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Abstract: The Australian continental margin hosts numerous canyons. Some of the most spectacular canyons are located offshore Kangaroo Island, and these are linked to ancient courses of the River Murray, which would have flowed across the very wide Lacepede Shelf during periods of low sea level. During the AUSCAN-1 project, modern sedimentation was assessed using a multi-tracer approach on interface sediments from 350 to 2500 m water depth. The presence of freshly deposited particles, tagged by ^{234}Th in excess, ^{210}Pb-based sediment accumulation (0.03–0.13 cm a^{-1}) and ^{230}Th-based focusing ratios, supports the occurrence of significant advection of marine sediments within these canyons. In the absence of direct riverine inputs, the shelf, being the site of intensive carbonate production, is the main supplier of material. The presence of incised channels in the eastern portion of the Murray Canyons Group (MCG) indicates recent to sub-recent activity along the canyons. The presence of underwater slides in the western side of the MCG confirms that sediment transport to the abyssal plain does occur. Based on our preliminary investigation and by synthesizing previous work on other canyons, we provide a conceptual model for sediment focusing and transfer within the canyons offshore Australia.

Canyons are often presented as natural conduits for the transfer of particulate matter from the shelf to the deep ocean (Carson *et al.* 1986; Gardner 1989). Although the Holocene sea-level rise drastically reduced the supply of coarse-grained sediments to abyssal depths, canyons continue to be favourable sites for the concentration and accumulation of fine-grained sediments (Biscaye & Olsen 1976; Hickey *et al.* 1986). Sediment is probably not produced locally within the canyon but transported from shallow coastal areas (Granata *et al.* 1999). Canyons seem to act as sediment traps for material transported along slope by oceanic currents (Liu & Lin 2004; Palanques *et al.* 2005). Some active downslope transport of sediments, such as in turbidity events, also occurs (Mulder *et al.* 2001; Khripounoff *et al.* 2003; Puig *et al.* 2003). However, the age and the frequency of sedimentary processes transporting sediments through canyons, and to the overbank deposits on the flanks of associated channels, are usually unknown. Nevertheless, this knowledge is important for understanding the reason for canyons being 'hotspots' for biological activity, and how changes in the quality and intensity of particle supply could affect a canyon and its associated productivity. It is known that additional supply of particulate matter, especially organic in origin, can enhance biological productivity and diversity (Ruhl & Smith 2004).

The Australian landmass is bordered by numerous canyons, some of which are not even charted on currently available maps. Along the southern margin of Australia, there are over 50 canyons, principally offshore the southern portion of Western Australia and offshore South Australia. It appears that some of the most spectacular canyons thus far known in the Australia region are located offshore Kangaroo Island (Fig. 1). Some of these appear to be linked to ancient courses of the River Murray, which would have flowed across the Lacepede Shelf during periods of low sea level (Fig. 2).

The objective of this investigation is to characterize sediment transport and deposition within the Murray Canyons Group on seasonal to century time scales using a multi-tracer approach. We refer here to the Murray Canyons Group as a series of canyons that coalesce from the continental rise down to 5000 m (Fig. 1). The largest canyon, called Sprigg Canyon (Figs 2 and 3), has two arms (West and East Sprigg Canyons) with, on its western side, the du Couedic Canyon and with the narrow Murray Canyon located further west, and the Gantheaume Canyon, located east of Sprigg Canyon (Fig. 1). The AUSCAN project (cruise MD131, R.V.

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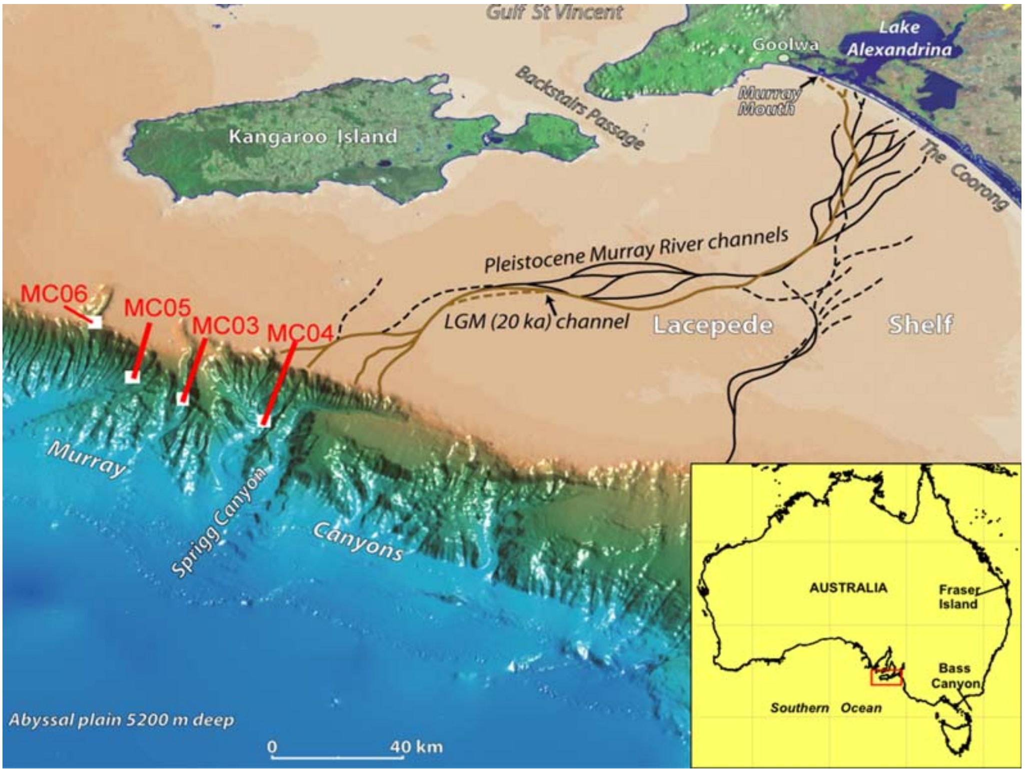

Fig. 1. Enlarged image of the Murray Canyons Group offshore Kangaroo Island in South Australia showing the location of the multicores studied here taken at various depths in the canyons area. The location of the Lacepede Shelf, and the various courses of the palaeo-Murray River for periods of low sea level (after Hill *et al.* 2009), should be noted. The image was generated by P. J. Hill. The inset shows the location of the Murray Canyons and the Lacepede Shelf in Australian waters.

Marion Dufresne, in February–March 2003) permitted the first investigation of these Australian canyons to assess if they are active today or have been in the recent past. We report here detailed depth profiles of the particle-reactive radionuclides ^{234}Th (half-life 24.1 days), ^{210}Pb (22.3 years), and ^{230}Th (75.3 ka) and of $CaCO_3$ and organic carbon (C_{org}) content in interface sediments collected at different depths within the canyons during the AUSCAN cruise (Hill & De Deckker 2004). These results are discussed to characterize the present sedimentation framework (bioturbation, sediment accumulation, focusing) of the Murray Canyons Group.

Physical setting

It is through the principal efforts of Francis Sheppard and colleagues in the USA (see Sheppard *et al.* 1979), starting in the 1950s, that oceanographers and marine geologists became interested in deep-sea canyons. It is only during the last two decades that marine biologists and ecologists commenced investigating the biodiversity, productivity and uniqueness of deep-sea canyons (see Vetter 1994; Vetter & Dayton 1998). Deep-sea canyons have been extensively studied offshore California, parts of Canada and along the east coast of the USA (Eittreim *et al.* 1982; Mullenbach *et al.* 2004; Mullenbach & Nittrouer 2006). Other canyons have received attention offshore the European margin (Radakovitch & Heussner 1999; van Weering *et al.* 2002; Palanques *et al.* 2005), as well as New Zealand (Lewis & Barnes 1999; Orpin 2004; Orpin *et al.* 2006), Taiwan (Liu & Lin 2004) and Japan (Nakajima *et al.* 1998; Noda *et al.* 2008).

Surprisingly, since the pioneering work of the eminent South Australian geologist R. C. Sprigg in 1947 when the canyons offshore South Australia became known, and the subsequent investigations of J. Conolly and C. von der Borch up to 1968 (von der Borch 1968; von der Borch *et al.* 1970), little work has been done except for the recent investigations of Bass Canyon on the eastern edge

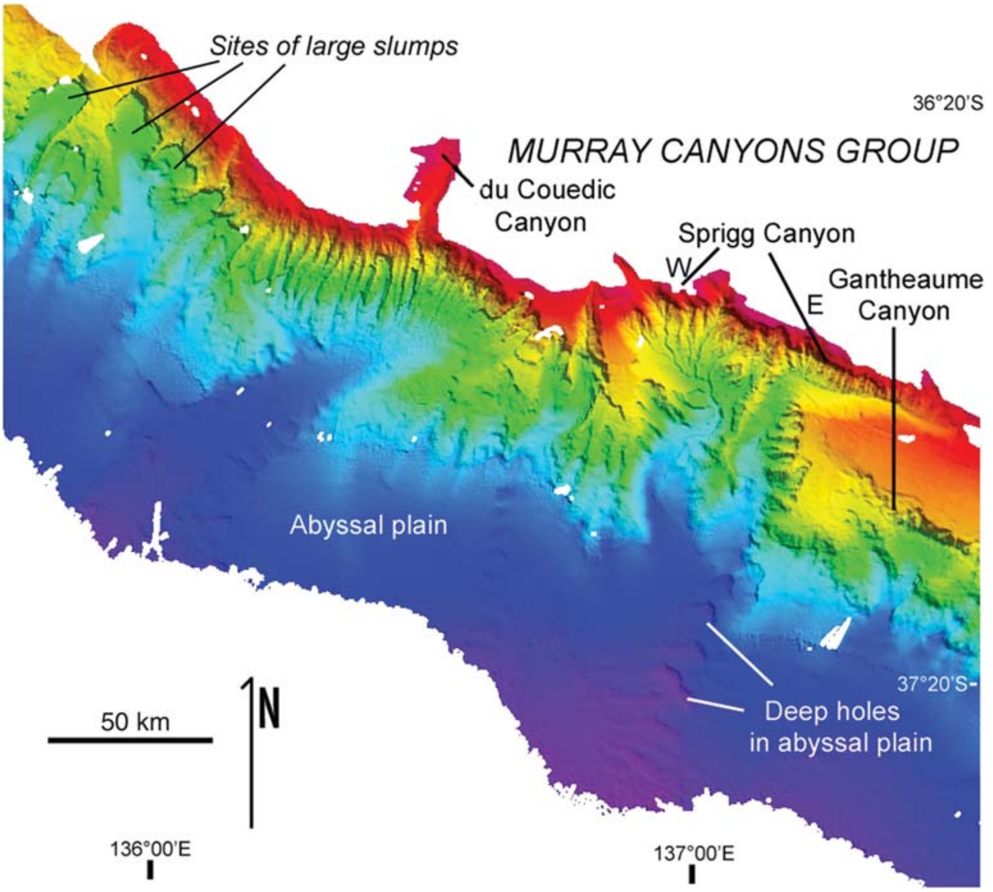

Fig. 2. Image generated from swath mapping data gathered during several cruises [for more details refer to Hill & De Deckker (2004) and updated with additional information gathered during the R.V. *Southern Surveyor* cruise SS02/06]. The white areas are those for which no information is currently available. A noteworthy feature is the presence of deep holes in the abyssal plain that appear to be lined up. Recent investigations by M. Mojtahid at the Australian National University have revealed obvious turbiditic sequences in a 2.71 m long gravity core (GC2), thus indicating that at least one hole can be considered to be a large 'plunge pool' formed by erosive turbidity flow down a canyon, as postulated by Hill *et al.* (2009). Their origin is still controversial. On the left side of the image can be seen the scars left by very large underwater slides, resulting in slope failure, which potentially could have generated large tsunamis. Such features are common along the continental slope of southern Australia (see also Exon *et al.* 2005) and have been mapped as far as the Victorian border during cruise SS02/06. They may be caused by water seepage along the shelf and be the trigger for the earlier formation of deep-sea canyons, prior to being incised further by large rivers, especially during periods of low sea level. Depths: red <200 m; yellow >200 m and <1000 m; green >1000 m and <4000 m; blue >4000 m.

of Bass Strait (Mitchell *et al.* 2007*a*, *b*). Hill *et al.* (2001) were the first to adequately document the nature and morphology of several of the deep canyons along the margin of southeastern Australia, including the Murray Canyons (see also the cruise report of Hill & De Deckker 2004). In addition, Exon *et al.* (2005) explored the Albany canyons offshore the SW of Western Australia. Subsequent studies on the sedimentological and geochemical aspects of two long cores taken in the vicinity of the Murray Canyons Group were published by Gingele *et al.* (2001, 2004, 2007; Gingele & De Deckker 2005).

Material and methods

Analytical method

Our investigation deals with sediments at the interface between the sea floor and the overlying water.

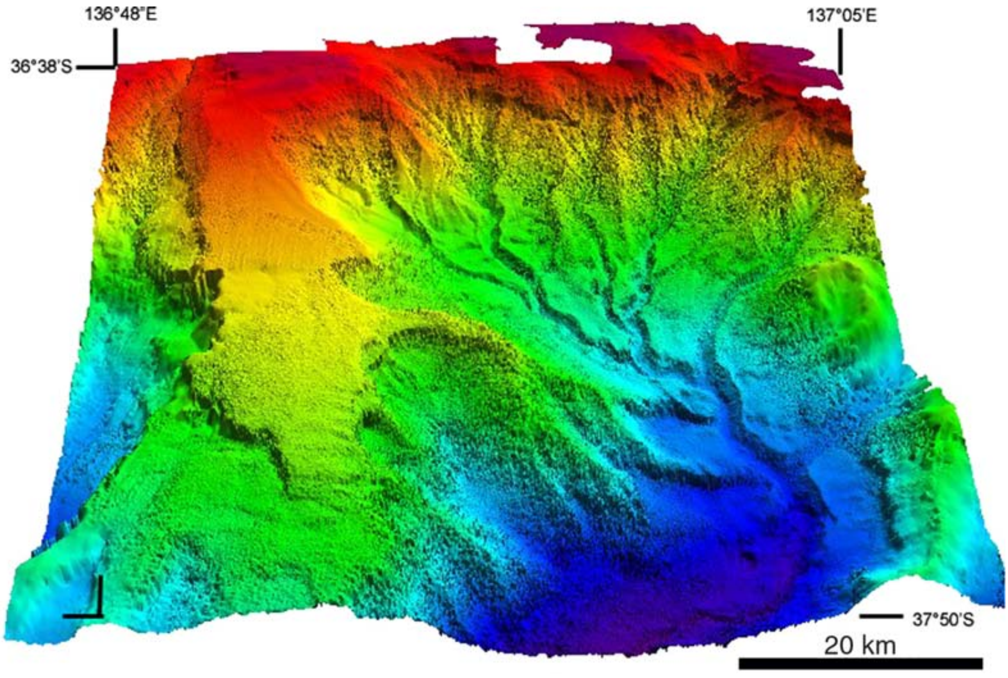

Fig. 3. Detailed view, tilted by *c*. 15°, of the western side of Sprigg Canyon showing the entrenched underwater 'fluvial' channels that display evidence of erosion and underwater transport, which therefore must still be effective today otherwise the channels would have filled up. The Sprigg Canyon is named after Reginald Sprigg, who was the first to document these underwater features (Sprigg 1947). Multicore MUC04 was taken on the 'peninsula' on the western side of the canyon. The colour scheme is similar to that used in Figure 2.

The sediments were obtained from the head of du Couedic Canyon and along the West Sprigg Canyon as well as the spur that separates the two arms of Sprigg Canyon (Figs 1–3; Table 1). Immediately after core retrieval from a multicorer, tubes were carefully extruded with sediment taken at 0.5 cm intervals from 0 to 5 cm, and 1 cm intervals below that depth.

In the laboratory, dry bulk density was measured by determining the weight after drying (60 °C) of a known volume of wet sediment. Following this procedure, ^{234}Th, ^{210}Pb and ^{226}Ra activities were measured using a low background, high-efficiency, well-shaped γ detector (Schmidt *et al.* 2001). Error on radionuclide activities are based on 1 SD counting statistics. Excess ^{234}Th and ^{210}Pb data were calculated by subtracting the activity supported by their parent isotope, ^{238}U and ^{226}Ra respectively, 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 because of its longer half-life). Errors on $^{234}Th_{xs}$ and $^{210}Pb_{xs}$ are calculated by propagation of errors in the corresponding pair, ^{234}Th and ^{238}U, or ^{210}Pb and ^{226}Ra.

The determination of U and Th isotopes relies on a complete dissolution of the sediment by a mixture of $HF{-}HNO_3{-}HClO_4$. The radionuclides of interest were purified by ion exchanges on anionic resins (Schmidt 2006). A known amount of a calibrated ^{228}Th/^{232}U spike was added at the beginning of the digestion to determine chemical yield. ^{230}Th, ^{234}U and ^{238}U activities were determined by α counting as previously explained by Schmidt (2006).

The organic carbon (C_{org}) and carbonate ($CaCO_3$) content were determined on dry weight sediment by combustion in an LECO CS 125 analyzer (Etcheber *et al.* 1999). Samples were acidified in crucibles with 2N HCl to destroy carbonates, then dried at 60 °C to remove inorganic C and most of the remaining acid and water. The analyses were performed on bulk and decarbonated sediments by direct combustion in an induction furnace, and the CO_2 formed was determined quantitatively by IR absorption.

Data treatment

Sediment accumulation rates derived from ^{210}Pb. The ^{210}Pb method is based on the measurement of

Table 1. *Site location, sedimentation and mass accumulation rates derived from $^{210}Pb_{xs}$ profiles, $^{234}Th_{xs}$ inventories and bioturbation rates for the multicores from the Murray Canyons Group (AUSCAN cruise)*

Site	Latitude (S)	Longitude (E)	Depth (m)	$^{210}Pb_{xs}$		$^{234}Th_{xs}$		$CaCO_3$ (%)	C_{org} (%)
				S ($cm\ a^{-1}$)	MAR ($mg\ cm^{-2}\ a^{-1}$)	I ($dpm\ cm^{-2}$)	D_b ($cm^{-2}\ a^{-1}$)		
Sprigg canyon, west side									
MD131-MC03	36°43.40′	136°47.32′	949	0.119	100	2.0	0.15	82	0.93
MD131-MC04	36°48.80′	136°48.93′	1619	0.025	33	0.7	<0.10	87	0.35
du Couedic canyon									
MD131-MC06	36°31.43′	136°25.96′	354	0.088	66	12.1	2.88	96	0.74
MD131-MC05	36°43.72′	136°32.87′	2476	0.030	23	1.5	0.48	87	1.12

C_{org} and $CaCO_3$ contents (%) in surficial sediment (0–0.5 cm).

the excess or unsupported activity of ^{210}Pb ($^{210}Pb_{xs}$) which is incorporated rapidly into the sediment from atmospheric fallout and water column scavenging (Appleby & Oldfield 1992, and references therein). Once incorporated into the sediment, unsupported ^{210}Pb decays with depth, equivalent to time, in the sediment column according to its known half-life. Sediment accumulation rate can be derived from ^{210}Pb, based on two assumptions: constant flux and constant sediment accumulation rates (referred to as the CF:CS method) (Robbins & Edgington 1975). Then, the decrease of $^{210}Pb_{xs}$ activities with depth is described by the following relation:

$$[^{210}\mathrm{Pb_{xs}}]_z = [^{210}\mathrm{Pb_0}]_0 \exp\left(-z\frac{\lambda}{S}\right) \quad (1)$$

where $[^{210}\mathrm{Pb_{xs}}]_{0,z}$ is the activitiy of excess ^{210}Pb at surface, or the base of the mixed layer, and depth z, λ is the decay constant of the nuclide, and S is the sediment accumulation rate. In this model, the compaction effect is not considered, and the sediment accumulation rates correspond to maximum values. An alternative method is to plot the regression of $^{210}Pb_{xs}$ against cumulative mass to calculate a mass accumulation rate (MAR), which integrates the compaction effect. Both estimates are given, and the first one is the more commonly used.

Bioturbation rates. Taking into account its very short half-life and the sedimentation rates (which are far less than $1\ cm\ a^{-1}$), $^{234}Th_{xs}$ should be present only at the water–sediment interface. Its penetration to variable depths indicates efficient mixing of the upper sediments, usually by bioturbation. The simplest way to derive bioturbation rates (D_b) from radionuclide profiles is to assume bioturbation as a diffusive process occurring at a constant rate within a surface mixed layer under steady state (Schmidt *et al.* 2001, 2002; Lecroart *et al.* 2007). The steady-state approximation is often used to derive bioturbation rates from radionuclide profiles and introduces only limited errors (Lecroart *et al.* 2007). The latter simplification is supposed to respect the inequality $S^2 \ll 4D_b\lambda$ (Wheatcroft 2006). Sedimentation accumulation rates obtained in this study are always $<0.2\ cm\ a^{-1}$ (Table 1); therefore one can assume that sediment accumulation rates are not likely to affect $^{234}Th_{xs}$ profiles. These simplifications allow the determination of bioturbation rates from a simple plot of radionuclide activity as a function of depth, using the equation

$$[^{234}\mathrm{Th_{xs}}]_z = [^{234}\mathrm{Th_0}]_0 \ \exp\left(-z\sqrt{\frac{\lambda}{D_b}}\right) \quad (2)$$

where $[^{234}\mathrm{Th_{xs}}]_{0,z}$ is the activity ($dpm\ g^{-1}$) of excess ^{234}Th at the water–sediment interface (Schmidt *et al.* 2001). We present ^{234}Th-derived bioturbation rates and inventories as an indication of particle input over the last few months. Such bioturbation rates must be considered as an instantaneous signal (Aller & Demaster 1984; Schmidt *et al.* 2002).

Sediment focusing

Sediment focusing is a process whereby water turbulence or other processes transfer sediment from shallow to deeper zones in the ocean. The focusing factor ϕ, based on ^{230}Th, has been proposed to distinguish between the contribution from vertical fluxes originating from the overlying waters, and lateral fluxes resulting from sediment redistribution by bottom currents (François *et al.* 2004, and references therein) using the relationship

$$\phi = \frac{F_s}{F_p} \quad (3)$$

where F_p, the flux of scavenged ^{230}Th reaching the sea floor with particles settling through the water column, is close to the rate of ^{230}Th production from the decay of ^{234}U over the depth (z in metres) of the overlying water column: $F_p = 0.0267 \times z$ dpm m^{-2} a^{-1}.

F_s is the accumulation rate of $^{230}Th_{xs}$ (dpm m^{-2} a^{-1}) in sediment: $F_s = [^{230}Th_{xs}]_0 \times S \times$ DBD, where $[^{230}Th_{xs}]_0$ is the concentration (decay-corrected) of $^{230}Th_{xs}$, S is the sedimentation rate (cm a^{-1}), and DBD is the dry bulk density (g cm^{-3}).

$^{230}Th_{xs}$ is calculated by subtracting from the measured total ^{230}Th the detrital and authigenic contributions (for details, see Veeh *et al.* 2000) to calculate the amount of ^{230}Th originating from scavenging in the water column, referred to as 'in excess' (in contrast to the supported detrital and authigenic fractions of ^{230}Th in sediment). Independent chronology was obtained for interface sediments using sedimentation rates derived from ^{210}Pb. Detrital uranium was derived from the measured total U and Th concentrations by assuming that all Th resides in detrital phases. Authigenic uranium was calculated as the difference of total and detrital uranium. Despite the occurrence of a significant fraction of authigenic U in our cores, the corrections for *in situ* growth of ^{230}Th are minor, with respect to the half-life of ^{230}Th, on such young sediments at the sediment–water interface.

Results

In the Murray Canyons Group, surface excess ^{210}Pb activities range from 14 to 27 dpm g^{-1} (Fig. 4). Profiles of $^{210}Pb_{xs}$ present an upper mixed layer, more pronounced in the du Couedic Canyon, followed by an exponential decrease, with ^{210}Pb activities reaching supported activity levels at about 5 cm depth. The absence of disturbance in $^{210}Pb_{xs}$ profiles is appropriate to the determination of sediment and mass accumulation rates (MAR) (Table 1). The MAR are high in the West Sprigg Canyon, with the highest value (100 mg cm^{-2} a^{-1}) registered at the site MC03 located at 949 m water depth (Fig. 4). In contrast, the shallowest site, MC06 (354 m) at the head of the du Couedic Canyon, registers a lower value (66 mg cm^{-2} a^{-1}). The deepest sites in the Murray Canyons Group have MAR ranging from 33 mg cm^{-2} a^{-1} (MC04; depth 1619 m) to 23 mg cm^{-2} a^{-1} (MC05; depth 2476 m). Sediment accumulation rates and MAR exhibit decreasing values with depth, as usually observed in margin and canyon sediments (Sanchez-Cabeza *et al.* 1999; Matthai *et al.* 2001; van Weering *et al.* 2002).

Excess ^{234}Th was always detected at substantial levels (4 and 22 dpm g^{-1}) in surface samples, in the range of values reported for continental margins elsewhere (Aller & Demaster 1984; Schmidt *et al.* 2002). Such an occurrence of ^{234}Th, with its short half-life (24.1 days), shows the presence of freshly deposited particles. The changes in activities are associated, to a lesser extent, with variations in penetration depth. The deepest penetration of $^{234}Th_{xs}$ does not exceed the mixed layer of ^{210}Pb, this latter registering a mixing event on a longer time scale. The sea-bed inventory of excess ^{234}Th can be used as an alternative tool to sediment traps for the investigation of particle dynamics at the water–sediment interface on the 100 day time scale. Sea-bed $^{234}Th_{xs}$ inventories range from 0.7 to 12.1 dpm cm^{-2} (Table 1). Sediments in the upper canyons are rather enriched in C_{org} compared with usual margin sediments (Etcheber *et al.* 1999; Fig. 4).

U and Th contents range between 1.5 and 2.6 ppm and 0.7 and 1.6 ppm respectively (Table 2), in the lower range of values for margin sediments (McManus *et al.* 2006; Yamada & Aono 2006; Yamada *et al.* 2006). The low Th concentration indicates a low fraction of detrital sediment, thus resulting in low calculated detrital uranium. This is corroborated by the high carbonate content ($>$80%; Fig. 4). Focusing factors, derived from ^{230}Th, are high, from 84 to 6, indicating a net lateral input of resuspended or advected sediment components containing excess ^{230}Th in addition to the vertical flux of particulate ^{230}Th out of the water column.

Discussion

Present-day sedimentation within the Murray Canyons Group

Bioturbation rates derived from ^{234}Th profiles (0.1–2.9 cm^2 a^{-1}) decrease with depth in the Murray Canyons Group. Mixing rates are in the range of reported values for margin environments (Soetaert *et al.* 1996), with the highest rates observed in the heads of the canyons. These values are higher than those reported for the Nazaré Canyon (Schmidt *et al.* 2001), an example of a canyon deeply incised into the continental shelf (the canyon head opens 500 m from Nazaré beach). In the Murray Canyons Group, we note significant organic inputs at the sediment–water interface, and this concurs with the observation of abundant faecal pellets on the sea floor and of significant C_{org} content (0.9–1.2%). Sediment accumulation rates based on ^{210}Pb (0.03–0.13 cm a^{-1}) exhibit the same decreasing trend with depth.

In the upper head of du Couedic Canyon (west side of the Murray Canyons Group), core MC06 displays evidence of bioturbation, which explains why ^{234}Th values are found down to 3 cm in depth

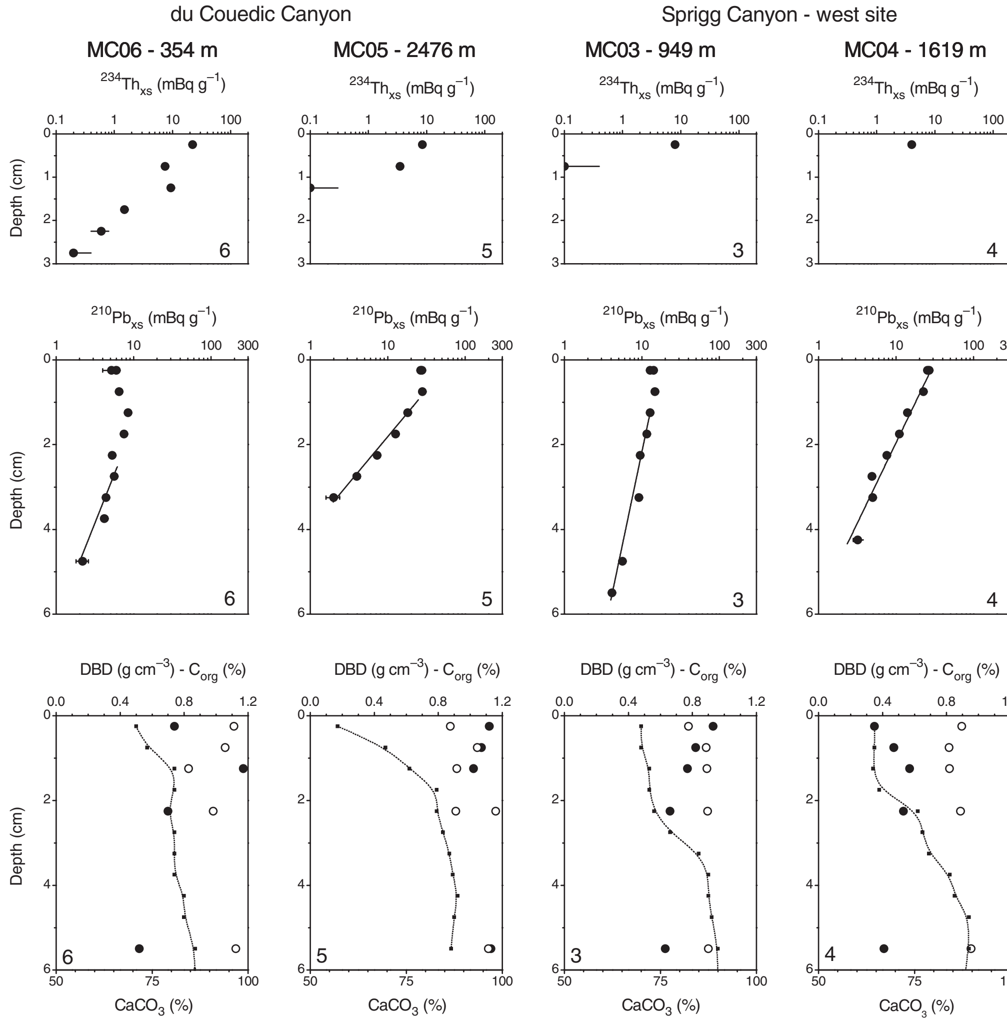

Fig. 4. $^{234}Th_{xs}$ and $^{210}Pb_{xs}$ profiles carried out on the four multicores from the two sides of the Murray Canyons Group. Dry bulk density (■, dotted line), C_{org} (●) and $CaCO_3$ (○) contents are also plotted with depth in the bottom row of panels. Error bars on radionuclides profiles correspond to 1 SD. For cores 6, 5 and 3, it is noticeable that the deepest penetration of the short-lived radionuclide corresponds to the base of the mixed layer of $^{210}Pb_{xs}$ profiles.

(Fig. 4). $^{234}Th_{xs}$-derived bioturbation rates are similar to those observed in other continental margins (Table 1; DeMaster *et al.* 1994; Schmidt *et al.* 2002). These highest signals are associated with highest $^{234}Th_{xs}$ inventories and the deepest mixed layer observed on $^{210}Pb_{xs}$ profiles. On the other hand, $^{234}Th_{xs}$-derived bioturbation rates in the west Sprigg Canyon are rather low, in agreement with a negligible mixed layer for $^{210}Pb_{xs}$ profiles. In particular, in the middle reaches of the Sprigg Canyon (MC03), there is the highest sediment deposition rate reported in this study, but the $^{234}Th_{xs}$-derived bioturbation rate and inventory are low (Table 1). Although we cannot exclude a possible loss of the uppermost layer, we interpret this trend based on the difference in particle supply to these two canyons. The decoupling between ^{234}Th and ^{210}Pb in the upper sediment can be explained by the nature and the intensity of sediment supply (Schmidt *et al.* 2001). The du Couedic Canyon appears to be a preferential conduit for fresh and organic material, although the Sprigg Canyon is active for particle transfer to the deep ocean. Dredging of the sea floor during AUSCAN-1 cruise supports this hypothesis, indicating the occurrence of abundant organisms and of faecal pellets in the Sprigg Canyon (Hill & De Deckker 2004).

Table 2. *U and Th concentrations (ppm), detrital uranium fraction ($^{238}U_d$, % of total U), ^{230}Th activities and focusing factors, ϕ, for the multicores from the Murray Canyons Group (AUSCAN cruise)*

Label	Layer (cm)	^{238}U (ppm)	$^{238}U_d$ (%)	^{232}Th (ppm)	^{230}Th (dpm g^{-1})	ϕ
Sprigg Canyon, west side						
MD131-MC03	1.25	1.55 ± 0.06	9	0.77 ± 0.08	0.72 ± 0.04	30
	5.50	1.88 ± 0.09	9	0.90 ± 0.08	0.80 ± 0.03	33
	15	2.31 ± 0.09	5	0.63 ± 0.06	0.89 ± 0.03	40
MD131-MC04	1.25	1.55 ± 0.06	11	0.97 ± 0.08	1.26 ± 0.05	6
	5.5	1.98 ± 0.08	8	0.86 ± 0.07	1.15 ± 0.04	6
du Couedic Canyon						
MD131-MC06	1.25	1.96 ± 0.05	7	0.75 ± 0.08	0.98 ± 0.04	67
	5.5	2.61 ± 0.09	5	0.70 ± 0.06	1.21 ± 0.04	84
MD131-MC05	0.75	1.69 ± 0.07	12	1.15 ± 0.08	1.58 ± 0.05	6
	5.5	2.44 ± 0.10	6	0.87 ± 0.09	1.46 ± 0.06	5

^{230}Th activities (dpm g^{-1}, number of disintegrations per minute per gram of dry sediment). ϕ, the ratio of the lateral fluxes resulting from sediment redistribution by bottom currents to the vertical particulate fluxes originating from the overlying waters.

In the Murray Canyons Group, Th and detrital U concentrations are low, indicating a limited contribution of detrital phase (Table 2). These values are very low compared with those obtained by Dosseto *et al.* (2006) for colloids and suspended sediments in the River Murray system, which have values that are at least one order of magnitude higher compared with the canyons' sediment. The findings by Dosseto *et al.* (2006) therefore indicate that contributions from the River Murray to the canyons are minimal. This result is consistent with the observation of high carbonate contents in these sediments and in long cores recovered at the same sites (Gingele *et al.* 2004); most of the sediments consist of carbonates, with a little terrigenous detritic component.

We can observe, as for the short-lived radionuclides, a decoupling of long-lived radionuclide data (Table 2) from the cores MC03 and MC06. MC03 exhibits the highest U content and increase in authigenic fraction. It has been previously suggested that the U accumulation rate is sensitive to organic carbon delivery to the sea-bed (Anderson *et al.* 1998) and therefore may indicate an enhanced input of fresh material at this site (MC03), which is consistent with high bioturbation rates and $^{234}Th_{xs}$ inventories, and C_{org} content. Focusing factors, derived from $^{230}Th_{xs}$, are between 80 and 6 (Table 2). As for the other parameters, the highest values are observed in the head of the du Couedic Canyon (MC06), thus supporting the occurrence of a significant horizontal advection of sediments within the canyon. Both tracers confirm that the upper part of Murray Canyons Group acts as an active locus for sedimentation.

Specificity of the Murray Canyons Group

In comparison with most canyons, which usually indent the coastline (Mulder *et al.* 2001; Schmidt *et al.* 2001; Palanques *et al.* 2005; Mullenbach & Nittrouer 2006), the Murray Canyons Group lies far away from the coastline and may present different dynamics of sediment particle supply. Today, fluvial inputs are likely to be negligible because of the high sea level, as well as the dams built during the last century across many locations along the River Murray (Gingele *et al.* 2004, 2007). The Murray Canyons Group multicore samples, with their extremely high carbonate contents, indicate that there is little supply of River Murray sediments.

The Lacepede Shelf is very wide, reaching 200 km width in places (Fig. 2). Along the eastern part of the Lacepede Shelf, seasonal upwellings have been recorded (Lewis 1981; Schalinger 1987), thus adding to the potential biological productivity on the shelf. This phenomenon potentially causes particulate matter to become recycled in this shallow area, and it may eventually become transported down canyons via their shallow conduits. The high percentage of carbonate sediments in the Murray Canyons multicores confirms the findings of James *et al.* (1992) that a large amount of biogenic carbonate is produced on the Lacepede Shelf.

Figure 3 clearly shows meandering channels that would have been formed by gravity flows of sediment-laden currents. The material would have obviously originated from the Lacepede Shelf as mentioned above, and the reader should refer to the description by James *et al.* (1992) of the nature of the biogenic sediment for more information. The fact that the channels are still clearly incised and empty indicates that either they must still be active or they were so in the recent past as they are not filled with sediments. Recent investigations of gravity core GC2 taken during the R.V. *Southern Surveyor* cruise SS02/06 (37°07.98′S, 136°29.753′E, 4978 m depth; 271 cm long), obtained from one of the deep holes in the abyssal plain, showed evidence of several superimposed turbiditic sequences. The unpublished work of M. Mojtahid at the Australian National University on core GC2 found that the sediment is mostly sandy and consists of calcareous biogenic remains, predominantly composed of benthic foraminifers and bryozoans, some of which would have lived in shallow water such as on the Lacepede Shelf. Of interest is the presence in some samples of fragile pteropod skeletons composed of aragonite, thus indicating a rapid burial and a shallow origin (<1000 m), as otherwise they would have been dissolved as the core location is well below the aragonite compensation depth.

The concept that underwater sediment drifts can occur today, even in the absence of onshore rivers, was elegantly illustrated by Boyd *et al.* (2008) who showed that deep-water sands that originate near the shelf edge can be delivered to great oceanic depths. In that case, Boyd *et al.* (2008) demonstrated that longshore transport occurs offshore Fraser Island along the east coast of Australia. Those workers documented obvious channels that converge towards submarine canyons. Similar channels had already been illustrated by Hill *et al.* (1998) at the head of the large Bass Canyon located on the eastern side of Bass Strait between the Australian mainland and Tasmania.

The presence of underwater slides as shown on the west of the de Couedic Canyon (Fig. 1) illustrates the presence of underwater slope failure. Jenkins & Keene (1992) found evidence of structures associated with large-scale slope failure along the southeastern Australia continental slope. Similar features were seen during R.V. *Southern Surveyor* cruise SS02/06 offshore the coast of Victoria, west of Portland. In addition, Exon *et al.* (2005) provided spectacular images of widespread and large slides on the southern tip of Western Australia, pointing to the commonness of such features. We argue here that perhaps these slides originate as a result of water seepage, of continental origin, that

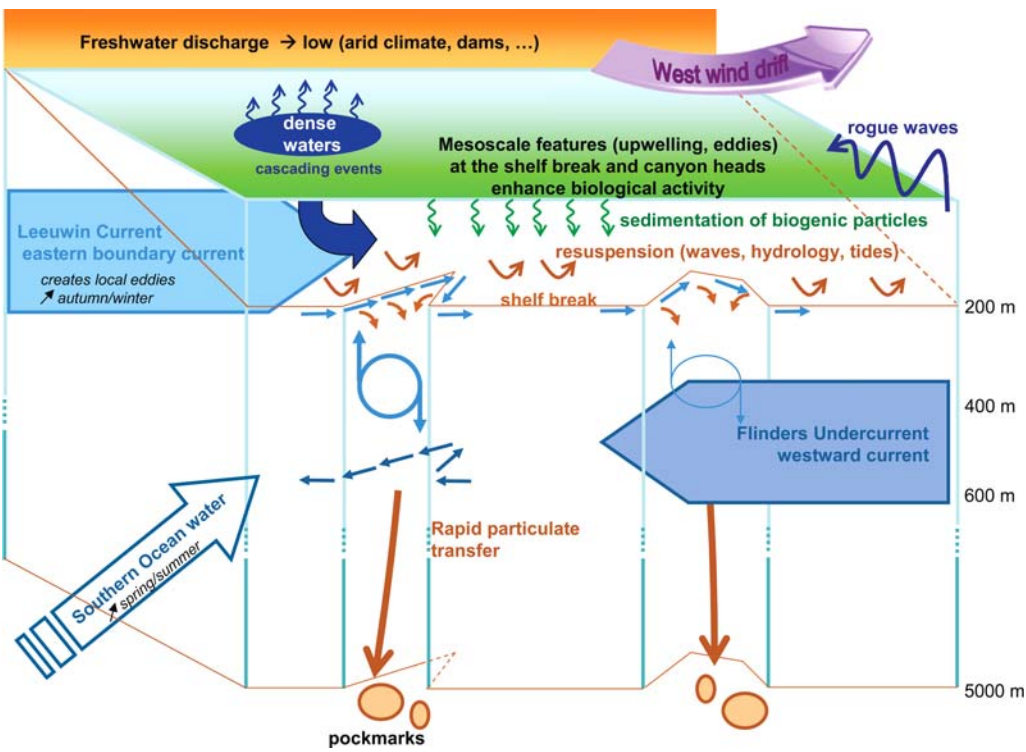

Fig. 5. Simplified model of sediment focusing and trapping mechanisms of the blind canyons off the southern margin of Australia. This model combines the various processes that are likely to contribute positively to particulate transfer towards the canyons (water fluxes in blue; particle production and transfer in green and brown). The main processes identified from the literature (Li *et al.* 1999; Ogston *et al.* 2008; Puig *et al.* 2008; Rennie *et al.* 2009*a*, *b*) principally involve hydrology, in particular the influence of the Leeuwin Current and the Flinders Undercurrent, and the occurrence of dense water formed on the Lacepede Shelf that cascades down the slope [for more information, refer to Lennon *et al.* (1987)].

'crops out' on the continental shelf and upper slope, engendering slope instability. The possible groundwater transfer along ancient courses of large rivers that are found on the continental shelf (such as documented by Hill *et al.* (2009) for palaeo-channels of the River Murray, and that would have been active during periods of low sea levels) and that contain coarse (and porous) fluvial sediments, could be the cause of underwater 'erosion' and gullying formation. This would eventually trigger the commencement of canyon formation. In addition, it is possible that such large underwater slides, as mentioned above, may potentially be able to generate tsunamis.

If the hypothesis of groundwater seepage and cropping out on the shelf and upper slope is accepted, this would explain the presence of canyons or channels that are not necessarily linked to rivers on land.

Conclusions

The Murray Canyons Group acts as an 'amplifier' of sediment supply through the conduits down to the deep ocean despite the fact that the River Murray today sheds little sediment to the ocean. In general, deep-sea canyons register much sediment deposition because they are directly linked with large rivers. Our Australian data on the Murray Canyons Group highlight, therefore, how different they are compared with many other deep-sea canyons. One plausible explanation is that Australia, as a continent, is not affected by rapid and substantial erosion, as a result of its low topography and reduced tectonic activity. The other important factor is the extensive breadth of the Lacepede Shelf.

Based on this preliminary investigation of the canyons in the MCG and by synthesizing previous work on equivalent features in deep-sea canyons (Li *et al.* 1999; Ogston *et al.* 2008; Puig *et al.* 2008; Rennie *et al.* 2009*a*, *b*), we provide a conceptual model for sediment focusing and transfer in the canyons along the southern margin of Australia (Fig. 5). Canyons do not necessarily need to be linked to specific fluvial sources to be active (Mullenbach *et al.* 2004). Our investigations of canyons offshore South Australia point to the importance of the interaction between currents and wind and the overall canyon bathymetry and configuration. Regarding circulation, the canyon topography influences the circulation dynamics of the Leeuwin Current and, subsequently, eddy development and vertical transport, which in turn affect upwelling and productivity (Li *et al.* 1999; Rennie *et al.* 2009*a*, *b*). As reported for the submarine canyons of the Gulf of Lions in the Mediterranean Sea, storm-induced downwelling and dense water cascading events efficiently transport sediment down-canyon (Ogston *et al.* 2008; Puig *et al.* 2008). The combination of these processes, acting at various degrees through different seasons, is assumed to act in favour of an efficient sediment transfer through canyons along the southern margin of Australia down to the deep ocean.

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References

Aller, R. C. & DeMaster, D. J. 1984. Estimates of particle flux and reworking at the deep-sea floor using $^{234}Th/^{238}U$ disequilibrium. *Earth and Planetary Science Letters*, **67**, 308–318.

Anderson, R. F., Kumar, N., Mortlock, R. A., Froelich, P. N., Kubik, P., Dittrich-Hannen, B. & Sutter, M. 1998. Late-Quaternary changes in productivity of the Southern Ocean. *Journal of Marine Systems*, **17**, 497–514.

Appleby, P. G. & Oldfield, F. 1992. Application of lead-210 to sedimentation studies. *In*: Ivanovich, M. & Harmon, R. S. (eds) *Uranium-Series Disequilibrium: Applications to Earth, Marine, and Environmental Sciences*. Clarendon Press, Oxford, 731–778.

Biscaye, P. E. & Olsen, C. R. 1976. Suspended particulate concentrations and compositions in the New York Bight. *In*: Gross, M. G. (ed.) *Middle Atlantic Continental Shelf and the New York Bight*. American Society of Limnology and Oceanography, Special Symposium 2, 124–137.

Boyd, R., Ruming, K., Goodwin, I., Sandsrom, M. & Schröder-Adams, C. 2008. Highstand transport of coastal sand to the deep ocean: A case study from Fraser Island. *Geology*, **36**, 15–18.

Carson, B., Baker, E. T., Hickey, B. M., Nittrouer, C. A., DeMaster, D. J., Thorbjarnarson, K. W. & Snyder, G. W. 1986. Modern sediment dispersal and accumulation in Quinault submarine canyon—a summary. *Marine Geology*, **71**, 1–13.

DeMaster, D. J., Pope, R. H., Levin, L. A. & Blair, N. E. 1994. Biological mixing intensity and rates of organic carbon accumulation in North Carolina slope sediments. *Deep-Sea Research II*, **41**, 735–753.

Dosseto, A., Turner, S. P. & Douglas, G. B. 2006. Uranium-series isotopes in colloids and suspended sediments: Timescale for sediment production and transport in the Murray–Darling River system. *Earth and Planetary Science Letters*, **246**, 418–431.

Eittreim, S., Grantz, A. & Greenberg, J. 1982. Active geologic processes in Barrow Canyon, northeast Chukchi Sea. *Marine Geology*, **50**, 61–76.

Etcheber, H., Relexans, J.-C., Beliard, M., Weber, O., Buscail, R. & Heussner, S. 1999. Distribution and quality of sedimentary organic matter on the Aquitanian margin (Bay of Biscay). *Deep-Sea Research II*, **46**, 2249–2288.

Exon, N. F., Hill, P. J., Mitchell, C. & Post, A. 2005. Nature and origin of the submarine Albany canyons offshore southwest Australia. *Australian Journal of Earth Sciences*, **52**, 101–115.

François, R., Frank, M., Rutgers, M. M., van der Loeff, M. R. & Bacon, M. P. 2004. ^{230}Th normalization: An essential tool for interpreting sedimentary fluxes during the late Quaternary. *Paleoceanography*, **19**, PA1018, doi: 10.1029/PA000939.

Gardner, W. D. 1989. Baltimore Canyon as a modern conduit of sediment to the deep sea. *Deep-Sea Research*, **36**, 323–358.

Gingele, F. X. & De Deckker, P. 2005. Late Quaternary fluctuations of palaeoproductivity in the Murray Canyons area, South Australian continental margin. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **220**, 361–373.

Gingele, F. X., De Deckker, P. & Hillenbrand, C.-D. 2001. Clay mineral distribution in surface sediments between Indonesia and NW Australia—source and transport by ocean currents. *Marine Geology*, **179**, 135–146.

Gingele, F. X., De Deckker, P. & Hillenbrand, C.-D. 2004. Late Quaternary terrigenous sediments from the Murray Canyons area, offshore South Australia and their implications for sea level change, palaeoclimate and palaeodrainage of the Murray–Darling Basin. *Marine Geology*, **212**, 183–197.

Gingele, F. X., De Deckker, P. & Norman, M. 2007. Late Pleistocene and Holocene climate of SE Australia reconstructed from dust and river loads deposited offshore the River Murray Mouth. *Earth and Planetary Science Letters*, **255**, 257–272.

Granata, T. C., Vidondo, B., Duarte, C. M., Satta, M. P. & Garcia, M. 1999. Hydrodynamics and particle transport associated with a submarine canyon off Blanes (Spain), NW Mediterranean Sea. *Continental Shelf Research*, **19**, 1249–1263.

Hickey, B., Baker, E. & Kachel, N. 1986. Suspended particle movement in and around Quinault submarine canyon. *Marine Geology*, **71**, 35–83.

Hill, P. J. & De Deckker, P. 2004. *AUSCAN Seafloor mapping and geological sampling survey on the Australian southern margin by RV* Marion Dufresne *in 2003*. Geoscience Australia Record, **2004/04**.

Hill, P. J., Exon, N. F., Keene, J. B. & Smith, S. M. 1998. The continental margin off east Tasmania and Gippsland: structure and development using new multibeam sonar data. *Exploration Geophysics*, **29**, 410–419.

Hill, P. J., Rollet, N. & Symonds, P. 2001. *Seafloor mapping of the South-east Marine Region and adjacent waters—AUSTREA final report: Lord Howe Island, south-east Australian margin (includes Tasmania and South Tasman Rise) and central Great Australian Bight*. Australian Geological Survey Organisation Record, **8**.

Hill, P. J., De Deckker, P. & Exon, F. 2005. Geomorphology and evolution of the gigantic Murray canyons on the Australian southern margin. *Australian Journal of Earth Sciences*, **52**, 117–136.

Hill, P. J., De Deckker, P., von der Borch, C. C. & Murray-Wallace, C. V. 2009. Ancestral Murray River on the Lacepede Shelf, southern Australia: Late Quaternary migrations of a major river outlet and strandline development. *Australian Journal of Earth Sciences*, **56**, 135–157.

James, N. P., Bone, Y., von der Borch, C. C. & Gostin, V. A. 1992. Modern carbonate and terrigenous clastic sediments on a cool-water, high-energy, mid-latitude shelf: Lacepede, southern Australia. *Sedimentology*, **39**, 877–903.

Jenkins, C. J. & Keene, J. B. 1992. Submarine slope failures of the southeast Australian continental slope: a thinly sedimented margin. *Deep-Sea Research A*, **39**, 121–136.

Khripounoff, A., Vangriesheim, N., Babonneau, Ph., Crassous, B., Dennielou, B. & Savoye, B. 2003. Direct observation of intense turbidity current activity in the Zaire submarine valley at 4000 m water depth. *Marine Geology*, **194**, 151–158.

Lecroart, P., Schmidt, S. & Jouanneau, J.-M. 2007. A numerical estimation of the error on the bioturbation coefficient in coastal environments by short-lived radioisotopes modelling. *Estuarine and Coastal Shelf Science*, **72**, 543–555.

Lennon, G. W., Bowers, D. G. *et al.* 1987. Gravity currents and the release of salt from an inverse estuary. *Nature*, **327**, 695–697.

Lewis, R. K. 1981. Seasonal upwelling along the south-eastern coastline of South Australia. *Australian Journal of Marine and Freshwater Research*, **32**, 843–854.

Lewis, K. B. & Barnes, P. M. 1999. Kaikoura Canyon, New Zealand: active conduit from nearshore sediment zones to trench-axis channel. *Marine Geology*, **162**, 39–69.

Li, Q., James, N. P., Bone, Y. & McGowran, B. 1999. Palaeoceanographic significance of recent foraminiferal biofacies on the southern shelf of Western Australia: a preliminary study. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **147**, 101–120.

Liu, J. T. & Lin, H.-L. 2004. Sediment dynamics in a submarine canyon: a case of river–sea interaction. *Marine Geology*, **207**, 55–81.

Matthai, C., Birch, G. F., Jenkinson, A. & Heijnis, H. 2001. Physical resuspension and vertical mixing of sediments on a high energy continental margin (Sydney, Australia). *Journal of Environmental Radioactivity*, **52**, 67–89.

McManus, J., Berelson, W. M., Severmann, S., Poulson, R. L., Hammond, D. E., Klinkhammer, G. P. & Holm, C. 2006. Molybdenum and uranium geochemistry in continental margin sediments: Paleoproxy potential. *Geochimica et Cosmochimica Acta*, **70**, 4643–4662.

MITCHELL, J. K., HOLDGATE, G. R., WALLACE, M. W. & GALLAGHER, S. J. 2007*a*. Marine geology of the Quaternary Bass Canyon system, southeast Australia: a cool-water carbonate system. *Marine Geology*, **237**, 71–96.

MITCHELL, J. K., HOLDGATE, G. R. & WALLACE, M. W. 2007*b*. Pliocene–Pleistocene history of the Gippsland Basin outer shelf and canyon heads, southeast Australia. *Australian Journal of Earth Sciences*, **54**, 49–64.

MULDER, T., WEBER, O., ANSCHUTZ, P., JORISSEN, F. J. & JOUANNEAU, J.-M. 2001. A few months old storm-generated turbidite deposited in the Capbreton Canyon (Bay of Biscay, SW France). *Geo-Marine Letters*, **21**, 149–156.

MULLENBACH, B. L. & NITTROUER, C. A. 2006. Decadal record of sediment export to the deep sea via Eel Canyon. *Continental Shelf Research*, **26**, 2157–2177.

MULLENBACH, B. L., NITTROUER, C. A., PUIG, P. & ORANGE, D. L. 2004. Sediment deposition in a modern submarine canyon: Eel Canyon, northern California. *Marine Geology*, **211**, 101–119.

NAKAJIMA, T., SATOH, M. & OKAMURA, Y. 1998. Channel-levee complexes, terminal deep-sea fan and sediment wave fields associated with the Toyama Deep-Sea Channel system in the Japan Sea. *Marine Geology*, **147**, 25–41.

NODA, A., TUZINO, T., FURUKAWA, R., JOSHIMA, M. & UCHIDA, J. I. 2008. Physiographical and sedimentological characteristics of submarine canyons developed upon an active forearc slope: The Kushiro Submarine Canyon, northern Japan. *Geological Society of America Bulletin*, **120**, 750–767.

OGSTON, A. S., DREXLER, T. M. & PUIG, P. 2008. Sediment delivery, resuspension, and transport in two contrasting canyon environments in the southwest Gulf of Lions. *Continental Shelf Research*, **28**, 2000–2016.

ORPIN, A. R. 2004. Holocene sediment deposition on the Poverty-slope margin by the muddy Waipara River, East Coast New Zealand. *Marine Geology*, **209**, 69–90.

ORPIN, A. R., ALEXANDER, C., CARTER, L., KUEHL, S. & WALSH, J. P. 2006. Temporal and spatial complexity in post-glacial sedimentation on the tectonically active, Poverty Bay continental margin of New Zealand. *Continental Shelf Research*, **26**, 2205–2224.

PALANQUES, A., EL KHATAB, M., PUIG, P., MASQUE, P., SANCHEZ-CABEZA, J. A. & ISLA, E. 2005. Downward particle fluxes in the Guadiaro submarine canyon depositional system (northwestern Alboran Sea), a river flood dominated system. *Marine Geology*, **220**, 23–40.

PUIG, P., OGSTON, A. S., MULLENBACH, B. L., NITTROUER, C. A. & STERNBERG, R. W. 2003. Shelf-to-canyon sediment-transport processes on the Eel continental margin (northern California). *Marine Geology*, **193**, 129–149.

PUIG, P., PALANQUES, A., ORANGE, D. L., LASTRAS, G. & CANALS, M. 2008. Dense shelf water cascades and sedimentary furrow formation in the Cap de Creus Canyon, northwestern Mediterranean Sea. *Continental Shelf Research*, **28**, 2017–2030.

RADAKOVITCH, O. & HEUSSNER, S. 1999. Fluxes and budget of ^{210}Pb on the continental margin of the Bay of Biscay (northeastern Atlantic). *Deep-Sea Research II*, **46**, 2175–2203.

RENNIE, S., HANSON, C. E. *ET AL.* 2009*a*. Physical properties and processes in the Perth Canyon, Western Australia: Links to water column production and seasonal pygmy blue whale abundance. *Journal of Marine Systems*, **77**, 21–44.

RENNIE, S. J., PATTIARATCHI, C. B. & MCCAULEY, R. D. 2009*b*. Numerical simulation of the circulation within the Perth Submarine Canyon, Western Australia. *Continental Shelf Research*, **29**, 2020–2036.

ROBBINS, J. & EDGINGTON, D. N. 1975. Determination of recent sedimentation rates in Lake Michigan using ^{210}Pb and ^{137}Cs. *Geochimica et Cosmochimica Acta*, **39**, 285–304.

RUHL, H. A. & SMITH, K. L., JR. 2004. Shifts in deep-sea community structure linked to climate and food supply. *Science* **305**, 513–515.

SANCHEZ-CABEZA, J. A., MASQUÉ, P. *ET AL.* 1999. Sediment accumulation rates in the southern Barcelona continental margin (NW Mediterranean Sea) derived from ^{210}Pb and ^{137}Cs chronology. *Progress in Oceanography*, **44**, 313–332.

SCHALINGER, R. B. 1987. Structure of coastal upwelling events observed off the south-east coast of South Australia during February 1983–April 1984. *Australian Journal of Marine and Freshwater Research*, **38**, 439–459.

SCHMIDT, S. 2006. Impact of the Mediterranean Outflow Water on particle dynamics in intermediate waters of the North-East Atlantic, as revealed by ^{234}Th and ^{228}Th. *Marine Chemistry*, **100**, 289–298.

SCHMIDT, S., DE STIGTER, H. C. & VAN WEERING, TJ. C. E. 2001. Enhanced short-term sediment deposition within the Nazare Canyon, North-East Atlantic. *Marine Geology*, **173**, 55–67.

SCHMIDT, S., VAN WEERING, TJ. C. E., REYSS, J.-L. & VAN BEEK, P. 2002. Seasonal deposition and reworking at the sediment–water interface on the north-western Iberian Margin. *Progress in Oceanography*, **52**, 331–348.

SHEPPARD, F. P., MARSHALL, N. F., MCLOGHLIN, P. A. & SULLICAN, G. G. 1979. Currents in submarine canyons and other sea valleys. *AAPG Studies in Geology*, **8**, 1–172.

SOETAERT, K., HERMAN, P. M. J., MIDDELBURG, J. J., DE STIGTER, H. S., VAN WEERING, TJ. C. E., EPPING, E. & HELDER, W. 1996. Modelling ^{210}Pb-derived mixing activity in ocean margin sediments: diffusive v. non-local mixing. *Journal of Marine Research*, **54**, 1207–1227.

SPRIGG, R. C. 1947. Submarine canyons of the New Guinea and South Australian coasts. *Transactions of the Royal Society of South Australia*, **71**, 296–310.

VAN WEERING, TJ. C. E., DE STIGTER, H. C., BOER, W. & DE HAAS, H. 2002. Recent sediment transport and accumulation on the NW Iberian margin. *Progress in Oceanography*, **52**, 349–371.

VEEH, H. H., MCCORKLE, D. C. & HEGGIE, D. T. 2000. Glacial/interglacial variations of sedimentation on the West Australian continental margin: constraints from excess ^{230}Th. *Marine Geology*, **166**, 11–30.

Vetter, E. W. 1994. Hotspots of benthic production. *Nature*, **372**, 47.

Vetter, E. W. & Dayton, P. K. 1998. Macrofaunal communities within and adjacent to a detritus-rich submarine canyon system. *Deep-Sea Research II*, **45**, 5–54.

von der Borch, C. C. 1968. Southern Australian submarine canyons: their distribution and ages. *Marine Geology*, **6**, 267–279.

von der Borch, C. C., Conolly, J. R. & Dietz, R. S. 1970. Sedimentation and structure of the continental margin in the vicinity of the Otway Basin, Southern Australia. *Marine Geology*, **8**, 59–83.

Wheatcroft, R. A. 2006. Time-series measurements of macrobenthos abundance and sediment bioturbation intensity on a flood-dominated shelf. *Progress in Oceanography*, **71**, 88–122.

Yamada, M. & Aono, T. 2006. ^{238}U, Th isotopes, ^{210}Pb and $^{239+240}Pu$ in settling particles on the continental margin of the East China Sea: Fluxes and particle transport processes. *Marine Geology*, **227**, 1–12.

Yamada, M., Wang, Z.-L. & Kato, Y. 2006. Precipitation of authigenic uranium in suboxic continental margin sediments from the Okinawa Trough. *Progress in Oceanography*, **66**, 570–579.