Geochronology of Holocene sediments on the western margin of South Africa

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ABSTRACT

The western continental margin of South Africa is a dynamic environment. It is a site of intense upwelling and high productivity, as well as a repository for large quantities of terrigenous sediment delivered by wind and rivers, most notably by the Orange River. Essential to understanding the complex dynamics of sedimentation on this margin is an accurate, robust age model. Here we present 32 radiocarbon ages of mollusc shells and foraminifera tests recovered from Holocene organic-rich mud deposits on the middle-inner shelf (the mudbelt), and from calcareous ooze on the continental slope. Sedimentation rates of between 0.25 and 2.4 mm/year are recorded in the Holocene mudbelt, whereas slope cores have average sedimentation rates of between 0.04 and 0.22 mm/year. Low sedimentation rates in the mudbelt correspond to increases in the coarse-silt fraction, associated with periods of winnowing. In the north, the mudbelt sediments have been deposited since 11 thousand years before present (11 ka), whereas sedimentation in the southern mudbelt was initiated at around 2 ka. From changes in sedimentation rate and the southward younging of the deposit, we infer that the mudbelt depo-centre has shifted during the Holocene in response to changes in sea level and accommodation space on the shelf. Holocene carbonate ooze on the slope contains 20 to 40 weight % terrigenous material, indicating significant off-shelf transport. Onshore Orange River palaeoflood deposits provide a terrestrial record spanning 12 ka. Linking high-resolution continental and marine records will allow for the comparison of oceanographic and climatic changes in southern Africa during the Holocene.

Introduction

An elongate, ribbon- or belt-shaped deposit of terrigenous mud occurs along the middle-inner shelf that parallels the western shoreline of southern Africa from 20 km north of the Orange River mouth to St Helena Bay, 500 km south (Figure 1). The mud deposit is Holocene in age (Birch, 1977; Rogers, 1977; Birch *et al.*, 1991; Rogers and Bremner, 1991; Mabote *et al.*, 1997; Meadows *et al.*, 1997; 2002; Rogers and Rau, 2006) and has been variably referred to as the West Coast mudbelt, the Orange River mudbelt, and the Namaqualand mudbelt (Birch *et al.*, 1986). Here it is referred to simply as the mudbelt.

The mudbelt provides a sediment record of unusually high resolution for southern Africa and is therefore of interest in determining Holocene climate change, as well as in documenting the impact of recent human activity on soil erosion. Terrestrial Holocene records exist for South Africa from the Cango Caves (Talma and Vogel, 1992), Tswaing crater (Partridge *et al.*, 1997), Makapansgat caves (Holmgren *et al.*, 2003) and the Cederberg region (Scott and Woodbourne, 2007), as well as from dune deposits along the West Coast (Franceschini and Compton, 2006; Chase and Thomas, 2006). These records indicate that the southern African climate was variable over the Holocene, with differences in regional climatic response patterns (Scott and Lee-Thorp, 2004). The offshore mudbelt records changes in terrigenous sediment input and margin processes, thereby linking terrestrial and marine sediment dynamics in southern Africa. Such high-resolution Holocene records are needed, in particular, from the Southern Hemisphere to document possible subtle variations in Holocene climate to compare with more abundant Northern Hemisphere records (Mayewski *et al.*, 2004).

Key to the interpretation of recovered Holocene sediment records is the development of reliable age models. Cores and surface grab samples were recovered in 1994 from the northern mudbelt from seven sites between the Orange River and the Buffels River during the HODSA (Holocene Denudation of South Africa) project (Meadows *et al.*, 1997; 2002). Bulk organic matter radiocarbon analyses were used to date sediment from the HODSA cores. In addition, one coarse sand sample, interpreted as being an aeolian deposit, from a core off the Buffels River underwent thermoluminescence dating. Gray *et al.* (2000) report two initial ^{210}Pb dates, obtained from the upper 2 m of the HODSA core off the Buffels River, which indicate recent sedimentation. The main problem experienced by Meadows *et al.* (1997; 2002) was anomalous inverted radiocarbon ages from cores near the Orange River mouth. These inverted ages were attributed to the presence of significant amounts of old, detrital soil organic matter derived from the floodplains of the Orange River. It was therefore recommended that any future study either make use of alternative material for radiocarbon dating or that a different dating method be employed.

The aim of this study is to establish a reliable age model for the mudbelt deposit and to identify similar aged sediments from the offshore continental slope and from along the Orange River, onshore. Here we present Holocene radiocarbon ages of mollusc shells from cores

doi:10.2113/gssajg.110.2-3.327

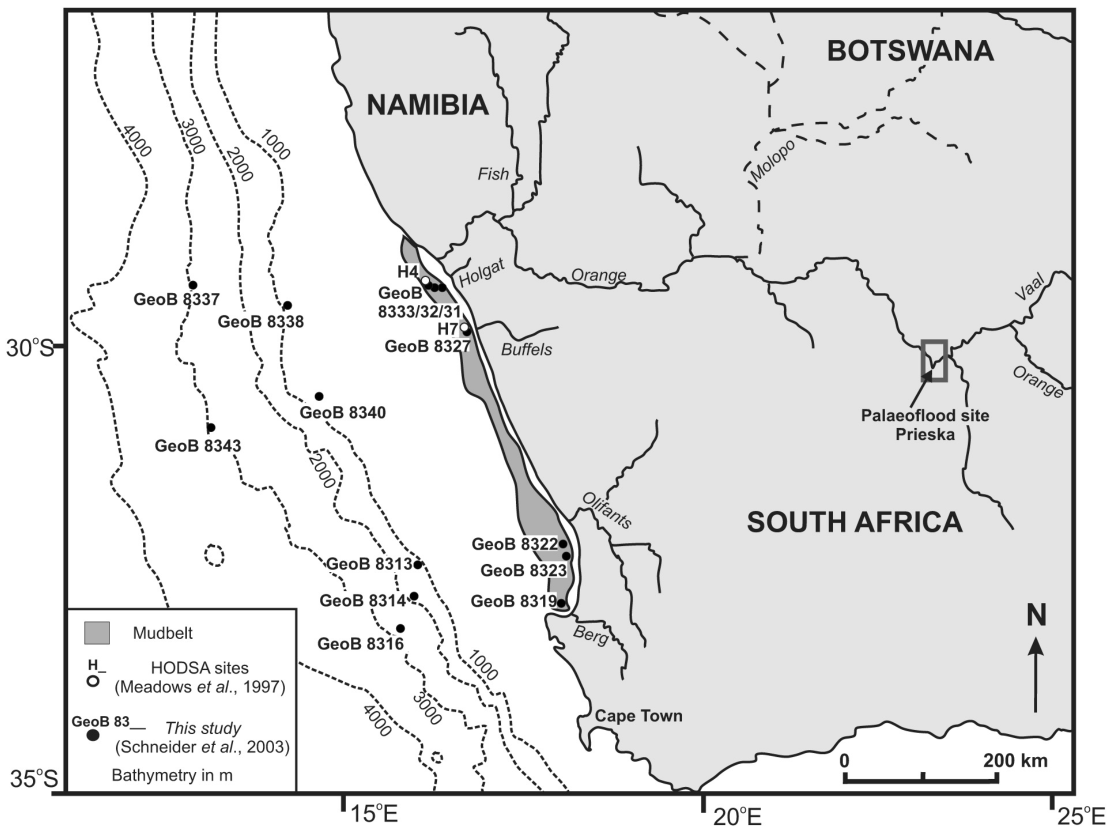


Figure 1. Map showing the distribution of core sites used in this study from the western continental margin of South Africa. The extent of the mudbelt (Rogers and Bremner, 1991), regional bathymetry (Birch, Rogers and Bremner, 1986) and location of the onshore Orange River palaeoflood deposits are also shown. St Helena Bay is located offshore of the Berg and Olifants rivers. The Cape Columbine upwelling cell is situated on the shelf offshore of cores GeoB 8319, 8322 and 8323. The Namaqualand upwelling cell is positioned offshore between the Buffels and Holgat river mouths.

of the mudbelt on the middle-inner shelf, foraminiferal tests from continental slope cores and gastropods from palaeoflood deposits of the Orange River. The radiocarbon ages are discussed in terms of ongoing research into Holocene sediment dynamics and climate change in southern Africa.

Regional setting

The Orange River is the primary source of terrigenous sediment deposited on the western margin of South Africa, with additional minor input by small, mainly ephemeral, rivers and aeolian transport (Rogers, 1977; Birch *et al*., 1991; Rogers and Bremner, 1991). Sediment delivered to the mouth of the Orange River is sorted, such that sand and gravel is transported north by wave-induced littoral drift and finer material (silt and clay) is transported southward (Rogers, 1977; Rogers and Bremner, 1991) by a weak, seasonal poleward undercurrent (Nelson, 1985; 1989; Shannon and Nelson, 1996). The mudbelt is restricted to water depths of between 40 and 140 m by high-energy waves at shallow depths and by the scouring action of poleward-moving water at greater water depths on the middle and outer shelf.

In addition to terrigenous sediment, both the continental slope and shelf are sites of calcareous and siliceous biogenic sediment deposition. The high productivity of the region (Carr and Kearns, 2003) is due to the Benguela Upwelling System that brings cold, nutrient-rich waters to the surface ocean. In the study area, two upwelling cells are of particular importance, the Cape Columbine cell and the Namaqualand cell located north of 33°S and north of 31°S, respectively. The Cape Columbine cell is strongly seasonal, whereas the Namaqualand cell is active, to a lesser or greater degree, year round (Shannon and Nelson, 1996).

Some sediment is transported off the shelf onto the slope where it is deposited in calcareous nannofossil-foraminiferal oozes (Rogers, 1977; Rogers and Bremner, 1991; Pufahl *et al.* 1998). In addition, some terrigenous sediment carried by the Orange River never makes it to the margin, but occurs in palaeoflood deposits along the middle and lower river course, preserved by the high aridity and low vegetation cover in the area (Zawada, 2000). Palaeoflood slack-water deposits consist of silty very fine sands, which settle out of suspension in back-flooded tributaries and along raised sections of the main river channels during large floods (Zawada *et al.* 1996;

Table 1. Location, water depth and length of multicores (MUC) and gravity cores (GC). "GeoB" sites are from this study (Schneider *et al.*, 2003); H4 and H7 are HODSA project core sites (Meadows *et al.*, 1997).

Core sites	Core type	Latitude °S	Longitude °E	Water depth (m)	Core length (m)
GeoB 8313	MUC	32°07'21.0"	15°56'37.8"	1090	0.20
GeoB 8314	MUC	32°29'57.0"	15°48'46.8"	1995	0.14
GeoB 8316	MUC	32°44'01.8"	15°44'01.8"	2663	0.18
GeoB 8319	MUC	32°29'44.4"	18°04'42.0"	69	0.29
GeoB 8322	MUC	31°37'13.2"	18°07'04.2"	105	0.41
GeoB 8323	GC	32°01'53.4"	18°13'17.4"	92	2.85
GeoB 8327	GC	29°42'04.8"	17°00'32.4"	88	8.60
GeoB 8331	GC	29°08'07.2"	16°42'59.4"	97	8.87
GeoB 8332	GC	29°07'39.6"	16°39'33.6"	115	8.08
GeoB 8333	GC	29°07'20.4"	16°36'52.2"	118	5.69
GeoB 8333	MUC	29°07'17.4"	16°36'52.2"	118	0.38
GeoB 8337	MUC	29°24'28.8"	13°10'39.0"	1000	0.20
GeoB 8338	MUC	29°29'55.8"	14°19'14.4"	914	0.20
GeoB 8340	MUC	30°19'02.4"	14°49'31.2"	604	0.22
GeoB 8343	MUC	30°50'54.6"	13°19'30.0"	3064	0.20
H4	GC	29°03'22.8"	16°35'09.0"	115	5.40
H7	GC	29°42'07.2"	17°00'41.4"	80	5.65

Zawada, 1997, 2000). The Orange River discharge of large Holocene palaeofloods is estimated to have ranged from 2480 m^3/s to as high as 28 000 m^3/s (Zawada *et al.*, 1996; Zawada, 2000), a discharge more than three times that of the 1988 flood (Bremner *et al.*, 1990). As the world's fourth most turbid river, and with a sediment discharge of 80.9 million tons during the 1988 flood (Bremner *et al.*, 1990), large floods are important in terms of sediment erosion along the Orange River and deposition of terrigenous mud on the western continental margin.

Methods

A suite of five gravity cores, up to 8.8 m in length, and nine multicores, up to 0.41 m in length, from the mudbelt and the upper and lower slope between St. Helena Bay and Alexander Bay, retrieved in January-February 2003 during the M57/1 *Meteor* cruise (Schneider *et al.*, 2003), were selected for this study (Figure 1, Table 1). The cores were selected such that a comparison could be made between inner shelf and lower slope sediment along a series of coast-perpendicular transects. Three cores from a coast-perpendicular transect off the Holgat River were studied to determine the east-west variation within the mudbelt.

The gravity coring device consists of a 9 m long metal pipe, lined with a 10 cm diameter PVC tube into which the sediment is recovered. Lead weight, on the order of three tonnes, at the top of the core allows the corer to penetrate the sediment under the force of gravity. The multicorer consists of a rosette of clear plastic tubes, 10 cm in diameter. The rosette is first lowered onto the sea floor and then released to recover both bottom water and surface sediment with minimum disturbance. The gravity cores were cut into one metre sections and halved onboard. These sections were then sampled at 5 cm intervals in the laboratory at the University of Cape Town. The multicores were sampled at 1 cm intervals onboard and sealed in plastic Petri dishes.

Onshore samples were collected from two palaeoflood deposits (sites F and G) along the Orange River on the farm Klein Noute, 27 km downstream of the town of Prieska (Figure 2, Table 2). At these sites, grey-

Table 2. Radiocarbon analysis of Orange River palaeoflood deposits near the town of Prieska (Figure 2). Radiocarbon ages calibrated using the Fairbanks calibration programme (Fairbanks *et al.*, 2005).

	Sample No.	Latitude °S	Longitude °E	Analytical No.	Material	Uncalib. ^{14}C age[1]	± (years)	Calibrated age[1] Mean	-1σ	+1σ	IRSL age (years)	± (years)
This study	CTH-F1	29°30'28.7"	22°38'28.8"	121498	Tomichia sp.	315	35	322	267	377	–	–
	CTH-F4	29°30'28.7"	22°38'28.8"	121499	Tomichia sp.	995	35	775	728	822	–	–
	CTH-G2	29°29'17.1"	22°38'01.3"	121500	Tomichia sp.	7765	35	8502	8460	8544	–	–
Zawada	*	29°29'10.0"	22°38'06.0"	Pta-6519	OM[2]	7060	90	7850	7757	7943	–	–
(2000)	*	29°29'10.0"	22°38'06.0"	Pta-5212	Sand	–	–	–	–	–	8400	1680

[1]Ages in years before present *i.e.* before AD 1950. Ages corrected for variations in isotopic fractionation.

[2]OM = organic matter.

*Refer to Figure 2.

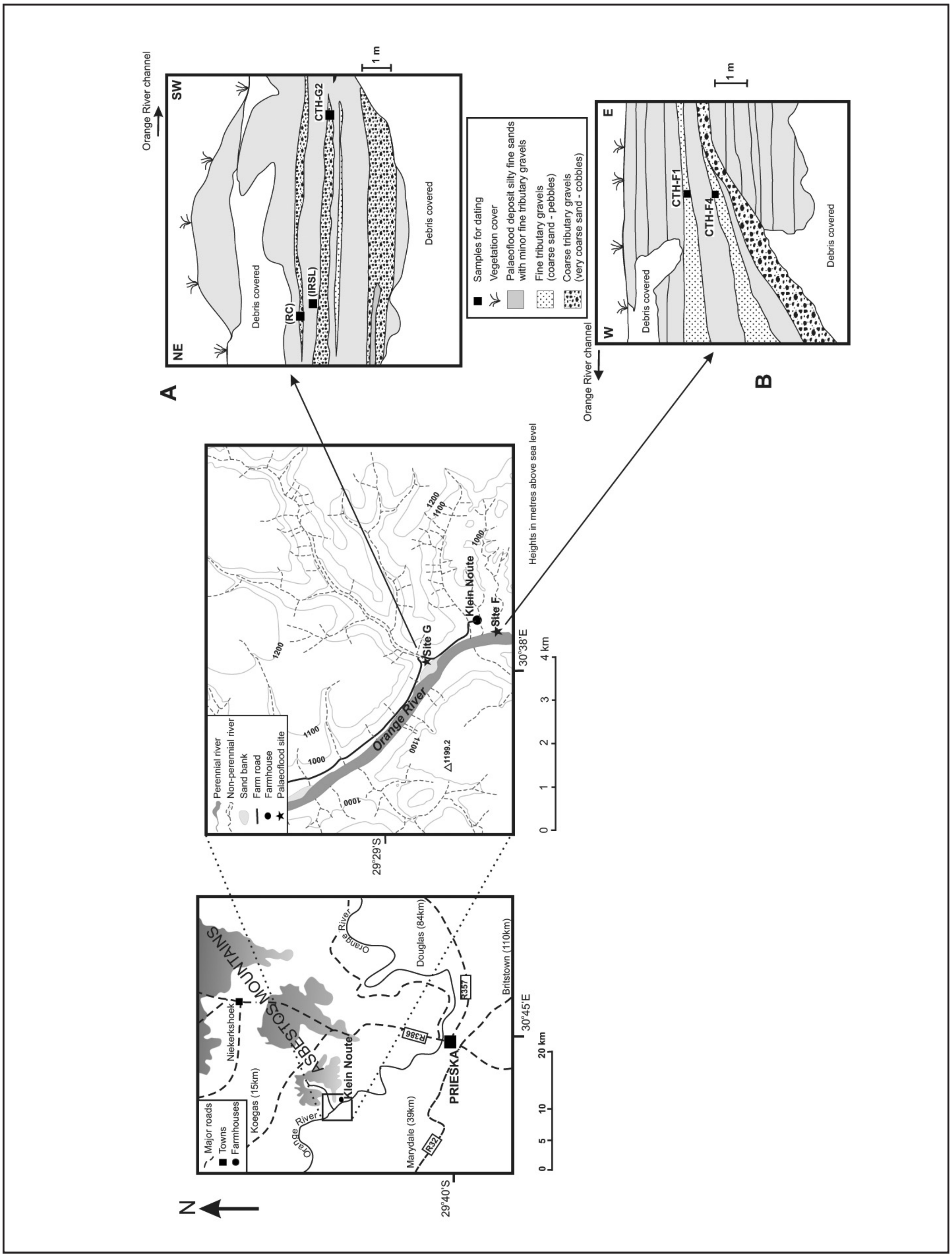


Figure 2. Location of the middle Orange River palaeoflood deposits, near the town of Prieska. Site G is located in a back-flood tributary, west of the farmhouse Klein Noute. Site F is located in the Orange River main channel where it intersects a small tributary. Orange River palaeoflood deposits consist of very fine sandy silts interbedded with tributary gravels (Zawada, 2000). (**A**) The Site G erosional section, referred to as Site 9 in Zawada (2000), with the location of sample CTH-G2 as well as the organic matter (RC) and IRSL ages from Zawada (2000). (**B**) The erosional section exposed at Site F, with locations of samples CTH-F1 and CTH-F4 marked.

brown Orange River palaeoflood silty fine sands are interbedded with tributary flash-flood deposits of reddish-brown, medium to very coarse sands containing angular fine pebble to cobble-size clasts (Zawada *et al.*, 1996; Zawada, 1997; 2000). Sample CTH-G2 was taken from a tributary deposit from Site 9, section 2, described in Zawada (2000) (Site G in this study). Site G near Prieska, along the middle Orange River, was chosen as it preserves a record back to the early Holocene (Zawada *et al*, 1996). Sites G and F are below the confluence of the Vaal and upper Orange Rivers and, therefore, the flood deposits sample the main sources of suspended load arriving at the river mouth (Bremner *et al.*, 1990; Compton and Maake, 2007). Samples CTH-F1 and -F4 were obtained from tributary deposits at Site F, 2 km upstream of Site G. Palaeoflood deposits of the lower Orange River provide a detailed record of the past 5 ka (Zawada *et al.*, 1996; Zawada, 2000) and incorporate sediments from the Fish River, but were not sampled in this study.

Sediment samples first underwent grain-size analysis, separating samples into a >63 micrometres (μm) sand fraction, a coarse silt (38 to 63 μm) and a fine mud fraction (<38 μm) by wet sieving. In the case of the northern mudbelt gravity cores, variations in the concentration of coarse silt (38 to 63 μm) were used to identify horizons for age dating. Grain-size data are not currently available for the southern mudbelt gravity core GeoB 8323. Due to the paucity of foraminiferal tests in the mudbelt, the gastropods *Nassarius vinctus* and *Volutacorbis lutosa*, and the bivalves *Dosinia lupinus* and *Tellina analogica* were selected for age determination by radiocarbon analysis. Material submitted for radiocarbon analysis did not appear altered based on the absence, when examined under a binocular microscope, of recrystallized textures or carbonate cement overgrowths. Approximately 120 unaltered tests of the planktonic foraminifer *Globorotalia inflata* were picked from the >125 μm fraction for the radiocarbon dating of the basal sediment recovered at the outer shelf and slope sites. The terrestrial gastropod, *Tomichia* sp. (<10 mm), was hand picked from palaeoflood deposits for radiocarbon dating. The terrestrial gastropods were bleached white and some were slightly etched, but none appeared recrystallized.

Shell material and foraminifera were submitted for accelerated mass spectrometry (AMS) radiocarbon analysis at the Lawrence Livermore Center for Accelerator Mass Spectrometry (CAMS). Four large shell samples from cores GeoB 8319, 8323, 8332 and 8333 were sent to QUADRU, Pretoria, for conventional ^{14}C dating. Two of the large shell samples proved to be too small and were sent to the University of Groningen (GrA) laboratory in the Netherlands for AMS dating.

In the upper atmosphere, ^{14}C is constantly produced by cosmic-rays and forms CO_2 molecules, which are rapidly dispersed in the hydrosphere and incorporated into the biosphere. When an organism dies, there is no further input of radiogenic ^{14}C and that which remains can be used to determine the time since death. The seemingly simple ^{14}C "clock" is, however, complicated by the secular variation in ^{14}C production, linked to changes in the intensity of cosmic-ray proton flux provided by the sun and in the strength of Earth's magnetic dipole (Faure, 1986). The ^{14}C clock has, therefore, been calibrated by using dendrochronology, lake varves, ice core data correlated to marine sediments and the U/Th dating of speleothems and corals to map out the changes in ^{14}C production over time (Stuiver and Braziunas, 1993; Hughen *et al.*, 2004, with references therein). In addition, because the ocean has a turnover time of 1 to 2 thousand years, marine carbonate shells may have precipitated in equilibrium with waters considerably older than the organism. Marine samples must therefore be corrected for the local "reservoir age" (Faure, 1986; Stuiver and Braziunas, 1993). In this study a constant reservoir age of 550 years is assumed for western margin shelf waters, based on the age difference of marine shell and charcoal from a coastal archaeological site 225 km north of Cape Town (Tonner, 2003).

Ages cited in this study were calculated in radiocarbon years, using the Libby half-life of 5568 years and following the conventions cited in Stuiver and Polach (1977). For marine samples, the uncalibrated ^{14}C ages were calibrated using the Fairbanks calibration program (Fairbanks *et al.*, 2005) version 0107, on the website http://radiocarbon.LDEO.columbia.edu/, which extends beyond the Pretoria calibration program WC93. WC93, which assumes a reservoir age of 550 years (Talma and Vogel, 1993) and applies the marine data set of Stuvier and Braziunas (1993), agrees with calibrated radiocarbon ages calculated using the Fairbanks calibration, within error of the radiocarbon analyses. The calibrated ages have an uncertainty (one sigma range) on the order of ± 100 years (Tables 2 and 3). Variation in the marine reservoir age is a possible additional uncertainty. If the marine reservoir age were to have varied by on the order of 10%, then the uncertainty would increase by ± 55 years. Calibrated radiocarbon ages are reported in the text in thousands of years before the present (ka), rounded to the nearest one hundred years.

Results

Sedimentology

Mudbelt cores consist of homogeneous olive green clayey fine silt (Schneider *et al.*, 2003), with a brown oxidized surface layer less than 1 m thick. A sandy, shelly basal layer was found in cores GeoB 8333 and 8332 off the Holgat River, and the St Helena Bay core GeoB 8323. Sand content is otherwise restricted to a few weight percent in the mudbelt cores. The coarse-silt fraction (38 to 63 μm) consists predominantly of quartz and mica. Core GeoB 8331 at 97 m water depth (mwd) shows a decreasing trend in the coarse-silt content up core (Figure 3). In the basal 3.4 m, the coarse-silt

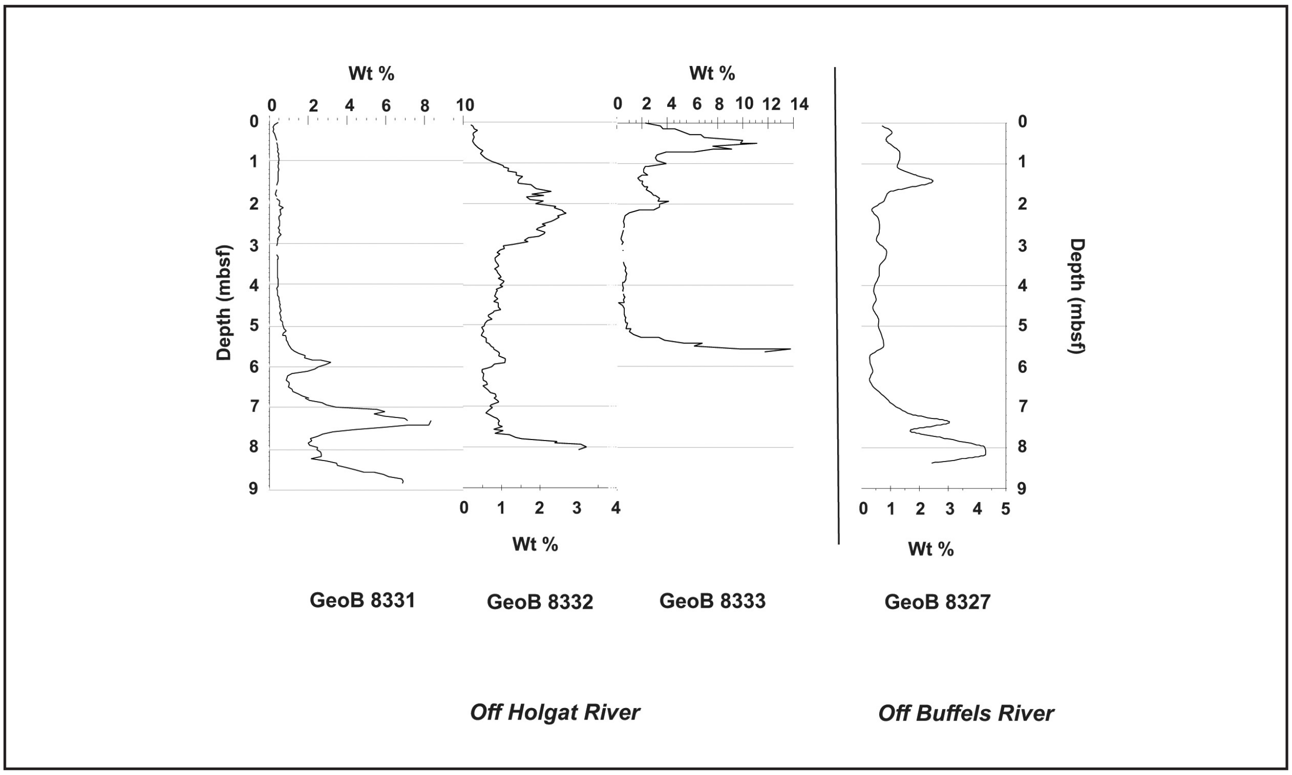


Figure 3. Down core variations in the coarse-silt size fraction (38-63 μm) for cores GeoB 8331, GeoB 8332 and GeoB 8333 off the Holgat River, sampled at 5 cm intervals. Coarse-silt size data for core GeoB 8327 off the Buffels River, sampled at 20 cm intervals, from MacHutchon (2003).

fraction fluctuates from 8.5 weight percent of the total sample to 1 weight %, with maxima at 8.8, 7.4 and 5.9 metres below sea floor (mbsf). In the upper 5.5 m of the core, the coarse-silt fraction varies between 0.25 and 1 weight %. The coarse-silt content at the base of core GeoB 8332 (115 mwd) is 3 weight %. This peak is followed by variations between 0.5 and 1 weight % from 7.8 to 3 mbsf (Figure 3). Between 3 and 1 mbsf, there is a second increase in coarse silt, reaching a maximum of 2.5 weight %. The coarse-silt content then drops to below 0.5 weight % in the upper 1 m. Core GeoB 8333 (118 mwd), contains 14 weight % coarse silt at the base. The basal layer is followed by a rapid decrease in the coarse-silt content to under 2 weight % between 5.2 and 2.2 mbsf. Two coarse-silt maxima occur at 1.9 mbsf (4 weight %) and at 0.5 mbsf (11.5 weight %). There are two peaks in the coarse silt near the base of the core GeoB 8327 at 8 mbsf (4 weight %) and at 7.3 mbsf (3 weight %). The coarse-silt content then decreases to 0.25 to 1 weight % between 6.5 and 1.7 mbsf. The coarse-silt fraction increases to a maximum of 2 weight % at 1.4 mbsf, followed by a decrease in the upper 1 m to approximately 1 weight %.

Radiocarbon analyses

Uncalibrated radiocarbon ages, with their analytical uncertainties, and the mean calibrated radiocarbon ages, along with their one sigma range, are reported in Tables 2 and 3. Shell material for radiocarbon analysis was generally selected away from core intervals of increased coarse-silt content and whole, pristine shells were selected in preference to broken or corroded shells to avoid dating reworked material. In the southern mudbelt, the oldest calibrated radiocarbon age is 12.8 ka from the shelly basal gravel of gravity core GeoB 8323 (2.85 mbsf). The youngest age recorded is 0.1 ka from a sediment depth of 12.5 cm in the multicore GeoB 8319. The oldest calibrated radiocarbon age in the northern mudbelt was from near the base of the gravity core GeoB 8332 (11.2 ka at 7.78 mbsf) and the youngest age was from multicore GeoB 8333 (<0.1 ka or "post-bomb", at 0.37 mbsf). Multicores from the northern slope sites (GeoB 8343, 8340, 8337 and 8338) and one southern slope site (GeoB 8313) have calibrated ages ranging between 3.9 and 4.9 ka at sample depths of 0.17 to 0.20 mbsf. The remaining two cores from the southern slope sites (GeoB 8314 and 8316) have calibrated ages of 0.7 (0.14 mbsf) and 1.3 ka (0.17 mbsf), respectively. Gastropods were sampled from the fine tributary gravels interbedded with finer-grained Orange River palaeoflood sediments (Figure 2). The oldest sample from the onland palaeoflood deposits (CTH-G2) has a calibrated age of 8.5 ka (Table 2). The second, upstream site yielded considerably younger calibrated ages of 0.8 ka (CTH-F4) and 0.3 ka (CTH-F1) (Table 2).

Discussion

Radiocarbon ages

Radiocarbon ages obtained for the molluscs from the mudbelt are believed to correspond to the age of sediment deposition. Ages young stratigraphically up core with no inverted ages. The thin-walled bivalves used in this study were articulated, suggesting that these fragile shells are in life position. The gastropods' shell colour is still preserved on the younger *Nassarius* specimens, indicating that these shells have not been bleached. Some older gastropod shells did show signs of bleaching and some corrosion. However, none showed signs of recrystallization or overgrowths and, therefore, the radiocarbon ages are not expected to have been altered. Live specimens of the gastropod *Nassarius vinctus* (<15 mm), retrieved by multicorer, were observed living on the sediment surface, with shells often coated by algae. These members of the family Nassariidae are active scavengers on muddy substrates and may live in large colonies (Kilburn and Rippey, 1982). Nassariidae burrow in response to falling tides (Kilburn and Rippey, 1982); however, tidal cycles would not have an influence on organisms living in the mudbelt. The 50 mm carnivorous gastropod *Volutacorbis lutosa* belongs to the family Volutidae; known to be burrowers, they never submerge their shells completely below the sediment (Kilburn and Rippey, 1982). The bivalves *Dosinia lupinus* (approx. 15 mm), a suspension feeder, and *Tellina analogica* (<15 mm), a surface-deposit feeder (Kilburn and Rippey, 1982), most likely burrow to within a few centimetres of the sediment-water interface. Burrowing and bioturbation by polychaete worms may have displaced shells by approximately 10 cm. However, burrows were only observed in the northern mudbelt core GeoB 8332 at 6.24 to 6.26 mbsf and 7.59 to 7.71 mbsf. Therefore, the age of the molluscs is interpreted to represent the age of sediment deposition to within 10 cm of their depth position in the core.

In the northern mudbelt, cores GeoB 8331, 8332 and 8333 from off the Holgat River span the last 11 ka. Core GeoB 8331 records ages from 9.5 ka at 8.56 mbsf to 0.8 ka at 1.95 mbsf. The biogenic carbonate ages obtained for the northern mudbelt cores are comparable to the bulk organic matter ages of nearby HODSA cores (Figure 4, Table 3). The general agreement of shell and bulk organic matter ages suggests a predominantly marine origin for the bulk organic matter off the Holgat River with older, terrestrial organic matter primarily focused near the Orange River mouth. A similar conclusion was drawn by Meadows *et al.* (1997; 2002) based on the $\delta^{13}C$ values of the bulk organic matter of HODSA cores. In addition to the general agreement between bulk organic carbon and carbonate shell AMS ages, unpublished AMS results from the GeoB 8332 core from off the Holgat River show that mollusc shell and foraminiferal tests picked from the same horizon have the same age (Weldeab, personal communication, 2005).

There are a few anomalous radiocarbon dates. The oldest of the three Holgat River cores, GeoB 8332, has a near basal age of 11.2 ka and a youngest age of 8.3 ka at 1.77 mbsf. The anomalously old age of 8.3 ka at 1.77 mbsf is considered a reworked, maximal age because the dated *Volutacorbis* was partially fragmented and recovered from an unusually sand-rich layer between 1.74 to 1.77 mbsf. The gravity core from site GeoB 8333 has a near basal age of 11.1 ka and a youngest age of 5.1 ka at a depth of 0.43 mbsf, which indicates a major erosional hiatus near the core top. The post-bomb age obtained at the base of the adjacent multicore at a sediment depth of 0.37 mbsf may suggest that the top 0.4 m or so of the sediment is a recent slump deposit. The only post-bomb age recorded from the mudbelt by Meadows *et al.* (1997, 2002) was from a core located between the Orange River and Holgat River mouths. The lack of more recent, post-bomb ages off the Holgat and Buffels rivers was explained as being possibly due to non-deposition.

In the southern mudbelt, off the Olifants River, the age of the sandy base of gravity core GeoB 8323 is 12.8 ka and the sediment just 0.58 m above it, at a core depth of 2.27 mbsf, has an age of 2.2 ka. The sandy, shelly basal sediment of core GeoB 8323 is interpreted to be a high-energy lag deposit formed as sea level rose during the last deglaciation. The large hiatus between these two samples indicates a long period of non-deposition or erosion. Surface sediment, recovered in multicores from off the Olifants River, ranges from 0.1 ka at 0.125 mbsf in core GeoB 8319 to 0.7 ka at 0.43 mbsf in core GeoB 8322 and are consistent with the mean sedimentation rate of 1.0 mm/year since 2.2 ka (see below).

Onshore, the focus of this study was to locate and date palaeoflood deposits of the Orange River for comparison with the mudbelt and slope sediments offshore. The age obtained for the gastropod sample (CTH-G2) of 8.5 ka agrees stratigraphically with both the bulk organic carbon radiocarbon and IRSL dates cited in Zawada (2000) (Table 2). Therefore, freshwater mollusc shells can provide reliable radiocarbon ages. The herbivorous freshwater *Tomichia* lives and grazes on the sediment surface and does not burrow (Day, personal communication, 2007). *Tomichia* most likely lived in the quiet, slack waters of the back-flooded tributary channels after the deposition of the fine-silt palaeoflood sediments. The *Tomichia* shells were then incorporated into the overlying fine-gravel tributary flash-flood deposits. In addition to the 8.5 ka flood, terrestrial gastropod ages at Site F indicate major Orange River floods at approximately 0.3 and 0.8 ka (Figure 2). Palaeoflood deposits between 8.5 and 0.8 ka occur in the Prieska area, but their ages are less certain than elsewhere along the Orange River (Zawada, 2000).

Sedimentation rates

Sedimentation rates for the mudbelt cores were calculated using the difference between two consecutive core depths divided by the respective calibrated ages. Slope-core sedimentation rates were calculated with the assumption that the surface sediment is modern (0 ka). Cores GeoB 8331 and 8333 (Holgat River) have average sedimentation rates of 0.8 mm/year. These

Table 3. AMS (number only and GrA-samples) and conventional (Pta- samples) radiocarbon analyses of carbonate material recovered from sites on the western continental margin of South Africa. Results from the HODSA project (OS samples) from Meadows *et al.* (1997) are included for comparison. Ages calibrated using the Fairbanks calibration program (Fairbanks *et al.*, 2005). A reservoir age of 550 years (see text) was used.

Analytical No.	Core site	Sample depth (cm)	(GC) / (MUC)	Dated material	Uncalib. ^{14}C age[1]	± (yrs)	Calibrated ^{14}C age[1] Mean	-1σ	+1σ	Rate[2] (mm/yr)
121496	8313	17-18	MUC	Globorotalia inflata	4575	35	4484	4437	4531	0.04
121497	8314	14-15	MUC	Globorotalia inflata	1275	35	671	655	687	0.22
121561	8316	16-17	MUC	Globorotalia inflata	1895	45	1277	1248	1306	0.13
GrA-25207	8319	12-13	MUC	Dosinia lupinus	685	35	143*	116*	238*	
104271	8319	27	MUC	Ammonia japonica	780	35	262	190	334	1.03
104272	8322	43	MUC	Ammonia japonica	1260	35	665	646	684	0.65
104275	8323	124	GC	Nassarius vinctus	1790	35	1175	1122	1228	
104273	8323	227	GC	Tellina analogica	2730	35	2191	2123	2259	1.01
GrA-24895	8323	285	GC	N.vinctus & bivalves	11420	35	12769	12727	12811	0.05
113286	8327	90	GC	Nassarius vinctus	1850	35	1248	1210	1286	
104266	8327	232	GC	Tellina analogica	2600	35	2000	1955	2045	1.89
113287	8327	532	GC	Tellina analogica	3575	35	3235	3179	3291	2.43
104265	8327	837	GC	Nassarius vinctus	8455	45	8699	8604	8794	0.56
113289	8331	195	GC	Nassarius vinctus	1420	35	773	726	820	
113290	8331	271	GC	Nassarius vinctus	1870	35	1264	1235	1293	1.55
121559	8331	475	GC	Nassarius vinctus	3145	35	2733	2711	2755	1.39
121560	8331	615	GC	Nassarius vinctus	5020	35	5116	5016	5216	0.59
121494	8331	704	GC	Nassarius vinctus	6215	35	6438	6401	6475	0.67
121495	8331	775	GC	Nassarius vinctus	8410	35	8626	8585	8667	0.32
113291	8331	858	GC	Nassarius vinctus	9130	40	9539	9520	9558	0.91
Pta-9217	8332	177	GC	Volutacorbis lutosa	8020	110	8290	8182	8398	
104270	8332	778	GC	Tellina analogica	10275	35	11177	10449	11205	
113288	8333	37	MUC	Nassarius vinctus	345	40	"post bomb"			
104269	8333	43	GC	Nassarius vinctus	5005	40	5083	5057	5109	
104267	8333	200	GC	Nassarius vinctus	7530	40	7810	7759	7861	0.58
104276	8333	237	GC	Nassarius vinctus	8835	35	9289	9223	9355	0.25
Pta-9179	8333	408.5	GC	Volutacorbis lutosa	9720	80	10317	10216	10418	1.67
104268	8333	520	GC	Nassarius vinctus	10195	40	11064	10954	11174	1.49
121563	8338	19-20	MUC	Globorotalia inflata	4825	35	4842	4825	4859	0.04
121562	8337	18-19	MUC	Globorotalia inflata	4170	45	3928	3867	3989	0.05
121564	8340	19-20	MUC	Globorotalia inflata	4535	35	4445	4405	4485	0.04
121565	8343	17-18	MUC	Globorotalia inflata	4930	35	4932	4869	4995	0.04
OS 8885	H4	5-8	GC	Bulk organic matter	950	30	475	437	513	
OS 8884	H4	95-100	GC	Bulk organic matter	6540	35	6819	6769	6869	0.14
OS 8883	H4	295-300	GC	Bulk organic matter	8850	50	9311	9226	9396	0.80
OS 8882	H4	505-510	GC	Bulk organic matter	9750	45	10342	10263	10421	2.04
OS 8894	H7	10-15	GC	Bulk organic matter	880	25	386	336	436	
OS 8893	H7	40-45	GC	Bulk organic matter	1170	25	603	569	637	1.38
OS 8892	H7	180-185	GC	Bulk organic matter	2220	40	1564	1517	1611	1.46
OS 8891	H7	345-350	GC	Bulk organic matter	3020	30	2561	2464	2658	1.65
OS 8890	H7	535-540	GC	Bulk organic matter	3290	35	2824	2786	2862	7.22

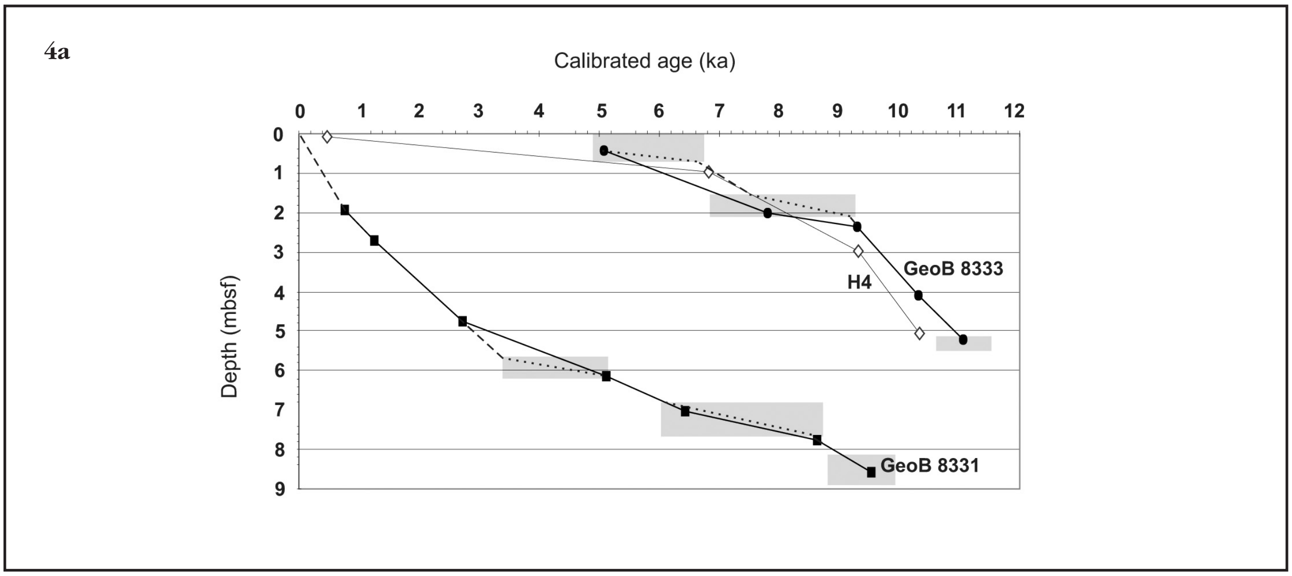
[1]Ages in years before present (BP), *i.e.* before AD 1950. Ages corrected for variations in isotopic fractionation.

[2]Sedimentation rate calculated as the difference in core depth divided by the difference in age between samples. In slope and mudbelt multicores assume surface is recent.

*Calibrated using WC93 (see text).

sedimentation rates are significantly higher than that of the nearby HODSA H4 core (0.5 mm/year). However, in the case of core GeoB 8327 off the Buffels River, the average sedimentation rate (1.0 mm/year) appears to be approximately half that of the nearby HODSA H7 core (2.2 mm/year). The variability in average sedimentation rate among cores can be explained by variable sedimentation rates down core. For example, the GeoB 8327 core (88 mwd) has an age of 3.2 ka at a depth of 5.32 mbsf and the nearby H7 core (80 mwd) is 2.8 ka near its base at 5.4 mbsf. Hence these cores have had similar sedimentation rates of 1.5 to 2.0 mm/year since 3.2 ka (Figure 4). Core GeoB 8327 includes older (>3.2 ka) sediments deposited at a slower sedimentation rate (Figure 4) resulting in a low average sedimentation rate for the entire core. Therefore, caution is required when comparing average sedimentation rates for mudbelt cores.

Northern-slope multicores (GeoB 8337, 8338, 8340 and 8343) consistently yield sedimentation rates of 0.04 to 0.05 mm/year. These results match those obtained by Rau (2002) and Berger *et al.* (2002), with mean Holocene sedimentation rates of 0.03 to 0.04 mm/year, from sites at similar water depths in the study area. In the south, the sedimentation rate of the shallow-water upper slope multicore (GeoB 8313) is also 0.04 mm/year. In contrast, the deeper water, upper slope multicores GeoB 8314 and 8316 yield significantly higher sedimentation rates of 0.22 and 0.13 mm/year, respectively. This increase in sedimentation rate from



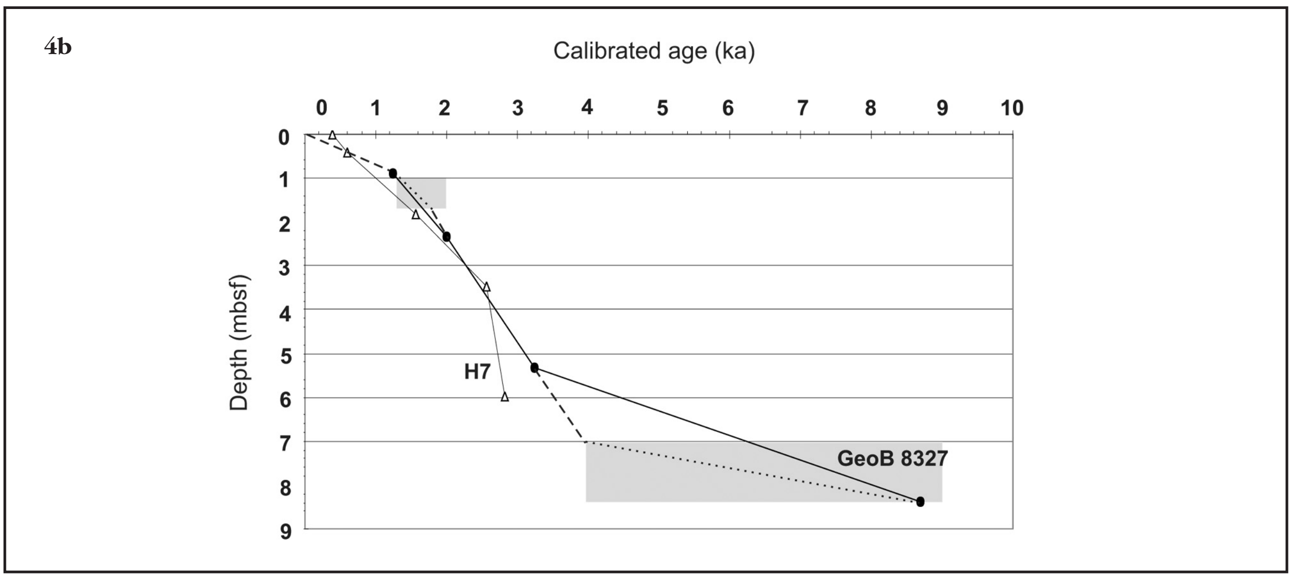


Figure 4. Sedimentation rates for northern mudbelt cores GeoB 8331 and 8333 from off the Holgat River (**a**) and off the Buffels River (**b**). Interpreted sedimentation rates (dashed and dotted lines) indicate where winnowing periods, horizons of high coarse-silt content (gray shading), have affected the calculated sedimentation rates. Dashed lines represent high sedimentation-rate sections, whereas dotted lines are low sedimentation-rate sections, corresponding to winnowed horizons. Age data for HODSA cores H4 and H7 (Meadows *et al.*, 1997, 2002) from the same vicinity are included for comparison.

north to south and from shallower to deeper water cores in the south may reflect the continual loss of terrigenous material from the shelf to the slope as sediment is transported south along the outer shelf by the poleward undercurrent (Nelson, 1985; 1989). A southerly trend in off-shelf transport of terrigenous material is supported by the lower carbonate content of the southern slope cores (unpublished data). The close proximity of the southern slope cores to the Cape Columbine upwelling cell may also contribute to their relatively high sedimentation rates.

The age-depth plots of cores from this study and from the HODSA project (Figures. 4) reveal that the sedimentation rate in the mudbelt was not constant during the Holocene. The position and extent of winnowed, coarse-silt rich horizons was used to modify sedimentation rate trends (Figures. 4). The two deeper water Holgat River cores GeoB 8333 (118 mwd) and H4 (115 mwd) have high sedimentation rates (>1.5 mm/year) between approximately 11 and 9.2 ka. The rate then decreases dramatically in GeoB 8333 to ~0.3 mm/year between 9.2 and 7.5 ka coinciding with an increase in the coarse-silt (38 to 63 mm) fraction. Sedimentation rates increase to at least 0.6 mm/year between 7.5 and 6.7 ka. The decrease in sedimentation rate since 6.7 ka corresponds to a greater coarse-silt content. Similar changes in sedimentation rate are observed in the H4 core, which has relatively low sedimentation rates since 6.7 ka (Meadows *et al.*, 2002). The shallowest Holgat River core, GeoB 8331 (97 mwd), exhibits a relatively high sedimentation rate (0.9 mm/year) between 9.2 and 8.6 ka. The sedimentation rate then decreases to 0.3 mm/year between 8.6 and 6 ka, corresponding to a greater coarse-silt content. The sedimentation rate is approximately 0.6 mm/year from 6 ka until around 5 ka when it declines to 0.3 mm/year in association with a greater coarse-silt content. The highest sedimentation rates (1.4 mm/year) in the GeoB 8331 core occur since 3.2 ka. The age-depth plots for the cores offshore of the Buffels River, GeoB 8327 and H7 (Figure 4), recovered at water depths of 88 and 80 m respectively, are similar and show a high sedimentation rate of 1.5 to 2.0 mm/year since 3.2 ka.

The gravity core recovered from the southern mudbelt (GeoB 8323) is considerably shorter (2.85 m) than those from the northern sites and reflects an overall more widely distributed (Birch *et al.*, 1991) and thinner mudbelt on the shelf off St Helena Bay. The coarse shell-rich sand base of core GeoB 8323 (92 mwd) is interpreted to be an upper Pleistocene beach deposit, with the basal dated shell occurring at the transition to deeper water deposition associated with the marine transgression. The sediment rapidly fines up core into clayey fine-silt typical of the mudbelt. The low sedimentation rate of the basal core indicates a hiatus and suggests that sediment derived from the Orange River has only been deposited at this site since 2.2 ka. The average sedimentation rate of the upper 2.27 m of the core is 1.1 mm/year, similar to the sedimentation rate of the upper 0.27 m of multicore GeoB 8319 (1.0 mm/year) and typical of the mean sedimentation rate of the northern mudbelt cores.

Regional sedimentation patterns

Although core sites are limited in this study, they reveal trends in the Holocene sedimentation pattern on the margin. Here we speculate on some of the large-scale depositional processes. The link between sedimentation rate and coarse-silt content indicates that coarse-silt-rich horizons represent periods of increased winnowing, perhaps related to greater bottom water current velocities. Variations in sedimentation rates could be related to changes in sediment supply, accommodation space or shifts in the mudbelt depo-centre associated with changes in sea level. Early Holocene (11 to 9 ka) sedimentation is largely restricted to the deeper water mudbelt recovered at sites GeoB 8333 and H4 off the Holgat River. Mudbelt deposition in deeper water from 11 to 9 ka corresponds to a rising sea level from approximately 45 m below mean sea level at 11 ka to 25 m below mean sea level at 9 ka, related to the marine transgression of the last deglaciation (Bard *et al.*, 1996). The maximum Holocene sea level of around 3 m above present-day occurred between 7.5 and 6.5 ka, based on dated coastal deposits along the West Coast (Compton, 2001, 2006). As sea level rose to this mid-Holocene maximum, mudbelt deposition shifted landward, as seen in the Holgat River transect. The landward shift in mudbelt deposition was limited by available accommodation space on the shelf. Maximum accommodation space is located in the bedrock knick point formed during sea-level lowstands. Sea level dropped by around 3 m between 6.5 and 5.5 ka and may have caused widespread erosion over the mudbelt corresponding to hiatuses in the recovered mudbelt cores GeoB 8331, and possibly GeoB 8327. Sea level has remained more or less at its present level (± 1 m) since 5.5 ka (Compton, 2001, 2006). Mudbelt deposits younger than 3 ka tend to be more evenly draped over the entire mudbelt, with sediments of this age present in cores south of the Orange River (Meadows *et al.*, 2002), core GeoB 8331 off the Holgat River and core GeoB 8327 off the Buffels River. Continuous sedimentation would eventually have filled the accommodation space nearer the Orange River mouth, causing a shift in the mudbelt depo-centre such that the mudbelt began to prograde southward. This progradation may explain the presence of young (<2.2 ka) mudbelt deposits off the Olifants River (core GeoB 8323) in the St Helena Bay area.

Sedimentation rates on the slope (0.04 to 0.2 mm/year) are considerably lower than those found in the mudbelt (1 to 2 mm/year). The high sedimentation rates of the mudbelt result from sediment focussing and provide perhaps one of the best high-resolution Holocene records for southern Africa. Of the terrigenous mud delivered by the Orange River, much of it has been deposited in the mudbelt, but some terrigenous sediment is lost from the shelf and deposited on the slope. The mud content and sedimentation rates of Holocene sediment increase from the north to south in the upper-slope core sites. This indicates that there is less across-shelf transport in the north (off the Holgat River) than in the south near St Helena Bay where the mudbelt is thinner and laterally more extensive, and more terrigenous mud is shunted off onto the slope.

In addition to sea level, changes in the input of terrigenous sediment would have impacted sedimentation rates in the mudbelt, because terrigenous sediment makes up >70 weight % of the mudbelt. The Orange River palaeoflood deposits near Prieska and elsewhere record flood events which delivered large quantities of terrigenous sediment to the western margin. The flood frequency for the Orange River over the past 200 years is 1 in 10 to 15 years (Benade, 1988), with flood discharges of less than 9000 m^3/s (Zawada, 2000). However, catastrophic floods (discharges of around 25 000 m^3/s) have estimated flood frequencies of from 1 in 200 years to 1 in 10 000 years, with the most likely frequency being 1 in 1000 years (Zawada, 2000).

The early Holocene (12 to 7 ka) was characterised by a series of smaller floods (maximum discharge of 4000 m^3/s), whereas the middle to late Holocene (5.5 to 0.2 ka) has larger floods (maximum discharge of 15 000 m^3/s) with a catastrophic flood at 0.5 ka of 28 000 m^3/s (Zawada *et al.*, 1996; Zawada, 2000). Periods of increased Holocene flooding could be tentatively correlated to periods of increased temperature and rainfall in the summer rainfall area (Zawada, 2000). The extent and thickness of early Holocene deposition in the mudbelt appears to be less than during the middle to late Holocene, and may relate to the generally smaller sized early Holocene flood events preserved along the Orange River course. Bremner *et al.* (1990) showed that discrete flood events, during the 1988 flood, could be linked to their respective source areas by using the sedimentology and clay mineralogy of suspended river loads as tracers. The 1988 flood muds deposited offshore could also be identified. Up to ten centimetres of suspended load were deposited on the usually sandy delta front prior to redistribution to the south, a process which could take several years (Bremner *et al.*, 1990). Major palaeofloods, therefore, may deliver much of the terrigenous sediment deposited in the mudbelt and ongoing geochemical analysis may allow major palaeoflood deposits to be linked to sediment deposition in the mudbelt.

Conclusions

An age model of sediment deposition in the mudbelt is established based on the radiocarbon analysis of mollusc shells. The mollusc shells used in this study do not show signs of reworking or transport and are believed to have been preserved in or near life position, with the exception of one reworked *Volutacorbis* shell recovered from a sand-rich sediment interval from the northern mudbelt core GeoB 8332. Mollusc shells from the mudbelt, such as the abundant *Nassarius vinctus*, provide reliable dating material for radiocarbon analysis in an area where foraminiferal tests are scarce.

The northern mudbelt spans 11 ka. The southern mudbelt is significantly thinner and younger than in the north and spans the past 2 to 3 ka. Holocene sedimentation rates for the mudbelt are not constant. Lower sedimentation rates are linked to increases in the coarse-silt content, corresponding to periods of increased winnowing. In the Holgat River offshore transect, mudbelt deposition was focussed in the deeper water site (GeoB 8333) during the early Holocene, whereas mudbelt deposition was focussed in shallower water sites (GeoB 8331 and 8332) during the middle to late Holocene. This suggests that there has been a landward shift in the depo-centre for sediments deposited in the northern mudbelt, possibly related to changes in Holocene sea level. The change from relatively rapid deposition during the early Holocene in the northern mudbelt, to a more uniform distribution of younger mudbelt sediments since 2 to 3 ka, may reflect greater input of terrigenous sediment during the mid to late Holocene and southward progradation of the mudbelt.

The high average sedimentation rates in the mudbelt cores (>0.75 mm/year) compared to those on the slope (mainly <0.05 mm/year) indicate the potential importance of the mudbelt deposit as a source of high-resolution Holocene records. Dated onshore Orange River palaeoflood deposits provide a direct link to the input of terrigenous sediment via major flood events to the margin. Together with other, established onland records, the mudbelt and Orange River palaeoflood deposits may help to document Holocene climatic and oceanographic variations in southern Africa.

Acknowledgements

We thank the officers, crew and scientists of the *Meteor* M57-1 cruise, particularly R. Schneider (Chief Scientist) for providing us with the cores used in this study. This research was funded by the National Research Foundation (partially through funds to the Inkaba ye Africa programme) and the University of Cape Town. J. Pether assisted in the identification of the marine molluscs and J. Day assisted in the identification of the terrestrial gastropods. The manuscript benefited from constructive reviews by M. Meadows and J. Rogers. This is Inkaba yeAfrica contribution number 14.

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Editorial handling: M. J. de Wit and Brian Horsfield