Present-day sedimentation rates on the southern and southeastern Australian continental margins

S. SCHMIDT1 AND P. DE DECKKER2*

1UMR5805 EPOC, CNRS—Université de Bordeaux, F-33615 Pessac Cedex, France.
2Research School of Earth Sciences, The Australian National University, Canberra ACT 2601, Australia.

The Australian continental margin presents highly contrasted settings depending on (1) the presence or absence of a fluvial sediment supply, (2) the distance from the Australian mainland, and (3) the local hydrological setting. Despite the importance in surface area of the continental margin around the Australian mainland, so far only a few studies have dealt with sedimentation, most of them focusing on the northeastern Australian Shelf. This work presents the first large-scale investigation of modern sedimentation along the southern margin of Australia in the SE Indian Ocean, and the western margin of the Tasman Sea. Sedimentation intensity was assessed on a century timescale using a multi-tracer approach ($^{234}$Th, $^{210}$Pb, $^{232}$Th) on interface cores around the 1000 m water depth contour. $^{234}$Th (half-life: 24.1 days) in excess was detected in all surface samples, testifying to the occurrence of freshly deposited particles. Sedimentation and mass accumulation rates based on sedimentary $^{210}$Pb excess profiles (CF:CS model) range between 0.027 and 0.280 cm y$^{-1}$ and between 14 and 222 mg cm$^{-2}$ y$^{-1}$, respectively. Whereas sedimentation rates are low and associated with carbonates on the western margin, sediments are more influenced by the detrital fraction and organic carbon on the eastern side of the continent. In comparison with northern continental margins (e.g. Timor Sea, Gulf of Papua), the southern Australian margin receives little sediment today, as it is rarely linked to a river system that would otherwise deliver large amounts of sediment, and also because of the presence of the extended shelf south of Australia.

KEYWORDS: Australian continental margin, sedimentation rate, mass accumulation rate, thorium-234, thorium-232, lead-210, particulate organic carbon, carbonate, grain size.

INTRODUCTION

Continental margins, particularly those influenced by upwelling, are among the most productive biological systems in the oceans and are, therefore, of particular interest for both biological and geological processes (Walsh 1991). These margins are characterised by high fluxes of organic carbon, nutrients and other trace elements, which may either be exported to the open ocean or are rapidly deposited and buried on geological scales. During the last decades, numerous studies have documented a large diversity in the intensity of mass fluxes and sedimentation on continental margins, mainly European and North American, depending on their morphologies, the occurrence of fluvial input and hydrological conditions (Nittrouer et al. 1984; Walsh et al. 1988; Biscaye & Anderson 1994; van Weering et al. 2002; Schmidt et al. 2009; Wheatcroft et al. 2015). In addition, the high sediment accumulation rates that characterise many continental margins make them ideal depositional settings for preserving high-resolution records of past climate change.

The Australian continent heralds a fairly large continental shield, such that during glacial maxima in the Quaternary (Yokoyama et al. 2000; Lambeck & Chappell 2001; De Deckker & Yokoyama 2009) when the sea level had dropped by the order of 120 m, the Australian landmass had almost doubled in size. The most extensive shelves are to be found offshore northern Australia, commonly referred to as the Sahul Shelf, which is bordered by the Timor Trough, and in the south the Great Australian Bight is well over 200 km wide and is bordered by an arid region to the north (The Nullarbor Plain, Figure 1) that today lacks active rivers. This is in contrast to the North West Shelf that is bordered by large, monsoonal (and therefore seasonal) rivers systems (Harris et al. 1990; Dunbar & Dickens 2003; Wasson et al. 2010). It is also reasonable to expect an input of aeolian sediment to the shelves, as already documented by Gingele et al. (2001, 2004) and De Deckker et al. (2014) for the North West Shelf, and Gingele et al. (2007) based on a core taken in the Murray Canyons Group area offshore the mouth of the Murray River, for the latter part of the Holocene. Nevertheless, this aeolian input is considered to be minimal compared with the hemipelagic clay deposition on the shelves that also contains much biogenic carbonate material. Despite the importance in surface area of the continental margin around the Australian...
mainland, there are so far only few studies dealing with present-day sedimentation, with most focused on the northern Australia shelf (Brunskill et al. 2002; Pfitzner et al. 2004). A 3D representation of the southeast Australian margin described it as being narrow, steep and sediment deficient as a result of its tectonic history of asymmetric passive margin rifting (Boyd et al. 2004).

**THIS STUDY**

The purpose of this investigation is to quantify modern sedimentation (bioturbation, sediment and mass accumulation rates) on the Australian margin on century timescale by using a multi-tracer approach. Here, we report detailed depth profiles of the particle-reactive radionuclides $^{234}$Th ($T_{1/2} = 24.1$ days), $^{210}$Pb ($T_{1/2} = 22.3$ years) and $^{232}$Th ($T_{1/2} = 1.40 \times 10^{10}$ years) in interface sediments collected around the 1000 m depth contour along the southern and southeastern Australian margins during several cruises (Figure 1): (1) SS2011-T01, along the western margin of the Tasman Sea in March 2011; (2) SS2011-T04 in November 2011 along the southern margin of Australia, using the RV Southern Surveyor; and (3) MD131 in March 2003 focusing on the Murray Canyons Group, offshore Kangaroo Island along the southern margin of Australia, using the RV Marion Dufresne.

This study was conducted in parallel with the examination of organic compounds ($U_{47}$ and TEX$^{1186}$; see Smith et al. 2013) in the same cores discussed here so as to reconstruct sea-surface temperatures for the last few centuries. For this purpose, we chose to collect sediment cores around the 1000 m contour so as to minimise terrigenous input and also for comparison along the Australian continental margin (see below). In another paper, we will use the data acquired here to provide a chronology for each level within samples in all the multicores analysed for organic compounds.

**MATERIAL AND METHODS**

**Sampling**

The core sampling targeted the 1000 m contour first to avoid reworking along the margin in shallower waters. In addition, sedimentation rates usually decrease with
Table 1 Location and water-column depth of the studied cores. Sedimentation and mass accumulation rates (SAR; MAR) calculated from $^{210}$Pb$_{xs}$ profiles. Bioturbation coefficients ($D_b$) calculated from $^{234}$Th$_{xs}$ profiles. When $^{234}$Th$_{xs}$ profile presents only a single point, $D_b$ is assumed to be $<0.1$ cm$^2$ y$^{-1}$. n.d.: there is some evidence of mixing of the first centimetre owing to sampling and $D_b$ was not determined.

| Site | Latitude | Longitude | Water depth | Water depth | $^{210}$Pb$_{xs}$ | $^{234}$Th$_{xs}$ |
|------|----------|-----------|-------------|-------------|-------------------|-------------------|
|      | °S       | °E        | m           | S cm$^{-1}$ y$^{-1}$ | MAR mg cm$^{-2}$ y$^{-1}$ | $D_b$ cm$^2$ y$^{-1}$ |
| Western Tasman Sea (SS2011-T1 cruise) |
| S2   | 41°25’   | 148°47’   | 1015        | 0.058       | 57                | <0.1             |
| S3   | 39°17’   | 148°55’   | 1249        | 0.087       | 74                | 0.60             |
| S4   | 37°41’   | 150°18’   | 732         | 0.143       | 125               | <0.1             |
| S5   | 35°27’   | 150°51’   | 765         | 0.280       | 222               | 2.09             |
| S8   | 28°05’   | 154°01’   | 586         | 0.059       | 53                | 0.16             |
| S10  | 27°39’   | 154°02’   | 954         | 0.052       | 41                | <0.1             |
| Southern Australian margin (SS2011-T4 and MD131* cruises) |
| S11  | 32°17’   | 114°33’   | 1034        | 0.046       | 47                | 0.34             |
| S15  | 34°46’   | 119°39’   | 1080        | 0.027       | 28                | <0.1             |
| S17  | 34°41’   | 122°41’   | 726         | 0.045       | 52                | n.d.             |
| S18  | 34°15’   | 125°17’   | 1297        | 0.043       | 41                | 0.37             |
| MUC03a | 36°43’   | 136°48’   | 949         | 0.119       | 100               | 0.15             |
| S19  | 37°53’   | 139°36’   | 1117        | 0.044       | 37                | 0.19             |
| S20  | 39°11’   | 142°29’   | 1160        | 0.048       | 36                | 0.52             |
| S21  | 42°46’   | 144°46’   | 1277        | 0.038       | 32                | 1.34             |

a: core MUC03a was the only core taken during cruise MD131

Sedimentation on Australian continental margins

depth; for example, Soetaert et al. (1996) proposed a relationship between water depth ($D$) and sedimentation rate ($S$, $S = 982 \cdot D^{-1.548}$, $n = 110$, $r^2 = 0.66$). Despite variability in sedimentation intensity, the 1000 m contour appears the optimal depth to recover interface sediments with little reworking and still measurable sedimentation rates. Each coring site was carefully selected based on previously acquired swath map data and seismic profiles so as to ensure suitable sediments for coring.

Sediments were collected using a multicorer [consisting of a tripod that holds up to eight short (<60 cm long) tubes that permit sampling of undisturbed sediments] in order to recover a well-preserved water–sediment interface. Visual inspection of each set of cores confirms the absence of disturbance related to coring or to bioturbation, except in core S5 where worm burrows were observed down to 6–8 cm. Immediately after core retrieval, tubes were carefully extruded with sediment subsampled at 0.5–1 cm intervals and stored on board in a cold room at 4°C.

Analysis of radionuclides

In the laboratory, dry bulk density (DBD) was measured by determining the weight after drying (60°C) of a known volume of wet sediment. Following this procedure, $^{234}$Th, $^{232}$Th, $^{210}$Pb, and $^{228}$Ra activities were measured using a very low background, high-efficiency, well-shaped $\gamma$-detector equipped with a Cryo-Cycle (CANBERRA) (Schmidt et al. 2014). The standards used for the efficiency calibration of the detector are RGU and RGTh gamma standards from IAEA. $^{210}$Pb is measured directly by its peak at 46.5 keV, $^{228}$Ra is measured by selected gamma rays of its progenies $^{214}$Pb (295.2 and 351.9 keV) and $^{214}$Bi (609.3 keV) and $^{232}$Th using the gamma rays emitted by its short-lived decay product $^{232}$Pb (238.6 keV) (Schmidt & Cochran 2010; Reys et al. 1995). Errors on radionuclide activities are based on 1 standard deviation counting statistics. Excess $^{234}$Th and $^{210}$Pb data were calculated by subtracting the activity supported by their respective parent isotope from the total activity in the sediment, and then by correcting $^{234}$Th values for radioactive decay that occurred between sample collection and counting (this correction is not necessary for $^{210}$Pb owing to its longer half-life). The long-lived $^{232}$Th is usually associated with the detrital fraction, and so activity levels can be an indication of lithological proportions (Stupar et al. 2014).

Complementary analyses

Grain size analyses on wet sediment aliquots were performed with a Malvern Laser diffraction particle sizer. The organic carbon ($C_{org}$) and carbonate ($CaCO_3$) contents were determined on bulk and decarbonated sediments by direct combustion in an LECO CS 125 analyser (Schmidt et al. 2010).

Determination of bioturbation, sediment and mass accumulation rates

Sedimentation and mixing rates are generally determined by means of tracers that reach the seafloor in association with particles settling through the water column (Nittouer et al. 1984; Krishnaswami & Cochran 2006). Taking into account its very short half-life ($t_1/2 = 24.1$ days) and sedimentation rates usually encountered...
on continental slopes and shelves (far less than 1 cm y⁻¹), ²³⁴Thxs penetration to variable depths indicates efficient mixing of the upper sediments, usually by bioturbation. The simplest way to derive bioturbation rates (Db) from ²³⁴Thxs profiles is to assume bioturbation as a diffusive process occurring at a constant rate within a surface mixed layer under steady state, according to:

\[
\frac{[²³⁴\text{Th}]_{xs}}{C_0} = \frac{[²³⁴\text{Th}]_{xs}}{C_0} \exp \left( -\frac{z}{D_b} \right)
\]

where \([²³⁴\text{Th}]_{xs},0\) denotes the activities of ²³⁴Thxs, respectively at the water–sediment interface and at depth \(z\), and \(\lambda\) is the radioactive decay constant of ²³⁴Th (Aller & DeMaster 1984). We present ²³⁴Th profiles and derived bioturbation rates as an indication of particle input over the last few months of sedimentation.

The ²¹⁰Pb measurements have been widely used to calculate short-term (years to decades) sediment accumulation rates in continental and oceanic environment over the last 40 years (Kirchner 2011; and references herein). Dating is calculated using excess activity of ²¹⁰Pb (²¹⁰Pbxs), which decays with time in the sediment column according to its half-life. It is assumed that the specific activity of newly deposited particles at a given site is nearly constant with time. Consequently, sediment accumulation rate can be derived from ²¹⁰Pb, based on two assumptions: (1) constant flux, and (2) constant sediment accumulation rate (referred to as the CF:CS method). As a result, the decrease in ²¹⁰Pbxs activities with depth is described by the following relation:

\[
\frac{[²¹⁰\text{Pb}]_{xs}}{C_0} = \frac{[²¹⁰\text{Pb}]_{xs}}{C_0} \exp ( -\lambda S / \lambda )
\]

where \([²¹⁰\text{Pb}]_{xs},0\) denotes the activities of excess ²¹⁰Pb at surface, or the base of the mixed layer and depth \(z\), \(\lambda\) is the decay constant of the nuclide, and \(S\) is the sediment accumulation rate. Sediment accumulation rates were calculated from the slope of the ²¹⁰Pb profile below the surface mixed layer (SML). The bioturbation effect is not considered, and \(S\) corresponds to maximum values. An alternative method is to plot the regression of ²¹⁰Pbxs against cumulative mass in order to calculate the mass accumulation rate (MAR), which integrates the compaction effect. Both estimates are given, but the first one is the one used most commonly.

RESULTS AND DISCUSSION

Margin of the western Tasman Sea

For the margin of the western Tasman Sea, surface ²³⁴Thxs activities ranged between 19 and 197 mBq.g⁻¹ (Figure 2) and were generally confined in the first 0.5 cm; only the core S3 showed a penetration down to nearly 2 cm, consistent with a mixed layer in the upper ²¹⁰Pbxs profile. Bioturbation rates range between negligible values up to 2.1 cm² y⁻¹. ²¹⁰Pb excesses are detected at depth ranging between 4 and 17 cm, depending on the sites (Figure 2), testifying to large differences in sedimentation rates. The highest MARs (125–222 mg cm⁻² y⁻¹) for the margin of the western Tasman Sea are observed in cores S4 and S5 (Figure 3) and are associated with the highest content in organic carbon. Off East Tasmania, core S2 records among the lowest sedimentation intensity of this transect associated with coarse surface sediments (121–153 μm) that present also a low Corg content (<0.3 % (dry weight)). Core S1 did not penetrate soft sediment and returned only a few gravels. This indicates a location not favourable to sediment deposition owing to a winnowing effect related to local hydrological conditions.

Figure 2 Depth profiles of ²¹⁰Pbxs (dark circles) and ²³⁴Thxs (grey triangles) activities for all the multicores studied here. Next to the core label numbers are the water depth at which the cores were collected. Error bars on radionuclides profiles correspond to 1 SD.
currents in the area are known to have reached speeds of up to 0.46 m s\(^{-1}\) (Harris et al. 1999).

**Southern Australian margin**

Along the 1000 m depth contour of the southern Australian margin, \(^{234}\)Th\textsubscript{xs} is mainly detected in the first 0.5 cm, with surface activities ranging between 14 and 59 mBq g\(^{-1}\). These are among the lowest values observed in this work (Figure 2). Surface \(^{210}\)Pb\textsubscript{xs} activities are also low, comprising between 32 and 279 mBq g\(^{-1}\). The lowest \(^{234}\)Th and \(^{210}\)Pb excesses are mainly observed on the west side of the southern Australian margin. Cores S11 to S18 are also characterised by the highest CaCO\(_3\) content reported in this work, with coarser surface sediment (mean grain size up to 67 \(\mu\)m) and low detrital content, as revealed by the low \(^{232}\)Th activities (below 4 mBq g\(^{-1}\)) (Figure 3 and supplementary data). Bioturbation rates are comprised between negligible values to 0.37 cm\(^2\) y\(^{-1}\), indicating negligible to low mixing of interface sediments. We failed to recover short cores between S11 and S15, along the southwestern corner of Western Australia (Figure 1) and assume that this indicates unfavourable area for sediment deposition and very slow sedimentation rates. On the southwestern border of the Australian margin, cores S11 to S18 present low sediment and MARs, varying between 0.027 and 0.046 cm y\(^{-1}\) and between 28 and 52 mg cm\(^{-2}\) y\(^{-1}\), with low-carbon sediment (0.2–0.5 wt% C\(_{org}\)).

On the eastern side of the southern Australian margin, apart from the Murray Canyon Group area (discussed below), cores S19 and S20 present enhanced
and a change in the composition, with enhanced C$_{org}$ and $^{232}$Th contents along with fine sediment (mean grain size around 10–14 μm). However, SAR and MAR do not notably differ in intensity compared with the western side (Figure 3). Core S21 on the western side of Tasmania is more comparable with core S2 on the eastern side of this island, with high carbonate (~70 % (dry weight)) and low C$_{org}$ (about 0.3 % (dry weight)) contents.

Submarine canyons area off South of Australia

Core MUC03, recovered at a water depth of 949 m on a platform in the Sprigg Canyon, shows the highest sedimentation rate (0.12 cm y$^{-1}$) recorded along the southern Australian margin (Figure 3; Table 1). The presence of freshly deposited particles, tagged by $^{234}$Th in excess, $^{210}$Pb-based sediment accumulation and focusing based on $^{230}$Th (see Schmidt et al. 2010 for details) support the occurrence of significant advection of marine sediments in comparison with the adjacent margin. The Australian continental margin host over 700 canyons, with 95 of these identified as shelf-incising and then likely to export sediment to the deep sea over geological timescales (Huang et al. 2014). The Sprigg Canyon, the largest canyon of the spectacular Murray Canyons Group (MCG), located offshore Kangaroo Island, coalesces from the continental rise down to 5000 m, some of which appears to be linked to ancient courses of the Murray River that would have flowed across the Lacepede Shelf during periods of low sea level (Hill et al. 2005; Figure 1). The MCG acts as an ‘amplifier’ of sediment supply through the conduits down to the deep ocean despite the fact that the Murray River today sheds little sediment to the ocean. Our core site MUC03 lies on a promontory within the MCG area and was already the subject of a study by Schmidt et al. (2010).

Synthesis of the present sedimentation on the Australian continental margin

For the southern margin of Australia (cores S11 to S21, but ignoring MUC3), we note that sediment rates range between 0.027 and 0.048 cm y$^{-1}$, with a minor increase in the sedimentation intensity, but mainly a change in sediment nature, eastward. Whereas sedimentation rates are low and associated with carbonates on the western side, sediments are more influenced by the detrital fraction and organic carbon on the eastern side. This change could be related to the continental sediment flux to the coastal zone. Wasson et al. (1996) have estimated the mean annual sediment yield for a 1000 km$^2$ rural basin to be 1 kt y$^{-1}$ in the southwest of the continent and between 8 and 22 kt y$^{-1}$ on the southeastern side of Australia, including the Murray-Darling Basin. The estimates correspond to sediment yield on the mainland with much of the material being transported only over short distances. Nevertheless, this gives an indication of the potential flux of sediment to the coastal zone. The difference between sediment deliveries could account for the changes in sedimentation between the western and eastern margins of southern Australia.

The western margin of the Tasman Sea (cores S2–S10) is characterised by a narrow continental shelf, and rivers there have moderate flows compared with the North West Shelf of Australia (Alongi et al. 2013). Consequently, sediment accumulation rates are moderate to high (compared with the other sites investigated in this work): between 0.052 and 0.280 cm y$^{-1}$. Unfortunately, we could not retrieve cores offshore Sydney owing to the presence of telephone cables in the area. However, Matthai et al. (2001) previously reported higher sedimentation accumulation rates, ranging between 0.2 and 0.4 cm y$^{-1}$, on the middle shelf adjacent to Sydney. It is possible therefore that this area may also register higher sedimentation rates on the upper slope, owing to the presence of abundant sediment that accumulated in the bays around Sydney and that could eventually be delivered to the shelf during periods of heavy river discharges. It is noticeable that cores S4 and S5 off southern New South Wales present the highest sedimentation rates.

The MCG multicore samples, on the other hand, with their extremely high carbonate contents, indicate that, over the last three centuries, there was little supply of River Murray sediments. In fact, over the last six decades, significant impoundment on this fluvial system seriously constrained river flows (Wasson et al. 1996, table 1). This is consistent with the findings of Gingele et al. (2007), which indicate minor river, as well as eolian, inputs in the upper section of gravity core MD03-2611. Dams constructed on the Murray River have further decreased sediment supply as seen in the ‘recent’ sediment recovered in the multicorers (Schmidt et al. 2010).

Comparison with nearby margins

Sediment and MARs along the 1000 m depth contour along the southern and southeastern Australian margin are in the lower range of values, based on $^{210}$Pb, reported for this oceanic region. For example, Muhammad et al. (2008) reported SAR ranging between 0.05 and 0.23 cm y$^{-1}$ at equivalent depths in the Gulf of Papua. Locally, high accumulations of modern sediments have also been reported as for the outer Poverty continental margin of New Zealand (Alexander et al. 2010). Further north, the continental margin off southern Taiwan registers high sediment MARs (around 100 mg cm$^{-2}$ y$^{-1}$ at 1000 m depth), sustained by high fluvial sediment inputs that lead to efficient trapping of organic carbon (Kao et al. 2006). The bottom part of the Kuroshio Current also transports particles as part of a bottom nepheloid layer that promotes silt to clay deposition (140 mg cm$^{-2}$ y$^{-1}$) on the upper slope of the East China Sea margin (Oguri et al. 2003; Yamada et al. 2006).

In contrast, the Australian MARs for around the 1000 m depth contour obtained from the multicores at opposite locations (north and southeast) regions reveal that this continent is a poor supplier of terrigenous material to the deep ocean in contrast to the mountainous regions to the north located in the tropics where erosion is also of several orders of magnitude higher. In addition, Australia’s sedimentation rates are known to have remained low, even during the Quaternary glacial periods (Helmsath et al. 2000). Australia, with 47% of its surface area benefiting from internal drainage, owing to
low rainfall and elevation, contributes little sediment to the coastal ocean (Wasson et al. 1996; Woolfe et al. 1998). Most of the sediment is derived from the tropical drainage along its northeastern coast and Timor (Wasson et al. 2010).

Observations of sediment characteristics and in particular sediment accumulation rates are generally interpreted with reference to regional differences in climate and river runoff. For the southern portion of Western Australia, as for the vast Great Australian Bight (over 1500 km wide), with no river reaching the ocean, sedimentation rates are explicity very low. The other rivers for the regions discussed here (Figure 1) are again small compared with European, Asian or American rivers. Even the large Murray-Darling system, which drains over 1 million km², frequently does not discharge to the sea today.

CONCLUSION

The aim of this work was to characterise modern sediment deposition on the southern and southeastern Australian continental margin using a multi-tracer approach based on 234Th, 210Pb and 228Ra. These data fill an information gap on a region of the world for which no sedimentation rates have been accurately assessed and would serve as a reference for further studies. Indeed, regarding the importance of the continental margin in general and the number of published studies on European margins by example, the lack of data on sedimentation rates for the Australian margin is wanting. Thus far, the profiles reported here are the first investigations to quantify the present-day sedimentation intensity for deep-water sediments in the Australian continental margin, apart from the work in the MCG area by Schmidt et al. (2010). MARs overall remain low to moderate, by comparison with the expected values on the upper slope of continental margins (Soetaert et al. 1996), and this is no surprise knowing the overall low relief of the Australian continent and the lack of tectonic activity in the region.

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SUPPLEMENTAL DATA

Supplementary Table 1 Dry Bulk Density (g cm⁻³) (DBD) activities of 210Pb, 226Ra, 228Ra and 234Th, mean grain size, percentage organic carbon (C_orp) and percentage CaCO₃ content for the cores collected obtained along the western margin of the Tasman Sea during the SS2011-T1 cruise.

Supplementary Table 2 Dry Bulk Density (g cm⁻³) (DBD) activities of 210Pb, 226Ra, 228Ra and 234Th, mean grain size, percentage organic carbon (C_orp) and percentage CaCO₃ content for the cores collected obtained along the southern margin of Australia during the SS2011-T4 cruise.

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