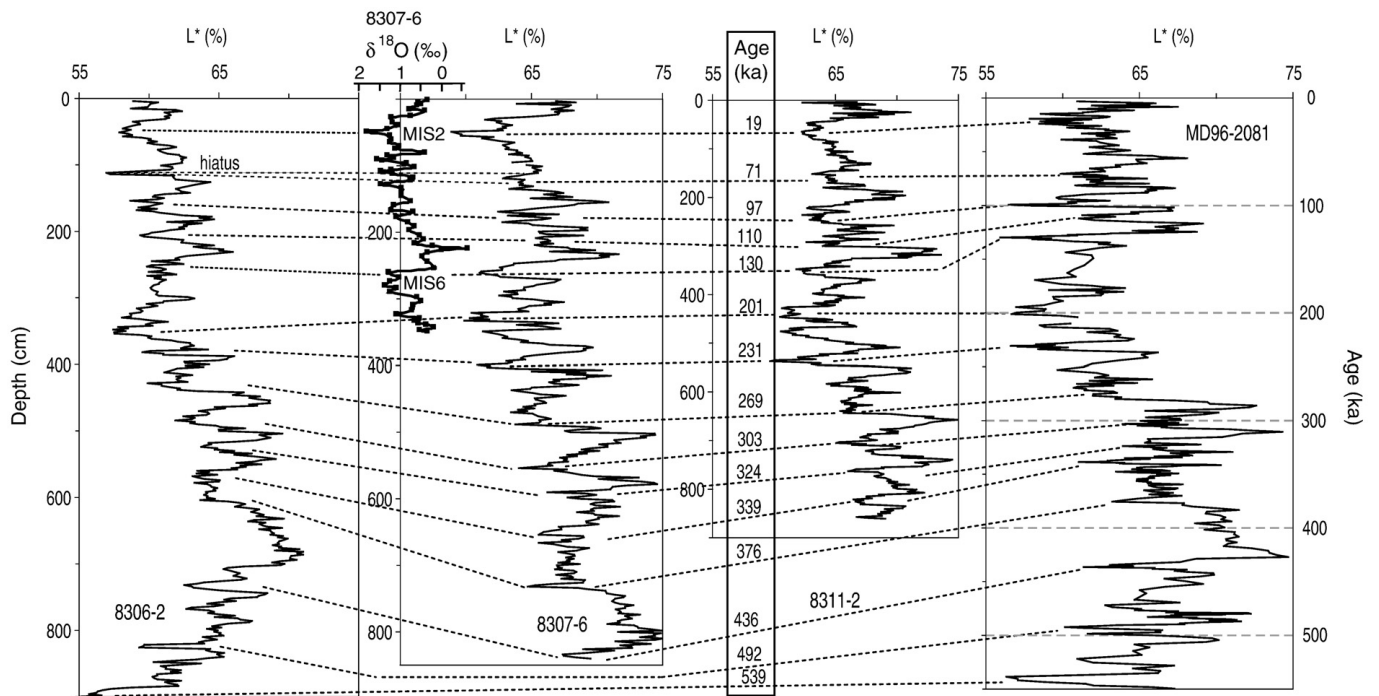


Fig. 2. L^* (% reflectance) records of GeoB cores 8306-2, 8307-6 and 8311-2, as well as the $\delta^{18}\text{O}$ record of core 8307-6 (Table 2), are plotted against core depth and correlated to the L^* record of core MD96-2081 (Bertrand, 2003) plotted against age (Peeters et al., 2004). The ages (ka) of the correlation lines are shown, as well as an interpreted hiatus between 50 and 70 ka at 110 cm depth in core 8306.

Table 2
Isotope composition of the foraminifer *G. inflata* from core GeoB 8307-6.

Depth (cm)	$\delta^{18}\text{O}$ (‰) PDB	$\delta^{13}\text{C}$ (‰) PDB
1	0.79	1.4
5	1.01	1.4
8	0.94	1.4
10	1.04	1.4
16	1.24	1.2
18	0.85	1.0
26	1.22	0.7
28	1.69	1.0
36	1.64	0.9
40	1.52	1.1
45	1.76	0.9
49	2.29	1.1
55	1.70	0.9
61	1.69	1.0
66	1.72	1.0
71	1.47	1.0
75	1.59	1.1
81	0.87	1.0
85	1.77	1.2
88	1.62	1.1
91	2.03	1.3
93	1.90	1.2
96	1.31	1.1
99	1.37	1.0
103	1.13	1.0
106	1.69	1.0
108	1.95	1.0
111	1.88	1.0
113	1.65	0.9
118	1.13	0.9
123	1.19	1.0
128	1.94	1.1
135	1.43	1.1
141	1.42	1.2
147	1.43	1.2
155	1.19	0.9
161	1.60	0.9
168	1.67	1.1
171	1.14	1.1
178	1.56	1.1
186	1.28	1.1
192	1.10	1.0
198	1.23	1.0
206	0.98	0.8
211	0.89	0.9
218	1.12	1.0
221	0.68	1.0
225	-0.20	0.7
228	0.45	1.0
231	0.80	0.9
237	0.92	0.7
245	0.78	0.2
255	0.63	0.4
261	1.73	0.7
268	1.49	0.2
275	1.72	0.4
280	1.84	0.6
285	1.56	0.7
290	1.71	0.7
298	1.06	0.7
305	0.96	0.7
311	1.14	0.6
318	1.18	0.5
325	1.55	0.8
331	0.99	1.0
335	1.10	1.0
338	1.01	1.0
340	0.84	1.0
345	0.64	0.9
348	1.00	0.9
350	0.79	1.0

Table 3

Calibrated AMS radiocarbon analyses and L^* ages for core GeoB-8307. CAMS: Centre for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory (California, USA). Sample 113292 from multicore GeoB 8307-5.

CAMS #	Sample depth (cm)	Radiocarbon age	Error +/-	Calibrated age ^a	1 σ	L^* age
113292	5	2040	30	1689	40	1938
113293	13	4415	35	4708	85	5039
121566	16	7850	35	8391	18	6202
121567	26	12,045	40	13,639	54	10,078
121568	28	11,525	40	13,096	53	10,853
121569	36	15,955	45	18,882	79	13,953
121570	45	18,430	60	21,620	134	17,442
113295	53	21,200	140	25,042	215	21,162
121571	63	25,710	130	30,631	181	26,568
121572	68	27,370	160	32,422	229	29,270

^a Refer to text.

ranging from 9 to 18 wt.%. The quartz occurs as angular to sub angular very fine sand whereas the glauconite occurs as sub angular to well rounded very fine to fine sand. There is a positive correlation between quartz and glauconite sand contents ($r^2 = 0.6-0.8$). Variations in the non carbonate sand content correlate to the marine oxygen isotope record with all cores analyzed showing a similar pattern: quartz and glauconite sand contents are low during interglacial periods and high during glacial periods (Fig. 3). Sedimentation rates range from 1 to 4.4 cm/kyr and the MAR of non carbonate mud ranges from 0.1 to 1.0 g/cm²/kyr; neither correlate to the marine oxygen isotope record (Fig. 3).

5. Discussion

5.1. Source of quartz and glauconite sand on the slope

The texture and distribution of quartz and glauconite sand grains on the slope indicate that they are derived primarily from erosion of relict deposits exposed on the outer shelf and shelf break (Figs. 1 and 4). The very fine quartz sand recovered from the slope is similar in texture to the very fine quartz that constitutes the bulk of the quartzose muddy sand facies that occurs on the shelf and extends out onto the uppermost slope. The quartzose muddy sand facies in the vicinity of the Cape Canyon is Pliocene in age and contains minor amounts (<5 wt.%) of biogenic calcite and glauconite (Wigley and Compton, 2006). Glauconite sand recovered from the slope has a finer mean grain size but is otherwise similar in texture to glauconite-rich deposits on the outer shelf. Glauconite is a marine authigenic mineral that is concentrated on the outer shelf in relict Pleistocene sandy lag deposits some of which contain >90 wt.% glauconite (Birch, 1979; Wigley and Compton, 2006; 2007). A shelf source is supported by the decrease in the mean quartz and glauconite sand content with increasing water depth down slope north of the Cape Canyon with 4 wt.% at 1923 m (core 8306), 2 wt.% at 2671 m (core 8307) and 1 wt.% at 3445 m (core 8303) (Fig. 4). The predominance of quartz to glauconite sand on the slope reflects the limited distribution of glauconite-rich sand on the outer shelf (Fig. 1) as well as the larger mean grain size of glauconite (fine to medium sand) compared to quartz (very fine sand). The high relative mean abundance (4–18 wt.%) of glauconite in the non carbonate sand fraction of the cores and the correlation of glauconite and quartz content exclude inner shelf beach, wind blown or ice rafted sand as a significant source of sand on the slope as none of these sources contains > 1 wt.% glauconite.

Variations in the amount of quartz and glauconite sand among the cores of this study and adjacent cores MD96-2080 and 2084 (Rau et al., 2002; 2006) correspond to the water depth and location of the cores in relation to the sediment facies distribution and bathymetric gradients of the margin (Fig. 1; Table 1). The greatest mean quartz and glauconite sand content is found in cores 8301 (8 wt.%) and 2080

(6 wt.%) located south of the Cape Canyon at the base of the steep (3.3°) upper slope where glauconitic sand and muddy sand are exposed on a relatively narrow shelf and quartzose muddy sand is exposed on the shelf break and the uppermost slope (Fig. 1). The mean quartz and glauconite sand content at the base of the upper slope (2000 m water depth) progressively decreases north of the Cape Canyon with 4 wt.% in core 8306, 0.6 wt.% in core 8310 and 0.17 wt.% in core 2084. This northward decrease in quartz and glauconite sand corresponds to a broadening of the shelf, where the outer shelf is draped by foraminifer sand and muddy sand of low quartz and glauconite sand content (Rogers and Rau, 2006), and a decrease in the upper slope gradient from 2.5° immediately north of the Cape Canyon to 0.7° south of Childs Bank.

5.2. Slope quartz sand content and changes in sea level

The correlation of quartz and glauconite sand content to the marine oxygen isotope record (Fig. 3) suggests that sand export onto the slope is primarily related to glacial/interglacial sea-level fluctuations. The correlation is supported by the similarity observed for the cores in this study dated by the L^* method and core 2080 dated by oxygen isotope stratigraphy (Rau et al., 2006). There is a general pattern of increasing sand content in the transition to glacial periods and an abrupt decrease at glacial terminations (Fig. 3). For example, in cores 8307 and 8311, the gradual increase in sand content corresponds to the transition from MIS11 interglacial to MIS10 glacial and from MIS7 interglacial to MIS6 glacial, and the sand content decreases abruptly with the rapid rise in sea level from MIS10 glacial to MIS9 interglacial and MIS6 glacial to MIS5 interglacial. Although most variations in the non carbonate sand content correlate with glacial/interglacial cycles within the resolution of the age model, there are exceptions. For example, all three cores have relatively small amounts of sand in the transition from MIS9 interglacial to MIS8 glacial with an abrupt increase in eroded sand occurring only during the MIS8 glacial maximum. In some core intervals the increase in sand content occurs during relative highstands (core 8307 at 195 ka) or marine transgressions (core 8307 at 290 ka). These exceptions may reflect uncertainty in the age model or unusual sand export events unrelated to sea level.

The significance of sea-level fluctuations on quartz sand export off the shelf can be evaluated by using the quartz sand content on the slope to estimate changes in relative sea level. Changes in relative sea level are estimated based on the difference in sand content during the Eemian (MIS5e; c. 121 ka) when sea level was 5 m higher than today and the preceding glacial maximum of MIS6 (c. 134 ka) when sea level was approximately 127 m lower than today (Waelbroeck et al., 2002). Comparison of relative sea level calculated for the three cores of this study (Fig. 5) to sea-level records derived from the oxygen isotope record (Waelbroeck et al., 2002) and salinity changes in the Red Sea (Siddall et al., 2003; 2005) indicates general agreement with the timing, but not the amplitude, of sea-level changes. For example, sea-level lowstands are over estimated for MIS8, 10 and 12 glacial periods and underestimated for the MIS2 glacial in cores 8306 and 8307, and over estimated for the MIS2 and 4 glacial periods in core 8311 (Fig. 5). The lack of agreement in the amplitude reflects variations in the total sand exported, which is determined by a number of complex factors such as margin bathymetry, sand supply (climate, erosion) and hydrodynamics (Nittrouer and Wright, 1994). In a high-resolution study of sand export since the Last Glacial Maximum (MIS2) on the California margin, the greatest amount of sand export occurred during the marine transgression rather than during the LGM lowstand perhaps because of increased sand supply from transgressive reworking of upslope deposits or changes in river discharge related to climate (Sommerfield and Lee, 2004). Therefore, although the export of sand from the western margin of South Africa is largely related to changes in sea level, the total amount of sand

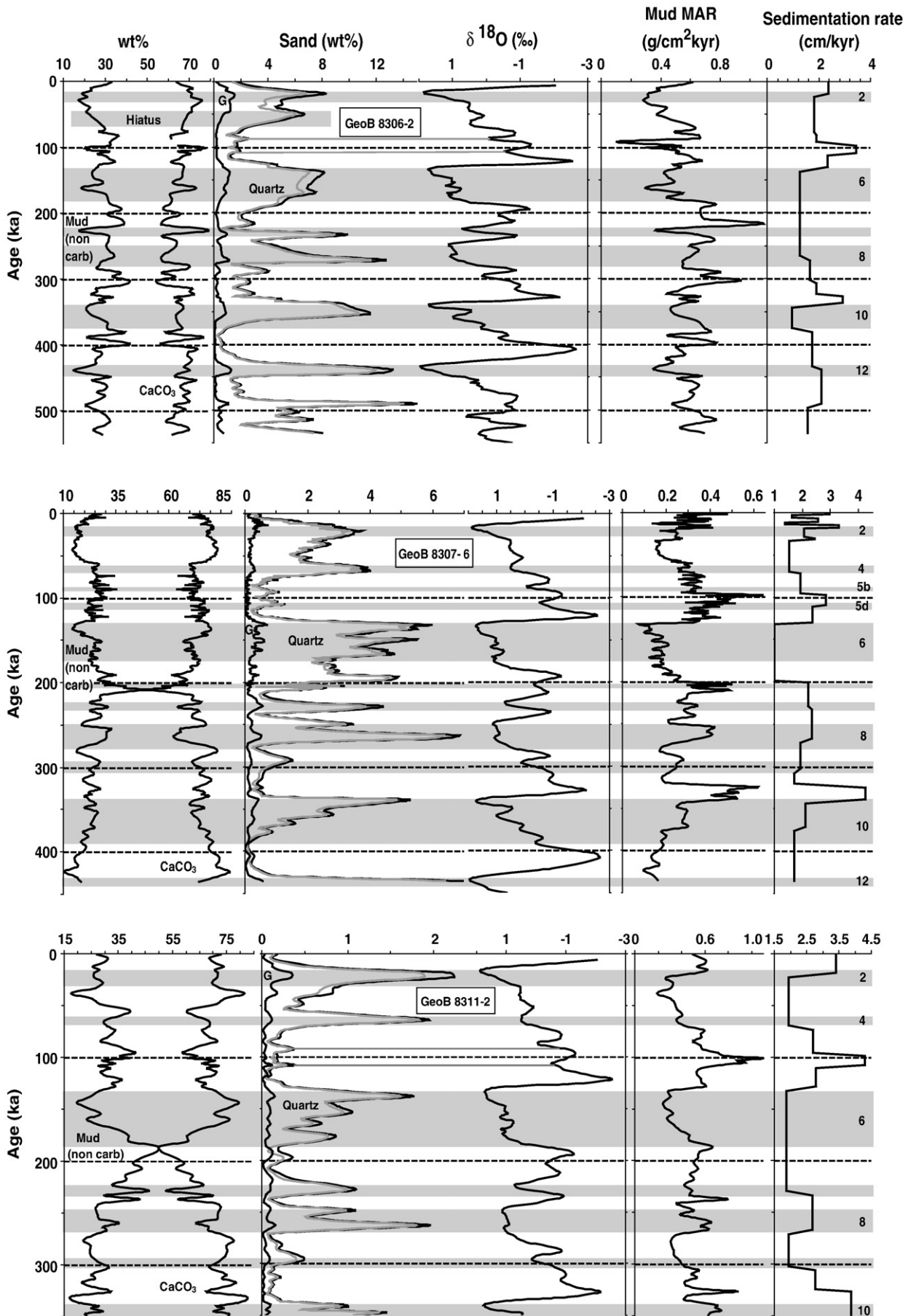
exported is highly variable and likely influenced by local variations in bathymetric features, ocean currents and the sediment facies of sand source areas.

5.3. Mechanisms for sand export onto the slope

How is the correlation of sand export with sea level explained? There are many processes, several of which are not well understood, on continental margins that could potentially erode sand off the shelf (Wefer et al., 2003; Nittrouer et al., 2007). The physical dynamics of the western margin of South Africa are generally understudied but there exist enough present-day measurements to evaluate possible mechanisms of sand export to the slope. Here it is proposed that the principal hydrodynamic force that erodes shelf sand onto the slope is the dissipation of internal tide energy whose position relative to the shelf break shifts in response to changes in sea level. Internal tides can produce sufficient bottom shear velocities to prevent fine sediment deposition at the shelf break (Cacchione et al., 2002) and have been documented off Namibia to generate vertical displacements in the temperature structure of 100–150 m adjacent to the shelf break at 450 m water depth (Monteiro et al., 2005). Internal tides generate shear stresses capable of fine sediment resuspension inshore and offshore of the shelf break on the Namibian margin and, although not yet measured, are thought to extend south of Namibia along the western margin of South Africa (Monteiro et al., 2005). The vertical movement associated with internal tides may suspend and transport bottom sediment downslope.

Variations in sand supply from rivers related to climate change appear less significant than the facies distribution and bathymetry of the western margin because the shelf is broad and generally starved of terrigenous sand. The present interglacial surface sediment facies distribution on the margin is largely similar to that observed elsewhere with a high-energy sand belt along the inner shelf, a mudbelt on the mid shelf and a largely nondepositional, relict outer shelf (e.g., Emery, 1952). The shelf is generally starved of quartz sand because most sand carried by the Orange River is transported north of the Orange River by longshore drift and by southerly winds to the Namib Desert. The arid western margin has small ephemeral rivers between the Orange and Olifants rivers and the sand discharge of the Olifants and Berg rivers is small and mostly retained on the inner shelf. In contrast, the suspended mud load of the Orange River is carried out onto the prodelta and south by the poleward undercurrent to infill progressively the inner to middle shelf wave-cut knickpoint (Bremner et al., 1990; Herbert and Compton, 2007). Major storm events with long-period waves may resuspend bottom sediment to water depths as great as 200 m (Komar et al., 1972) and the poleward undercurrent flowing at 4.6–5.7 cm/s (Nelson, 1989) transports the finer mud (clay) fraction south and off the shelf as indicated by the winnowed, silt-rich mudbelt deposit (Herbert and Compton, 2007). However, the shelf break occurs at water depths too deep (400–500 m) to be eroded by storm waves even during glacial maxima.

The measured flow velocities of bottom water currents are generally below those needed to suspend muddy sand, but sediment suspended by internal tides or storm waves may be transported off the shelf by south (poleward undercurrent) and cross-shelf (Ekman veering) bottom currents (Shannon and Nelson, 1996). Bottom currents together with internal tides appear to sustain an erosional outer shelf to shelf break between water depths of 200 and 500 m, and an upper slope mud line, the transition from muddy sand to sandy mud, at water depths of between 500 and 1800 m (Fig. 4). The available bottom current data from current meters placed at intervals along the 1000 m contour from Lüderitz (225 km north of the Orange River mouth) to Cape Point indicate an overall poleward flow with a slight off-shelf component along with frequent events of current slowing and reversals over periods of 2 to 3 days (Nelson, 1989). A current meter placed at 3000 m water depth in the Cape Basin



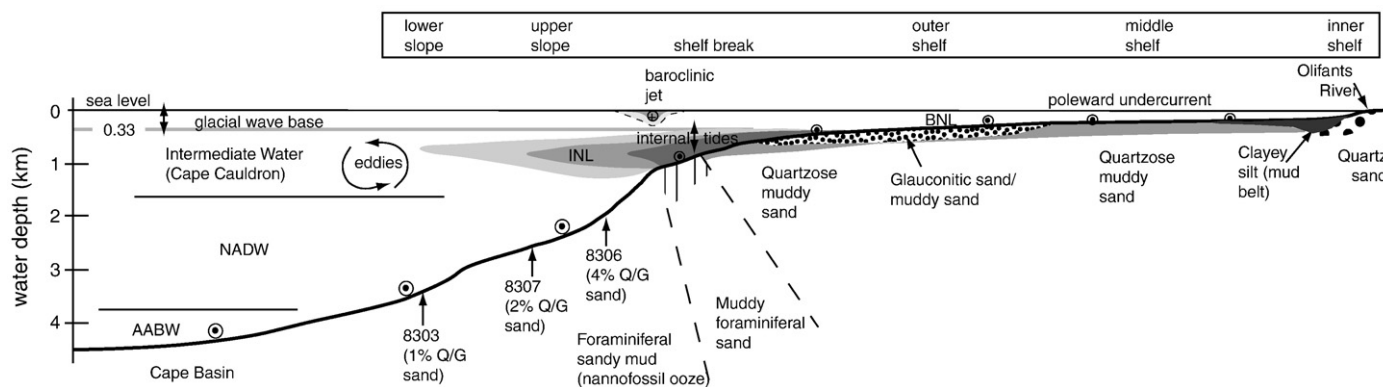


Fig. 4. Bathymetric profile across the margin from the Olifants River mouth to the Cape Basin which shows the distribution of sediment facies (subsurface depth not to scale) and ocean currents on the margin (all bottom waters flow south). Maximum storm wave base during glacial lowstands is approximately 330 m below present-day sea level. Internal tides may extend from 200 to 500 m water depth during the present interglacial. Baroclinic jet flows north with velocity decreasing with water depth and poleward undercurrent flows south over the shelf (Shannon and Nelson, 1996). Fine sediment is suspended in bottom nepheloid layers (BNL) (Swart, 2008) and may extend off the shelf as intermediate nepheloid layers (INL) as documented off Namibia (Inthorn et al., 2006) and northern California (Sommerfield et al., 2007).

recorded an average poleward current speed of 2.1 cm/s running parallel to the local bathymetry. Poleward flowing bottom currents can be influenced by bathymetry and can be exceptionally strong off Cape Columbine (16.1 cm/s) with the potential to erode the upper slope locally. However, most cores in this study show no correlation or only a slight negative correlation between terrigenous mud and sand contents suggesting that winnowing of mud by bottom currents on the slope was relatively minor. Therefore, variations in quartz sand content on the slope do not appear to result from an increase in bottom current flow velocities during glacial periods.

The high glauconite to quartz sand ratio on the slope during highstands, with glauconite constituting 64 wt.% of the total non carbonate sand in some samples (Fig. 3), suggests that the small amount of sand exported during interglacial periods is largely sourced from glauconite-rich outer shelf deposits. Lowering of sea level during glacial periods shifts internal tide forces seaward more directly over exposures of the quartzose sand facies at the shelf break. The very fine sand is more easily suspended than the coarser outer shelf glauconitic sand and is situated on or adjacent to the steep upper slope gradient to facilitate downslope transport (Fig. 4). The result is a large increase in the erosion of very fine quartz sand, primarily from the shelf break, onto the slope during glacial lowstands. Lowering of sea level may also result in the seaward transport of inner shelf sand onto the middle or outer shelf, but the low quartz sand supply and the broad shelf limit significant transport of inner shelf sand beyond the shelf break throughout glacial to interglacial cycles.

The export of sand off the shelf on many margins is primarily through downslope gravity flows such as turbidity currents with infrequent but significant sand transport down submarine canyons (e.g., Wynn et al., 2000). Downslope gravity flow deposits (debris flows, turbidity currents) are rarely recovered in Pleistocene cores from the western margin of South Africa (Rau et al., 2006; Wiltshire, 2007) despite moderate seismicity. The few turbidites on the western margin, in contrast to the eastern margin, may result from a broad, sand-starved shelf cut by few large submarine canyons and relatively low magnitude earthquakes (Rau et al., 2006). The head of the Cape Canyon is located 50 km offshore on the middle and outer shelf. The canyon cuts into Cretaceous sediments and the medium to coarse quartzose sand and sandy gravel recovered from the canyon floor (Wigley, 2005) indicate high-energy flows within the canyon. In addition to gravity flows such as turbidity currents, erosion of the canyon may be enhanced by the focused dissipation of internal tide

and wave energy in response to the steep bathymetry of the canyon walls (Shannon and Nelson, 1996). Core 8303 located near the terminus of the Cape Canyon is capped by a quartzose sand-rich layer containing 17 wt.% quartz sand (Wiltshire, 2007). This sand-rich layer is interpreted to be a canyon-derived turbidity current which cut an erosional hiatus down to sediment 28 kyr old. Although the quartz sand content increases during glacial periods down core to maximum values of 1.7 wt.%, no other sand-rich layers were observed in core 8303 whose sediment record extends to 200 ka (Wiltshire, 2007). Therefore, it remains uncertain to what extent the Cape Canyon has served as a conduit of sand transport off the margin during the late Pleistocene.

5.4. Terrigenous mud export off the shelf

Most of the terrigenous mud on the margin is sourced from the Orange River, transported south in repeated suspension-transport-deposition cycles by the poleward undercurrent and across the shelf by Ekman veering in the bottom boundary layer (Smith and Long, 1976; Drake and Cacchione, 1985) during which much of the finer mud is winnowed off the shelf. Equatorward flowing baroclinic jets result in shelf-edge upwelling and are well defined offshore of Cape Columbine (Bang and Andrews, 1974; Nelson, 1989). These surface equatorward jets flow well offshore of suspended river flood plumes and do not extend to the seafloor (Shannon and Nelson, 1996) and, therefore, are not likely to transport terrigenous sediment north. Some terrigenous mud is sourced from the Olifants and Berg rivers, as well as from erosion of outer shelf deposits, but these sources are negligible in comparison to the mean Holocene (pre-anthropogenic) Orange River mud flux of 5.1 million tons/yr (Compton et al., in press B).

In the present interglacial (Holocene, 11.5 ka) most terrigenous mud on the margin (72%) has accumulated on the inner to middle shelf mudbelt; only 8% of the Orange River terrigenous mud flux has accumulated on the slope and the remaining 20% has been transported beyond the margin (Compton et al., in press B). The mudbelt rests on reworked late Pleistocene sand and gravel associated with the glacial lowstand knick point between the inner and middle shelf at 130 m water depth (Compton et al., 2002). Therefore, there is no long-term accommodation space for Pleistocene mud accumulation on the shelf and most of the mud deposited during interglacial highstands is eroded off the shelf during glacial lowstands.

Fig. 3. Variation with respect to age of non carbonate mud, calcite, non carbonate sand (total, quartz and glauconite (G)) (wt.%), mass accumulation rate (MAR) of the non carbonate mud fraction and sedimentation rate of GeoB cores 8306-2, 8307-6 and 8311-2 compared to the stacked marine oxygen isotope record (Bassinot et al., 1994). Glacial marine isotope stages (MIS) are shaded and numbered.

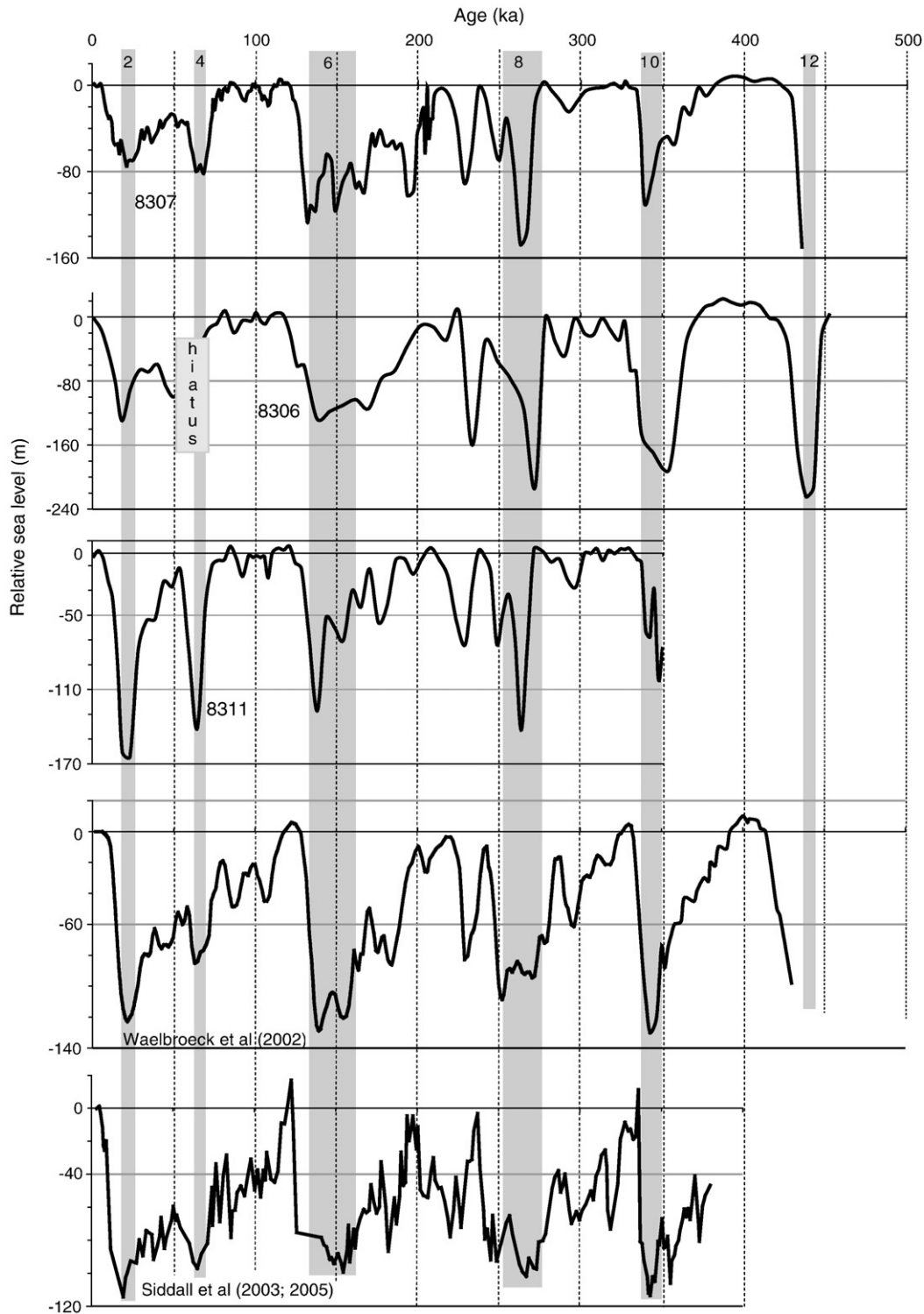


Fig. 5. Relative sea-level fluctuations derived from the quartz and glauconite sand content of GeoB cores 8307, 8306 and 8311 with respect to a +5 m sea level at 121 ka and a –127 m sea level at 134 ka are compared to the sea-level curves proposed by Waelbroeck et al. (2002) and Siddall et al. (2003; 2005). Glacial marine isotope stages (MIS) are shaded and numbered.

However, the increase in shelf export from interglacial to glacial periods is not observed to result in higher sedimentation rates or mud MAR on the slope (Fig. 3). Although the calculated sedimentation rates and mud MAR values are not known with certainty, both vary significantly and neither correlates to glacial/interglacial cycles. The highest mud MAR is more commonly associated with interglacial rather than glacial periods (Fig. 3) and this suggests that most of the

terrigenous mud exported off the shelf during glacial periods is transported beyond the margin rather than deposited on the slope.

Mud transport beyond the margin may have significant impacts on shelf exchange with the open ocean. Mud transport off the shelf occurs in part as benthic nepheloid layers (BNL) (Swart, 2008), and these BNL sediment suspensions may extend off the shelf break along isopycnal surfaces to form intermediate nepheloid layers (INL) as

observed on the Namibian (Inthorn et al., 2006) and northern California margins (Sommerfield et al., 2007). At intermediate water depths on the western margin, turbulent cyclonic and anticyclonic eddies associated with the Cape Cauldron (Boebel et al., 2003) may suspend and transport sediment off the upper slope, and North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW) current flow may suspend and transport sediment from the lower slope. The terrigenous fraction of a sediment drift (ODP site 1089) in the southern Cape Basin is derived primarily from southern Africa (Kuhn and Diekmann, 2002) and most of its Fe was deposited by sediment focusing rather than from the surface (Latimer and Filippelli, 2007). Terrigenous sediment from the margin may be dispersed to far more distal sites than the Cape Basin, transported south and east by NADW and AABW as suggested by higher terrigenous sedimentation rates observed at Southern Ocean sites during glacial periods (Latimer and Filippelli, 2001). The net movement of bottom waters at all water depths along the margin is south (Shannon and Nelson, 1996) (Fig. 4) and the transport of terrigenous mud by these southward flowing currents may ultimately supply nutrients, such as iron, at intermediate water depths to upwelling regions along the subtropical convergence zone of the Southern Ocean (Compton et al., in press A).

6. Conclusions

Quartz and glauconite sand in calcareous ooze on the slope of the western margin of South Africa is derived from the erosion of outer shelf to shelf break Neogene deposits with the presence of glauconite providing a tracer of off-shelf transport. Quartz and glauconite sand contents show a positive correlation and are most abundant in slope cores located along the steepest gradients of the upper slope below outer shelf sediment facies rich in quartz and glauconite. Quartz and glauconite sand contents increase during glacial periods and decrease during interglacial periods over the last 450 kyr. A relative sea-level record estimated from the variations in quartz sand content is consistent with the timing but not the amplitude of eustatic sea-level records proposed by others. Local variations in the amount of sand eroded from the margin related to bathymetry, facies distribution and hydrodynamics limit the application of sand content to derive the amplitude of relative sea-level changes.

Unlike many margins where terrigenous sand is transported off the shelf by downslope gravity flows, turbidites are rare on the western margin of South Africa. Turbidites are rare because the broad shelf has a deep (300–500 m) shelf break that is cut by few submarine canyons and the margin is generally sand-starved with infrequent and relatively low magnitude seismic activity. Variations in the supply of sand from the continent in response to climate variations (rainfall) appear to be small on the outer shelf region of the margin. Here it is proposed that the dissipation of internal tides, documented on the Namibian margin to the north, may be the dominant mechanism for erosion of outer shelf to shelf break deposits. Although the shelf break remains at water depths below storm wave base, energy dissipation related to internal tides is predicted to shift seaward during glacial lowstands and may increase erosion of very fine quartz sand exposed at the shelf break onto the slope. Bottom currents may reach velocities in the vicinity of the Cape Canyon to locally erode sediment but most bottom currents measured on the margin are not capable of suspending sand. The lack of significant negative correlation between terrigenous sand and mud contents suggests that the glacial increase in sand content results from a greater supply of sand to the slope rather than from concentration by winnowing of mud. Therefore, sand derived from relict Neogene deposits on the outer shelf appears to be eroded onto the slope by a combination of internal tides and bottom water currents whose energy dispersion on the margin varies in response to sea-level fluctuations.

Margin bathymetry combined with highly dynamic physical processes, such as poleward bottom water currents and large-

amplitude (130 m) sea-level fluctuations severely limit the accumulation of terrigenous mud on the western margin of South Africa over glacial/interglacial cycles during the late Pleistocene. Terrigenous mud primarily sourced from the Orange River mostly accumulates on the shelf during interglacial periods and is reworked off the shelf during glacial periods. The bulk sedimentation rate and mass accumulation rate of terrigenous mud on the slope do not correlate with glacial to interglacial cycles suggesting that, during both glacial and interglacial periods, relatively little of the terrigenous mud transported off the shelf accumulates on the slope. Bottom currents, which flow south at all water depths along the margin, may transport the mud beyond the margin and provide a potentially important lateral advective supply of suspended sediment and nutrients to the Southern Ocean.

Acknowledgements

We are grateful for the support and assistance of R Schneider (chief scientist), and the officers, crew and participants of the RV *Meteor* cruise M57-1 in the collection of the cores used in this study. This work was funded by the National Research Foundation (South Africa) and the University of Cape Town. We thank J. Rogers for providing unpublished data and R Schneider and R Zahn for comments and suggestions on an earlier version of the manuscript. The manuscript benefited from the comments of H. de Haas and an anonymous reviewer.

References

- Bang, N.D., Andrews, W.R.H., 1974. Direct current measurements of a shelf-edge frontal jet in the southern Benguela system. *Journal of Marine Research* 32 (3), 405–417.
- Bassinot, F.C., Labeyrie, L.D., Vincent, E., Quidelleur, X., Shackleton, N.J., Lancelot, Y., 1994. The astronomical theory of climate and the age of the Brunhes–Matuyama magnetic reversal. *Earth and Planetary Science Letters* 126, 91–108.
- Bertrand, P., 2003. Color reflectance of sediment core MD96-2081. <http://doi.pangaea.de/10.1594/PANGAEA.124233>.
- Birch, G.F., 1979. The nature and origin of mixed apatite/glauconite pellets from the continental shelf off South Africa. *Marine Geology* 29, 313–334.
- Boebel, O., Lutjeharms, J., Schimid, C., Zenk, W., Rossby, T., Barron, C., 2003. The Cape Cauldron: a regime of turbulent inter-ocean exchange. *Deep-Sea Research Part II* 50, 57–86.
- Bremner, J.M., Rogers, J., Willis, J.P., 1990. Sedimentological aspects of the 1988 Orange River floods. *Transactions of the Royal Society of South Africa* 47, 247–294.
- Butzin, M., Prange, M., Lohmann, G., 2005. Radiocarbon simulations for the glacial ocean: the effects of wind stress, Southern Ocean sea ice and Heinrich events. *Earth and Planetary Science Letters* 235, 45–61.
- Cacchione, D.A., Pratson, L.F., Ogston, A.S., 2002. The shaping of continental slopes by internal tides. *Science* 296, 724–727.
- Compton, J.S., Mulabisana, J., McMillan, I.K., 2002. Origin and age of phosphorite from the Last Glacial Maximum to Holocene transgressive succession off the Orange River, South Africa. *Marine Geology* 186, 243–261.
- Compton, J.S., Herbert, C., Schneider, R. Organic-rich mud on the western margin of South Africa: nutrient source to the Southern Ocean? *Global Biogeochemical Cycles*, in press A.
- Compton, J.S., Herbert, C., Hoffman, M.T., Schneider, R., Stuut, J.-B. A tenfold increase in the Orange River mean Holocene mud flux: implications for soil erosion in South Africa. *Holocene*, in press B.
- Dingle, R.V., Birch, G.F., Bremner, J.M., De Decker, R.H., Du Plessis, A., Englebrecht, J.C., Fincham, M.J., Fitton, T., Flemming, B.W., Gentle, R.I., Goodlad, S.W., Martin, A.K., Mills, E.G., Moir, G.J., Parker, R.J., Robson, S.H., Rogers, J., Salmon, D.A., Siesser, W.G., Simpson, E.S.W., Summerhayes, C.P., Westall, F., Winter, A., Woodborne, M.W., 1987. Deep-sea sedimentary environments around southern Africa (south-east Atlantic and south-west Indian Oceans). *Annals of the South African Museum* 98, 1–27 2 separate maps.
- Drake, D.E., Cacchione, D.A., 1985. Seasonal variation in sediment transport on the Russian River shelf, California. *Continental Shelf Research* 4, 495–514.
- Emery, K.O., 1952. Continental shelf sediments off southern California. *Geological Society of America Bulletin* 63, 1105–1108.
- Fairbanks, R.G., Mortlock, R.A., Chiu, T.-C., Cao, L., Kaplan, A., Guilderson, T.P., Fairbanks, T.W., Bloom, A.L., Grootes, P.M., Nadeau, M.-J., 2005. Radiocarbon calibration curve spanning 0 to 50,000 years BP based on paired $^{230}\text{Th}/^{234}\text{U}/^{238}\text{U}$ and ^{14}C dates on pristine corals. *Quaternary Science Reviews* 24, 1781–1796.
- Flemming, B.W., 1981. Factors controlling shelf sediment dispersal along the southeast African continental margin. *Marine Geology* 42, 259–277.
- Herbert, C., Compton, J.S., 2007. Geochronology of Holocene sediments on the western margin of South Africa. *South African Journal of Geology* 110, 327–338.

- Inthorn, M., Wagner, T., Scheeder, G., Zabel, M., 2006. Lateral transport controls distribution, quality, and burial of organic matter along continental slopes in high-productivity areas. *Geology* 34, 205–208.
- Komar, P.D., Neudeck, R.H., Kulm, L.D., 1972. Observations and significance of deep-water oscillatory ripple marks on the Oregon continental shelf. In: Swift, D.J.P., Duane, D.B., Pilkey, O.H. (Eds.), *Shelf Sediment Transport: Process and Pattern*. Dowden, Hutchinson and Ross, Stroudsburg, PA (USA), pp. 601–624.
- Kuhn, G., Diekmann, B., 2002. Late Quaternary variability of ocean circulation in the southeastern South Atlantic inferred from the terrigenous sediment record of a drift deposit in the southern Cape Basin (ODP Site 1089). *Palaeogeography Palaeoclimatology Palaeoecology* 182, 287–303.
- Lam, P.J., Bishop, J.K.B., Henning, C.C., Marcus, M.A., Waychunas, G.A., Fung, I.Y., 2006. Wintertime phytoplankton bloom in the subarctic Pacific supported by continental margin iron. *Global Biogeochemical Cycles* 20, GB1006. doi:10.1029/2005GB002557.
- Latimer, J.C., Filippelli, G.M., 2001. Terrigenous input and paleoproductivity in the Southern Ocean. *Paleoceanography* 16, 627–643.
- Latimer, J.C., Filippelli, G.M., 2007. Sedimentary iron records from the Cape Basin. *Deep-Sea Research Part II*. doi:10.1016/j.dsr2.2007.07.022.
- McCave, I.N., 2003. Sedimentary settings on continental margins – an overview. In: Wefer, G., Billett, D., Hebbeln, D., Jørgensen, B.B., Schlüter, M., van Weering, T.C.E. (Eds.), *Ocean Margin Systems*. Springer-Verlag, Berlin, pp. 1–14.
- Meadows, M.E., Rogers, J., Lee-Thorp, J.A., Bateman, M.D., Dingle, R.V., 2002. Holocene geochronology of a continental-shelf mudbelt off southwestern Africa. *Holocene* 12, 59–67.
- Monteiro, P.M.S., Nelson, G., van der Plas, A., Mabile, E., Bailey, G.W., Klingelhoeffer, E., 2005. Internal tide–shelf topography interactions as a forcing factor governing the large-scale distribution and burial fluxes of particulate organic matter (POM) in the Benguela upwelling system. *Continental Shelf Research* 25, 1864–1876.
- Nelson, G., 1989. Poleward motion in the Benguela area. In: Neshbya, A.J., Mooers, C.N.K., Smith, R.L., Barber, R.T. (Eds.), *Poleward Flows along Eastern Ocean Boundaries, Coastal and Estuarine Studies*. Springer-Verlag, New York 34, pp. 110–130.
- Nittrouer, C.A., Wright, L.D., 1994. Transport of particles across continental shelves. *Reviews in Geophysics* 32, 85–113.
- Nittrouer, C.A., Austin, J.A., Field, M.E., Kravitz, J.H., Syvitski, J.P.M., Wiberg, P.L. (Eds.), 2007. Continental margin sedimentation, from sediment transport to sequence stratigraphy. *International Assoc. Sedimentologists, Spec. Publ. No. 37*. Blackwell Publishing, Oxford UK. 549 p.
- Parkington, J., Nilssen, P., Reeler, C., Henshilwood, C., 1992. Making sense of space at Dunefield Midden Campsite, Western Cape, South Africa. *South African Field Archaeology* 1, 63–70.
- Partridge, T.C., Maud, R.R., 2000. Macro-scale geomorphic evolution of southern Africa. In: Partridge, T.C., Maud, R.R. (Eds.), *The Cenozoic of Southern Africa*. Oxford University Press, New York, pp. 3–18.
- Peeters, F.J.C., Acheson, R., Brummer, G.-J.A., de Ruijter, W.P.M., Schneider, R.R., Ganssen, G.M., Ufkes, E., Kroon, D., 2004. Vigorous exchange between the Indian and Atlantic oceans at the end of the past five glacial periods. *Nature* 430, 661–665.
- Rau, A.J., Rogers, J., Lutjeharms, J.R.E., Giraudeau, J., Lee-Thorp, J.A., Chen, M.-T., Waelbroeck, C., 2002. A 450-kyr record of hydrological conditions on the western Agulhas Bank Slope, south of Africa. *Marine Geology* 180, 183–201.
- Rau, A.J., Rogers, J., Chen, M.T., 2006. Late Quaternary palaeoceanography record in giant piston cores off South Africa, possibly including evidence of neotectonism. *Quaternary International* 148, 65–77.
- Rogers, J., Rau, A.J., 2006. Surficial sediments of the wave-dominated Orange river delta and the adjacent continental margin off south-western Africa. *African Journal of Marine Science* 28 (3&4), 511–524.
- Schneider, R. and cruise participants, 2003. Report and preliminary results of METEOR Cruise M 57/1: Cape Town – Walvis Bay 20.01.2003–08.02.2003, Bremen, 123 pp.
- Shannon, L.V., Nelson, G., 1996. The Benguela: large scale features and processes and system variability. In: Wefer, G., Berger, W.H., Siedler, G., Webb, D.J. (Eds.), *The South Atlantic: Present and Past Circulation*. Springer-Verlag, Berlin Heidelberg, pp. 163–210.
- Siddall, M., Rohling, E.J., Almogi-Labin, A., Hemleben, C., Meischner, D., Schmelzer, I., Smeed, D.A., 2003. Sea-level fluctuations during the last glacial cycle. *Nature* 423, 853–858.
- Siddall, M., Smeed, D.A., Hemleben, C., Rohling, E.J., Schmelzer, I., Peltier, W.R., 2005. Understanding the Red Sea response to sea level. *Earth and Planetary Science Letters* 225, 421–434.
- Smith, J.D., Long, C.E., 1976. The effects of turning in the bottom boundary layer on continental shelf sediment transport. *Société Royale des Sciences de Liège Mémoires* 10, 369–396.
- Sommerfield, C.K., Lee, H.J., 2004. Cross-shelf sediment transport since the Last Glacial Maximum, southern California margin. *Geology* 32, 345–348.
- Sommerfield, C.K., Ogston, A.S., Mullenbach, B.L., Drake, D.E., Alexander, C.R., Nittrouer, C.A., Borgeld, J.C., Wheatcroft, R.A., Leithold, E.L., 2007. Oceanic dispersal and accumulation of river sediment. In: Nittrouer, C.A., Austin, J.A., Field, M.E., Kravitz, J.H., Syvitski, J.P.M., Wiberg, P.L. (Eds.), *Continental margin sedimentation, from sediment transport to sequence stratigraphy*. Int. Assoc. Sedimentol. Spec. Publ. No. 37. Blackwell Publishing, Oxford UK, pp. 157–212.
- Swart, N.C., 2008. Lateral carbon export from the southern Benguela upwelling system. Unpublished MSc thesis, Department of Oceanography, University of Cape Town, 177 p.
- Theron, J.N., 1974. Seismic history of the Southwest Cape Province. *Geological Survey (South Africa). Seismological Series* 4, 9–15.
- Waelbroeck, C., Labeyrie, L., Michel, E., Duplessy, J.C., McManus, J.F., Lambeck, K., Balbon, E., Labracherie, M., 2002. Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. *Quaternary Science Reviews* 21, 295–305.
- Wefer, G., Billett, D., Hebbeln, D., Jørgensen, B.B., Schlüter, M., van Weering, T.C.E. (Eds.), 2003. *Ocean Margin Systems*. Springer-Verlag, Berlin. 495 p.
- Wigley, R.A., 2005. Sedimentary facies from the head of the Cape Canyon: insights into the Cenozoic evolution of the western margin of South Africa. Unpublished PhD thesis, Department of Geological Sciences, University of Cape Town, 289 p.
- Wigley, R.A., Compton, J.S., 2006. Late Cenozoic evolution of the outer continental shelf at the Head of the Cape Canyon, South Africa. *Marine Geology* 226, 1–23.
- Wigley, R., Compton, J.S., 2007. Oligocene to Holocene glauconite–phosphorite grains from the Head of the Cape Canyon on the western margin of South Africa. *Deep-Sea Research Part II* 54, 1375–1395.
- Wiltshire, J.G., 2007. Late Quaternary sediments on the continental slope off Cape Columbine: variations in off-shelf transport related to glacial driven sea-level fluctuations. Unpublished MSc thesis, Department of Geological Sciences, University of Cape Town, 138 p.
- Wynn, R.B., Masson, D.G., Stow, D., Weaver, P., 2000. The northwest African slope apron: a modern analogue for deep-water systems with complex seafloor topography. *Marine Petroleum Geology* 17, 253–265.