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Are the Murray Canyons offshore southern Australia still active for sediment transport?

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Notes

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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.
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 Shepard 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 & Nittouer 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
of Bass Strait (Mitchell et al. 2007a, 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 off-shore 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.
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 $\gamma$ 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$_{ex}$ and $^{210}$Pb$_{ex}$ 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 $\alpha$ 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
the excess or unsupported activity of $^{210}$Pb ($^{210}\text{Pb}_{xs}$) 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 $^{210}\text{Pb}_{xs}$ activities with depth is described by the following relation:

\[ [^{210}\text{Pb}_{xs}]_z = [^{210}\text{Pb}_{0}]_0 \exp \left( -\frac{\lambda}{S} z \right) \]  

(1)

where $[^{210}\text{Pb}_{xs}]_0$ is the activity of excess $^{210}$Pb 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. 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 $^{210}\text{Pb}_{xs}$ 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$^{-1}$), $^{234}\text{Th}_{xs}$ 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 $S^2 < 4D_b\lambda$ (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 $^{234}\text{Th}_{xs}$ profiles. These simplifications allow the determination of bioturbation rates from a simple plot of radionuclide activity as a function of depth, using the equation

\[ [^{234}\text{Th}_{xs}]_z = [^{234}\text{Th}_{0}]_0 \exp \left( -\frac{\lambda}{\sqrt{4D_b}} z \right) \]  

(2)

where $[^{234}\text{Th}_{xs}]_0$ is the activity (dpm g$^{-1}$) of excess $^{234}\text{Th}$ at the water–sediment interface (Schmidt et al. 2001). We present $^{234}\text{Th}$-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 $\phi$, 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

\[ \phi = \frac{F_s}{F_p} \]  

(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: $F_s = \left(\frac{^{230}Th_{xs,0} \times S \times DBD}{z} - \frac{^{230}Th_{xs}}{C_2}F_1\right)$, 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 Cogedic 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). 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 Cogedic 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.
234Thxs-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 234Thxs inventories and the deepest mixed layer observed on 210Pbxs profiles. On the other hand, 234Thxs-derived bioturbation rates in the west Sprigg Canyon are rather low, in agreement with a negligible mixed layer for 210Pbxs 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 234Thxs-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 234Th and 210Pb 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).

Fig. 4. 234Thxs and 210Pbxs profiles carried out on the four multicores from the two sides of the Murray Canyons Group. Dry bulk density (■, dotted line), Corg (●) and CaCO3 (○) 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 210Pbxs profiles.
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.

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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. 2009a, 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. 2009a, 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. 2009a, 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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