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Geomorphology and evolution of the gigantic Murray canyons on the Australian southern margin

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The Murray canyons are a group of deeply incised submarine canyons on a steep 400 km section of the continental slope off Kangaroo Island, South Australia. Some of the canyons are amongst the largest on Earth. The canyons, some 80 km long, descend from the shelf edge to the abyssal plain 5200 m deep. Sprigg Canyon, the deepest and one of the largest, has walls 2 km high. The thalwegs of the larger canyons are concave in profile, steepest on the upper continental slope (15 – 30°), with about 4° gradient on the mid slope, then level out on the lower slope to merge with the 1° continental rise. Between canyons, the continental slope is slightly convex to linear with a gradient of about 5 – 6°. Canyon walls commonly slope at 15 – 22°. The passive continental margin narrows to 65 km at the Murray canyons and links the Bight and Otway Basins. West-northwest-trending Jurassic – Cretaceous rift structures control the irregular shape of the central canyons. At the western end, large box canyons, 1 km deep, are incised into thick sediments of the Ceduna Sub-basin. Formed by headscarp erosion, some of these canyons have coalesced by canyon capture. The upper parts of most canyons are cut into Cretaceous sediments and in some places are floored by basement rocks. Large deep-water holes, spaced about 5 km apart and up to several hundred metres deep, along the outlet channels of the larger and steeper canyons were probably gouged by turbidity currents resulting from major slope failures at the shelf edge, but may be sites of fluid discharges. Quaternary turbidites were deposited on the abyssal plain more than 100 km from the foot of slope. Canyon downcutting has been episodic since the latest Cretaceous, with peak activity since the Oligocene due to strong glacioeustatic fluctuations and cycles. Canyon development occurred during lowstands and early in transgressions when sediment input at the shelf edge was usually highest. The timing of canyon development is linked to major unconformities in adjacent basins, with downcutting events recorded or inferred during the Early Paleocene, Middle Eocene, Early Oligocene, Oligocene/Miocene transition (*ca* 24 Ma), Middle Miocene (*ca* 14 Ma) and latest Miocene – Pleistocene. The early phases involved siliciclastic sediments only, while post-Early Eocene canyon cutting was dominated by biogenic carbonates generated on the shelf and upper continental slope. The Murray River dumped its sediment load directly into Sprigg Canyon during extreme lowstands of the Late Pleistocene when the Lacepede Shelf was mostly dry land.

KEY WORDS: Bight Basin, continental margin, geomorphology, Lacepede Shelf, multibeam sonar, Murray canyons, Murray River, Otway Basin, piston core, submarine canyon, turbidites.

INTRODUCTION

The continental slope off southern Australia is deeply dissected by numerous submarine canyons and canyon systems. Of these, a group of canyons known as the Murray canyons (Hill & De Deckker 2004), located south of Adelaide on the continental margin roughly between 135°E and 138.5°E (Figures 1, 2), are the most spectacular in size and relief (Figures 3, 4). With a fall of over 5 km and canyon walls up to 2 km high, these canyons rival terrestrial canyons such as the Grand Canyon in the USA and other submarine canyons such as the canyon of Capbreton off northern Spain that is claimed to be the deepest on Earth (Mulder *et al.* 2004).

Despite their enormous size and obvious importance in shaping continental margins and as conduits for continent – ocean sediment transfer, relatively little research has been done on the canyons on Australia's southern margin. Indeed, even from a global perspective, the mechanisms and timing involved in the development of large submarine canyons remain topics for debate (Shepard 1981; Pratson *et al.* 1994). Exon *et al.* (2005) review the historic development of ideas on canyon evolution, as well as previous studies of canyons off southern Australia.

Our understanding of the canyons on the Australian southern margin has been enhanced considerably in recent years, aided by modern deep-sea multibeam sonar technology, which has allowed these features to be

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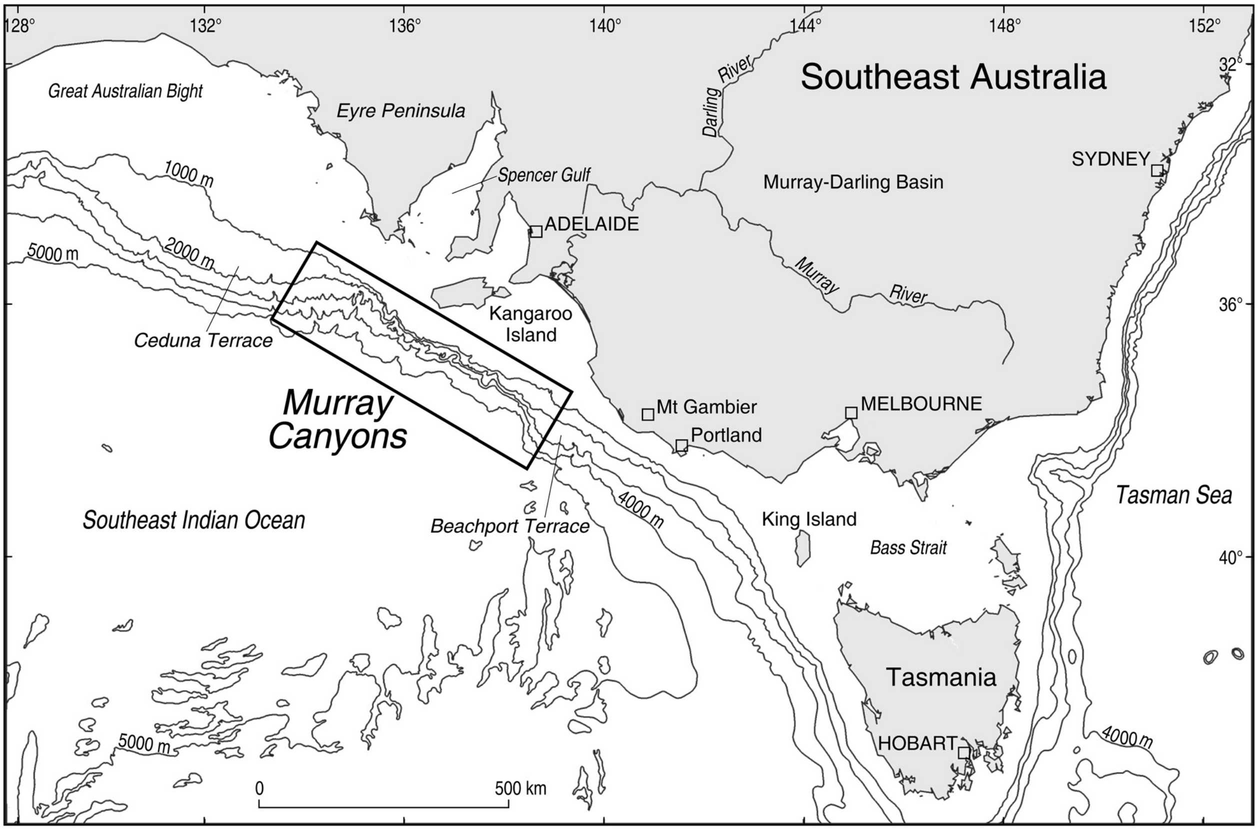

GEBCO 1000 m isobaths shown

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Figure 1 Location of the Murray canyons south of Adelaide on the Australian southern margin between the Ceduna and Beachport Terraces. The Murray–Darling river system drains onto the adjacent continental shelf.

mapped and imaged at high resolution. This paper examines the geomorphology and formation of the Murray canyons based on the results of the new surveys.

The Murray canyons are of special interest not only because of their immense size and geomorphic significance but also because of their location off the mouth of the Murray River (Figure 3), which drains Australia's largest inland river basin, the 10^6 km^2 Murray–Darling Basin (Figure 1). Sediments from this basin, carrying geochemical and palaeontological signatures of past climatic and environmental conditions and flowing into the canyons directly or indirectly for millions of years, now form part of the sedimentary record in the canyon system (Gingele & De Deckker 2004). The canyons are also the site of remarkable oceanographic phenomena such as nutrient-rich deep-water upwellings (Lewis 1981) and seasonal hypersaline outflows from Spencer Gulf (Lennon *et al.* 1987), and are the habitat and feeding grounds of a number of cetacean species. For these reasons, and the expected unique ecosystems associated with the spectacular seabed topography, the Murray canyons are considered to be of high conservation value (Flaherty 1999).

Recent surveys

The most recent and comprehensive investigation of the Murray canyons was the AUSCAN (AUStralian CANyons) survey of 2003 (Hill & De Deckker 2004). The investigation, using the French RV *Marion Dufresne* of the Institut Polaire Français – Paul-Emile Victor (IPEV), included multibeam swath-mapping using the 12 kHz Thales Sea Falcon 11, geophysical profiling, geological and biological sampling, as well as oceanographic measurements. Three Calypso piston cores to 35 m in length and a 12 m gravity core were recovered (Figure 5).

AUSCAN completed the multibeam mapping of the Murray canyons begun in 2000 during the AUSTREA-1 survey (Hill *et al.* 2001) using RV *L'Atalante* of the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER). The multibeam on *L'Atalante* was a 13 kHz Simrad EM12D system. Geophysical acquisition included the shooting of several multichannel seismic lines across the canyons, including seismic profile 1 (Figure 5).

Earlier surveys and studies

Sprigg (1947) first recognised that a major canyon system ('Murray submarine canyons') existed off Kangaroo Island, based on a single navy echo-sounder profile across the upper slope.

Using a regional dataset of seabed samples from the continental margin south of Western and South Australia, Conolly and von der Borch (1967) examined the interrelationship of Quaternary sedimentation patterns and physiography. Von der Borch (1968) used echo sounder profiles to map the distribution of canyons on the margin, deducing general ages of the canyons from their relationship to onshore morphology, drainage and geology. Von der Borch *et al.* (1970) described the structural and sedimentary characteristics of the Otway–Kangaroo Island margin, including the Murray canyons sector, based on bathymetry and seismic profiles plus seabed samples. Von der Borch (1979) presented ideas on the evolution of the Murray canyons, suggesting that some of the canyons may have begun as modified rift valleys, but were later significantly enlarged by input of sediment during times of glacially lowered sea-level.

The first swath-mapping survey on the southern margin was in 1989 off the Lacepede Shelf, roughly south of the Murray River mouth, and used the former Australian naval research vessel HMAS *Cook* fitted with an original 16-beam 12 kHz SeaBeam multibeam system. The towed British ultra-long range, 6.5 kHz GLORIA sidescan system was used in conjunction with the SeaBeam on this survey to map part of the eastern Murray canyons between 137°25′E and 138°55′E (von der Borch & Hughes Clarke 1993).

In the early 1990s, the Australian Geological Survey Organisation (now Geoscience Australia) produced a series of bathymetric contour maps of the southern margin extending eastwards from Western Australia to Kangaroo Island. The easternmost sheet (Ceduna: Jongsma *et al.* 1991) of this 1:1 000 000 Offshore Resource Map Series (ORMS) includes most of the Murray canyons and names a dozen canyons of this group. Because the ORMS maps were based mainly on widely spaced trackline soundings, the true shape of some canyons was not well portrayed and some confusion in nomenclature exists now that we have more accurate multibeam maps. However, for most of the Murray canyons the nomenclature is unambiguous and in this paper we use the official names (Figure 5) as currently listed in the Gazetteer of Australia.

In 1994, a single EM12D multibeam transit line was run across the far eastern end of the Murray canyons as RV *L'Atalante* headed to Adelaide at the end of the TASMANTE cruise (Exon *et al.* 1994).

REGIONAL PHYSIOGRAPHIC SETTING

Australia's southern continental margin, on which the Murray canyons lie, stretches 3500 km from the Naturaliste Plateau off southwest Western Australia in the west to southern Tasmania and the South Tasman Rise in the east. Formed as the Australian and Antarctic continents fractured and then separated by continental drift, the conjugate Australian and Antarctic passive margins are now separated by 3000 km of Southeast Indian and Southern Oceans.

The southern margin of Australia is generally 150–450 km wide, but narrows to less than 100 km at the Murray canyons. A relatively flat continental shelf extends out from the coastline to a depth of about 200 m. Beyond the shelf edge the sea floor generally drops steeply across the continental slope to depths of around 4000 m, starts to flatten out at depths of 4000–5000 m, and then levels out onto the adjacent abyssal plain which is 4500–5500 m deep. The width of the continental shelf varies considerably, but is typically about 70 km. In the Great Australian Bight and off the mouth of the Murray River (Lacepede Shelf) it is more than 150 km wide, but south of Kangaroo Island, it narrows to 50 km.

The Murray canyons occupy one of the steepest and most rugged sections of the entire Australian continental margin. Here, south of Kangaroo Island, the continental slope commonly descends from the 1000 to the 4000 m isobaths over a horizontal distance of only 25 km ($\sim 7^\circ$ slope). Locally, some seabed slopes are much steeper, with 25–30° slopes not uncommon on canyon walls and escarpments. The Murray canyons are bounded by lobate parts of the margin comprising thick piles of deltaic sediments rapidly deposited and outbuilt in the Late Cretaceous, during late stage rifting of the Australian margin from Antarctica. The most prominent is the Ceduna Terrace (Figure 1) just to the west in the Great Australian Bight. Lying mostly between the 500 and 2500 m isobaths, it covers about 70 000 km^2 (Tilbury & Fraser 1981). A smaller bulge, the Beachport Terrace (Figure 1) off southeast South Australia, marks the eastern end of the Murray canyons.

Onshore the topography is relatively subdued, apart from Kangaroo Island (307 m high) and the Mt Lofty Ranges (710 m high: Figure 3). A series of palaeo-strandline calcarenite ridges, typically 20–30 m high, extend more than 100 km inland from the Lacepede Shelf (Brown & Stephenson 1991; Murray-Wallace *et al.* 1998).

TECTONIC AND GEOLOGICAL EVOLUTION OF THE REGION

The physiographic provinces and features of Australia's southern margin are largely the result of the progressive rifting of Gondwana since the Middle–Late Jurassic (*ca* 160 Ma), and separation of Australia and Antarctica by sea-floor spreading to form the Southern Ocean beginning in the early Late Cretaceous (Norvick & Smith 2001). Mesozoic extension in the Southern Rift System (Willcox & Stagg 1990) resulted in development of the major sedimentary basins along the southern margin, including the Bight and Otway Basins (Figure 2). The Bight and Otway Basins neck on the 65 km-wide margin south of Kangaroo Island where the Murray canyons lie, and do not extend beneath the Lacepede Shelf which is underlain by shallow basement (about 600 m of sediment cover: Willcox 1974).

Cratonic basement rocks of Archaean to Early Palaeozoic age underpin the southern margin. The Late Archaean–Early Mesoproterozoic (?2700–1450 Ma) Gawler Craton forms basement to the Eyre Peninsula region from the Head of Bight to Kangaroo Island. Kangaroo Island and the region to the east are part of the Tasman Fold Belt System (Scheibner & Veevers 2000) and basement rocks here are Neoproterozoic to Early Palaeozoic in age. Cambrian sediments of the

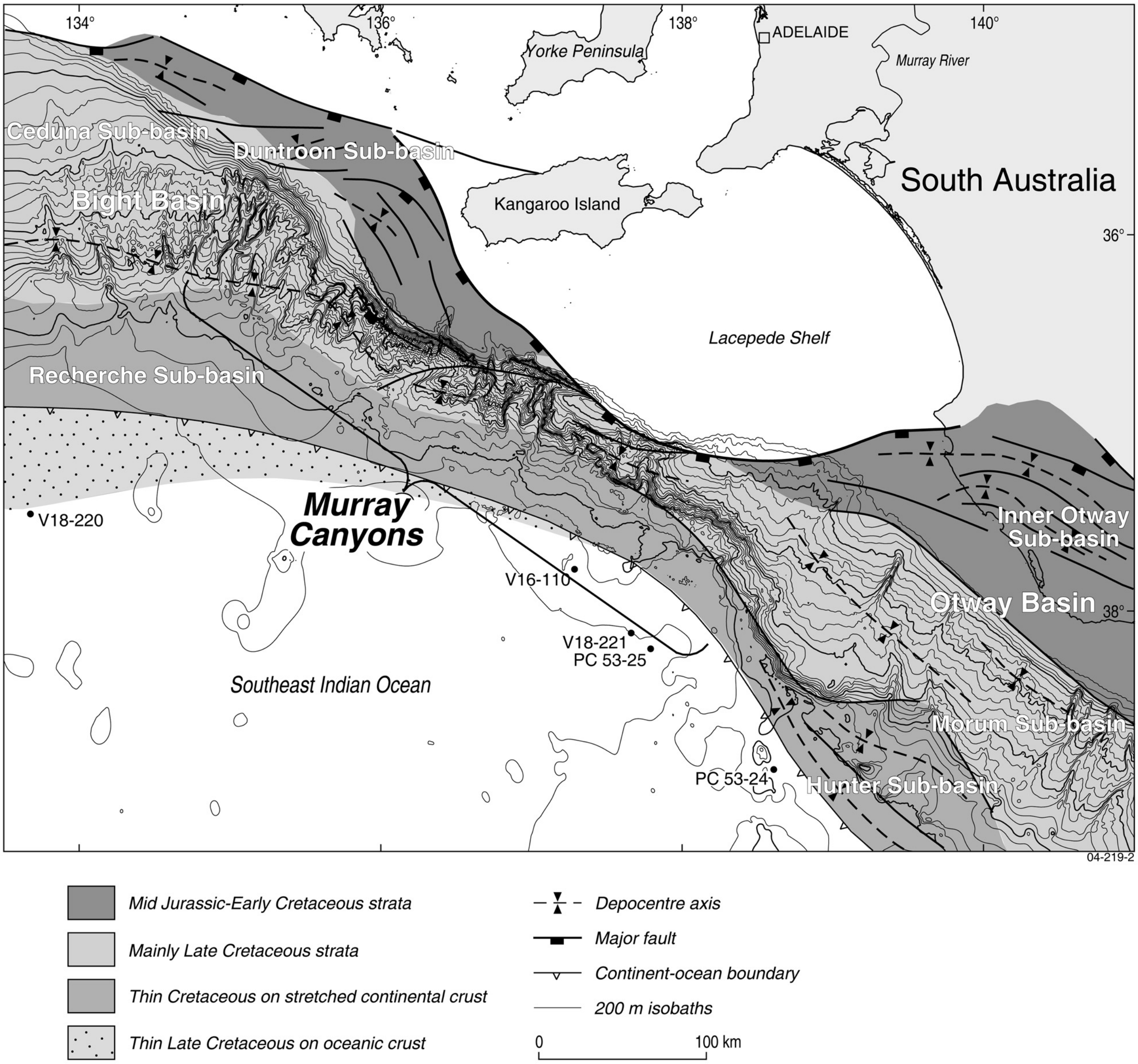

Figure 2 Structural elements and Mesozoic–Cenozoic sedimentary basins along the margin in the vicinity of the Murray canyons. Structures and boundaries modified after Stagg *et al.* (1990), Moore *et al.* (2000) and Bradshaw *et al.* (2003). Core sites on the continental rise and abyssal plain are indicated by annotated dots: V, *Vema*; PC, *Eltanin*.

Stansbury Basin (Flöttmann *et al.* 1998) underlie eastern Yorke Peninsula, Gulf St Vincent, Fleurieu Peninsula and Kangaroo Island. In the west, little-deformed marine-shelf carbonate and clastic sedimentary rocks onlap the Gawler Craton. To the east and south, the basin comprises metamorphosed sediments of the Kanmantoo Trough, intruded on Kangaroo Island by some Cambro-Ordovician granites.

Initial extension in the Southern Rift System was roughly northwest–southeast (Willcox & Stagg 1990), with large rift grabens developing in the western Great Australian Bight. Linked northeast-trending pullapart basins and oblique rifts developed eastward forming the Duntroon Sub-basin and Otway Basin. Phases of extension and subsidence continued through to the end of the Early Cretaceous and led to filling of both Bight and Otway Basins with thick sequences of mainly fluviolacustrine sediments (Totterdell *et al.* 2000; Krassay *et al.* 2004). In the Bight Basin, a phase of accelerated subsidence that began in the late Albian and ended at breakup in the early Campanian at *ca* 83 Ma (Sayers *et al.* 2001) resulted in the deposition of up to 10 km of deltaic and marine fine-grained sediments in the central Ceduna Sub-basin. This depositional phase includes a prominent sequence boundary in the early Cenomanian thought to represent the beginnings of breakup. In contrast, much of the southeast region of Australia was uplifted in the Cenomanian, with erosional denudation and development of a regional unconformity in the Otway Basin (Hill *et al.* 1995; O'Sullivan & Kohn 1997). Extension recommenced soon after, with deposition of thick deltaic and shallow-marine sequences as the sea entered from the west, but ended in the Maastrichtian when sea-floor spreading propagated into the Otway Basin (Lavin 1997). In the Ceduna Sub-basin, Campanian to Maastrichtian post-breakup thermal subsidence coincided with progradation and aggradation of massive sand-dominated delta and shelf-margin complexes up to 5 km thick that were being supplied with sediment from the northeast (Totterdell *et al.* 2000). A marked reduction in sediment input to both Otway and Bight Basins towards the end of the Maastrichtian contributed to a regional hiatus that extended into the Early Paleocene. In the Otway Basin, uplift and faulting were associated with breakup and transpressional movements at the plate boundary (Moore *et al.* 2000).

The southern margin had become starved of siliciclastic sediments by the beginning of the Tertiary (Stagg *et al.* 1999), the only major accumulation being Palaeogene prograding siliciclastics, up to 2 km thick, in the central Otway Basin. Evolution in the Paleocene of the Murray Basin as a shallow intracratonic downwarp, now filled with up to 600 m of Cenozoic fluviolacustrine and marine deposits (Brown & Stephenson 1991), would have contributed to starvation of the Murray canyons margin by acting as a trap for terrestrial sediments.

An overall transgressive phase of sedimentation in the Early Tertiary was followed by widespread, open-marine carbonate sedimentation that resulted from accelerated north – south sea-floor spreading from the Middle Eocene (*ca* 43 Ma) onward. Australia and Antarctica completed separation at *ca* 33 Ma, opening the Tasmanian 'gateway' and initiating the Antarctic Circumpolar Current with profound effects on regional climate and sedimentation (Kennett 1977; Exon *et al.* 2001). Ice sheets formed on Antarctica, and southern Australia became cooler and drier, further reducing siliciclastic sediment supply and ensuring the continued dominance of temperate biogenic carbonate sedimentation on the margin (McGowran *et al.* 1997). At about this time, there was an accelerated subsidence of the southeast Australian margins (Totterdell *et al.* 2000; Hill & Moore 2001), probably associated with the onset of faster spreading.

The shelves adjacent to the Murray canyons, those of the eastern Great Australian Bight and the Lacepede Shelf, are part of a temperate cool-water carbonate depositional province and 'carbonate factory' that is the largest in the modern world (Gostin *et al.* 1988; James *et al.* 2001). Sediments are dominantly bryozoan-rich biogenic carbonates, with quartz sands being a significant component only in some nearshore zones such as off the mouth of the Murray River. The distribution of facies on the shelf, particularly within the zone of wave abrasion (water depths shallower than 60 m), indicates that the rocky substrate produces sediment that is mostly swept away in the energetic hydrodynamic environment forming what James *et al.* (1994) called a 'shaved shelf'. In deeper environments, sediments are moved at least during winter months, but not continuously (James *et al.* 2001). The angularity of Holocene biofragments and lack of fine particles suggests winnowing and off-shelf transport as the major physical process. The sedimentary facies on the Lacepede Shelf are a product of its high-energy setting, carbonate production (particularly bryozoans at the shelf edge) and terrigenous clastic input from the Murray River, with considerable reworking of relict shelf deposits (James *et al.* 1992). Off the mouth of the Murray River and beneath the central part of the shelf, the seabed sediments are molluscan quartz sands. Quartzose bryozoan sand underlies the outer shelf, and bryozoan sand is the main lithofacies at the shelf edge. The sediments fine downslope, and are mainly pelagic muds from 500 m depth on the upper continental slope at the Murray canyons.

Apart from minor intraplate warping, there has been little post-Eocene tectonic activity on the southern margin. Minor Miocene – Pliocene compression and inversion recorded in the Otway Basin is attributed to far-field intraplate stress arising from collision tectonics at the northern edge of the Australian Plate (Hill *et al.* 1995; Perincek & Cockshell 1995). Uplift of the Mt Lofty Ranges began at the end of the Miocene and has continued into the Quaternary (Sandiford 2003). Raised strandlines on the coastal plain southeast of the Coorong, representing highstands and *de facto* Milankovitch cycles, have been uplifted at a steady 7 cm per thousand years for the past 800 000 years (Harvey *et al.* 2001). This uplift has pushed the Murray River westward against the Mt Lofty Ranges.

GEOMORPHOLOGICAL DESCRIPTION

The new multibeam data, combined with other existing bathymetric datasets, have allowed the generation of detailed 3-D images (Figures 3, 4) and bathymetric contour maps (Figure 5) for studying the geomorphology of the Murray canyons and adjacent areas.

Ten of the larger canyons in the group are (from west to east) Topgallant, Spencer, Lincoln, Neptune, Althorpe, Du Couedic, Murray, Sprigg, Seal and Gantheaume Canyons (Figure 5). The larger canyons begin on the outer shelf to upper continental slope and end on the relatively flat abyssal plain at about 5200 m depth. The continental slope is steepest in the middle section, between Du Couedic and Sprigg Canyons, with an average slope of 5.6° (gradient of 1:10) across a width of 46 km. Towards the western (Ceduna Terrace) and eastern (Beachport Terrace) ends of the region studied, the mean slope decreases to about 3.4° across a 75 km-wide continental slope. From shelf to abyssal plain, the larger canyons are 80 km or more in length.

The character of the canyons varies along the margin. In the west, adjacent to the Ceduna Terrace, the canyons (such as Topgallant, Spencer, Lincoln, Neptune and Althorpe) are deeply incised and mostly of box-shaped cross-section with very steep sidewalls and, in some cases, headwalls. They run roughly downslope, are slightly sinuous in plan and some have linked up due to canyon capture, leaving several areas of the slope as isolated high-standing erosional residuals. Though there are indentations at the shelf break, most of these canyons have well-developed heads farther down, on the upper continental slope.

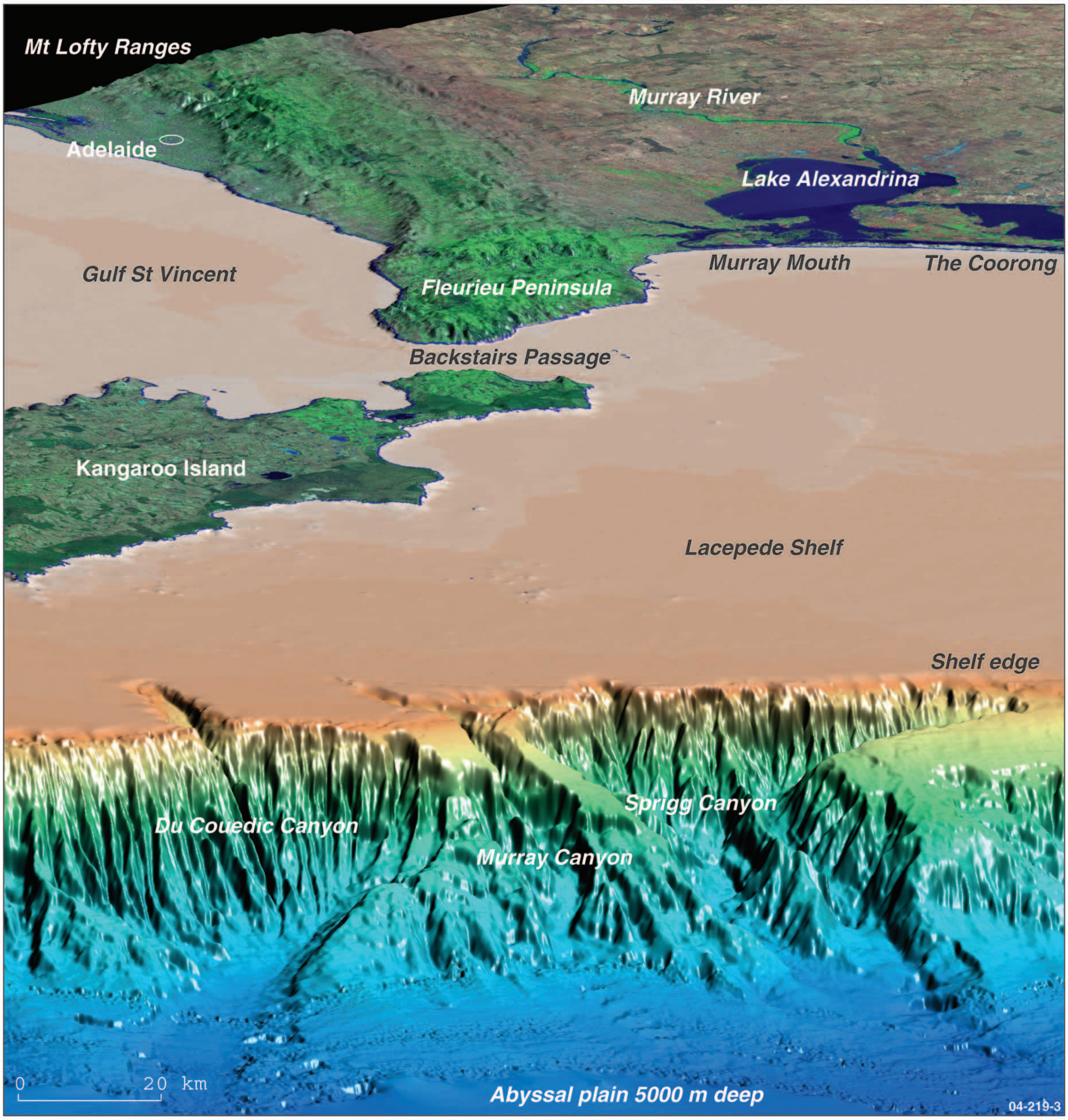

Figure 3 View of the central Murray canyons looking towards Kangaroo Island and the South Australian mainland, showing the relationship between canyon and coastal geomorphology. This is one of the steepest and most rugged sections of the entire Australian continental margin with submarine relief of 5 km. Vertical exaggeration is about 6:1. Canyon topography is based on AUSCAN and AUSTREA-1 multibeam surveys. Landsat 7 satellite imagery is draped on onshore topography.

The canyons on the central Murray canyons margin (Du Couedic to Gantheaume) are more irregular in shape, with parts running oblique to the slope. Fault lines (Figure 2) appear to have controlled the orientation of the canyons. The upper parts of Du Couedic, Sprigg, Seal and Gantheaume Canyons show strong cross-slope trends: west-northwest in the case of the first three and west for Gantheaume. The lower part of Du Couedic Canyon has a pronounced angle to the slope, curving left slightly but with overall west-southwest trend (Figure 5). Du Couedic, Murray and West Sprigg Canyons have prominent incisions (entrants) on the outer shelf about 50 km south of the western end of Kangaroo Island (Figure 4).

There has been comparatively little modern canyon development at the eastern end of the Murray canyons next to the Beachport Terrace, although a number of gullies 50–200 m deep radiate down the upper slope (Figure 5). The lower part of the continental slope is quite steep (about 9°) where a 40 km-wide embayment appears to have been excavated by erosion.

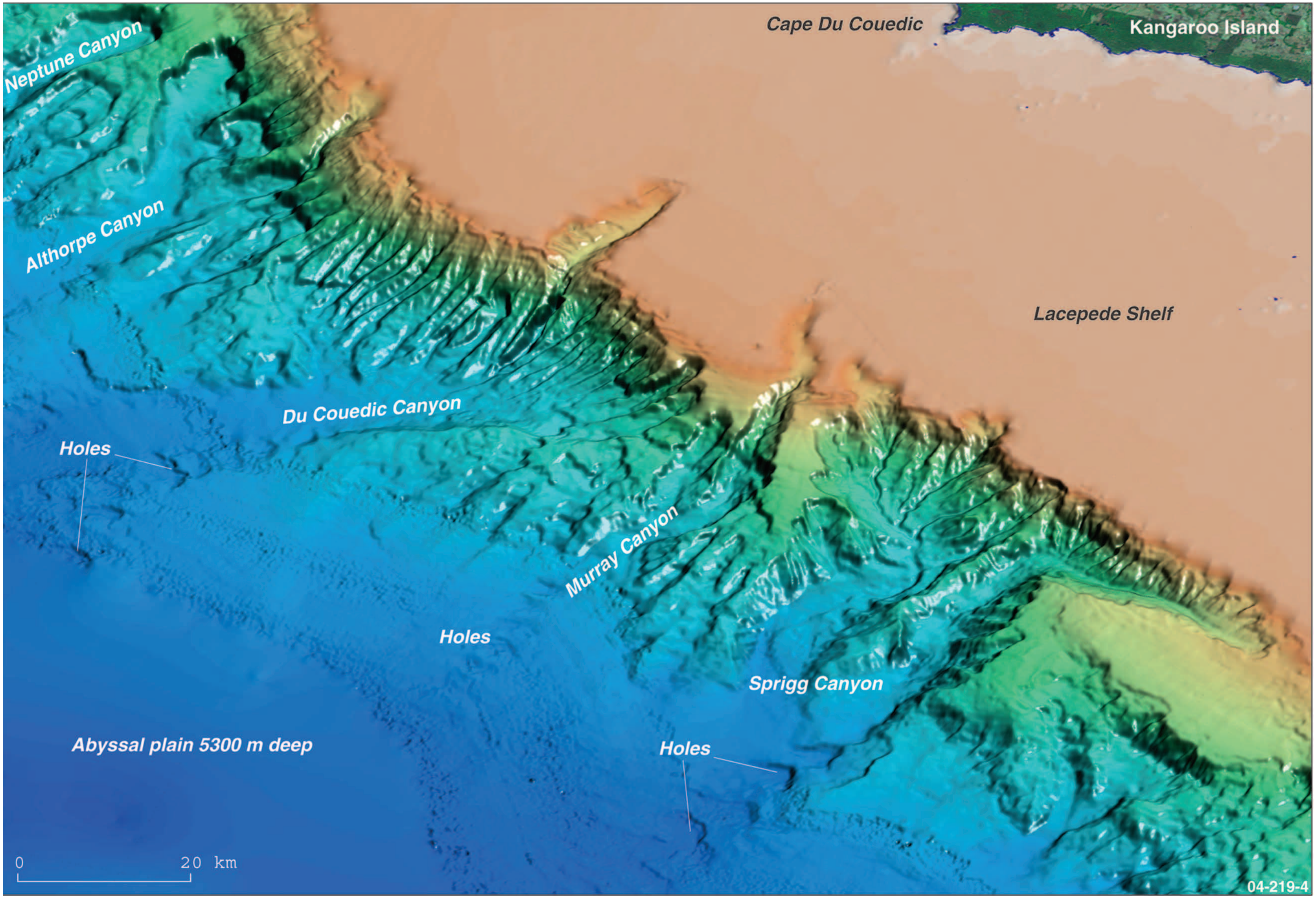

Figure 4 View of the Murray canyons looking north-northwest and obliquely down, showing details such as submarine channels, escarpments and holes within the canyons. Vertical exaggeration is about 2:1.

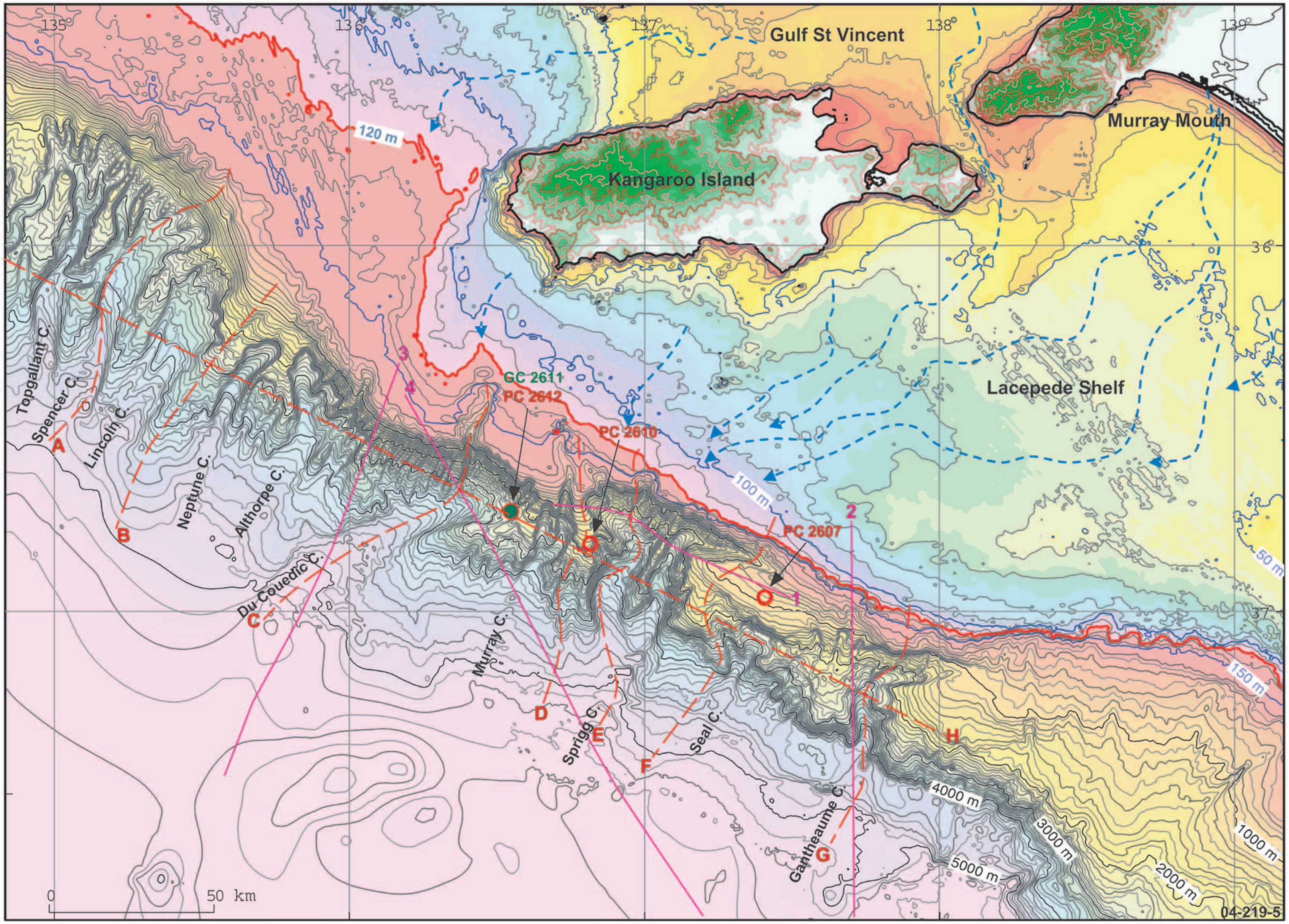

Figure 5 Detailed topographic contours of the Murray canyons and adjacent continental shelf. The contour interval above the 150 m isobath is 10 m, below the 200 m isobath it is 100 m; onshore contours are at 50 m intervals. The 120 m isobath (thick red line and change from mauve to red bathymetry colour code) marks the approximate position of the palaeo-shoreline of southeast South Australia during the Last Glacial Maximum (*ca* 20 ka). The blue arrowed and dashed lines indicate possible drainage paths across the exposed shelf during Pleistocene lowstands. The red dashed lines (A–H) are locations of bathymetric profiles (Figure 6). Pink lines (1–4) are locations of interpreted seismic profiles (Figures 8, 9); Profile 2 extends 48 km beyond the southern boundary of the map. Locations of AUSCAN core sites are indicated: red circle, Calypso piston core; green dot, gravity core).

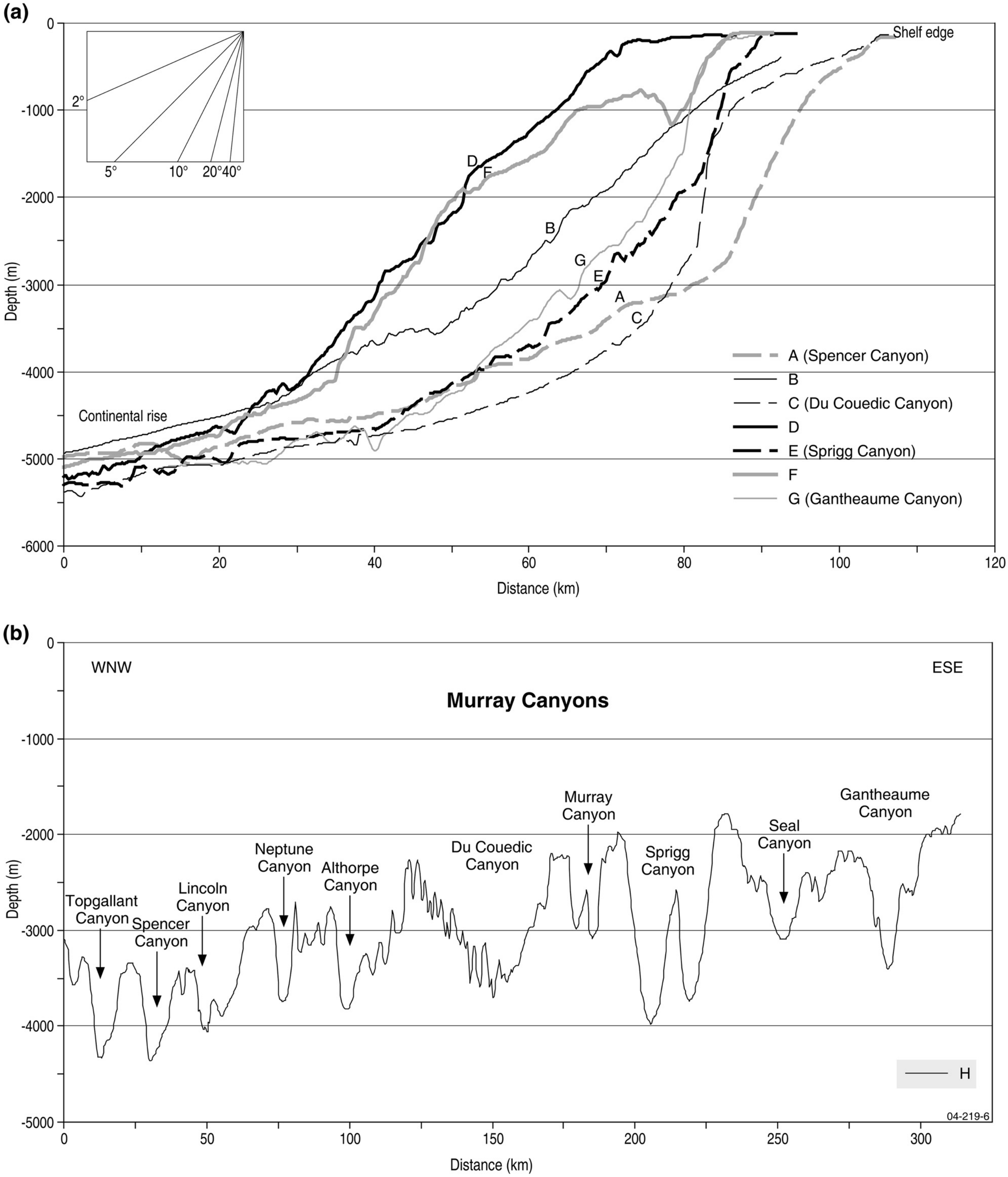

Figure 6 Bathymetry profiles across the Murray canyons (locations in Figure 5). (a) Downslope thalweg (A, C, E, G) and ridge (B, D, F) profiles. (b) Mid-continental slope profile (H).

Shape and slope of the seabed from profiles

Downslope and cross-slope bathymetric profiles (Figure 6: locations in Figure 5), together with an image of seabed slope of the central Murray canyons (Figure 7a), illustrate the shape of the margin and its canyons in detail.

The bathymetric profile across the mid-continental slope (Figure 6b), where canyon relief is generally highest, compares relief of the canyon systems on the Murray canyons margin. Sprigg Canyon is the deepest with canyon walls 2 km high; its two arms (East and West Sprigg Canyons) are of almost equal depth. The Du

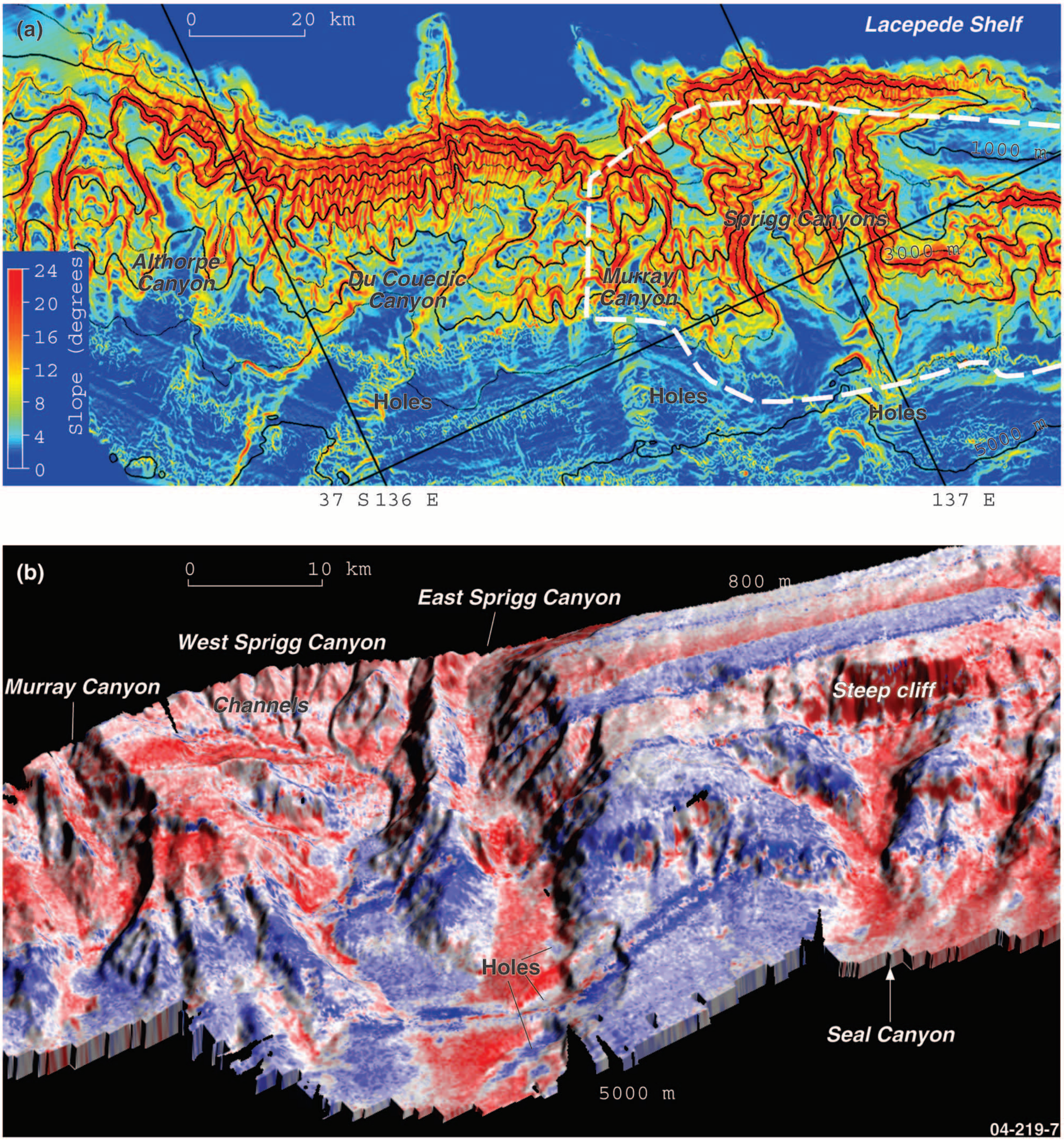

Figure 7 Details of seabed character in the central Murray canyons. (a) Seabed slope (with 500 m isobaths). (b) Acoustic backscatter strength (red, high, blue, low) draped on 3-D topography [location of area is indicated by thick broken white line in (a)]. Based on 13 kHz Simrad EM12D data (Hill *et al.* 2001).

Couedic Canyon system, though not as deep, is of similar or slightly larger size in plan. The western headslope of Du Couedic Canyon is incised by a remarkable series of downslope channels and chutes 200–500 m deep that begin at the shelf edge. The other major canyons of the group are mostly 1000 m deep. Canyon walls are commonly inclined at 15–22°.

Figure 6a compares profiles of canyon thalwegs and intervening spurs, the latter being relatively erosion-free parts of the slope, from shelf edge to continental rise. The thalweg profiles across the continental slope are concave, while the spur profiles are slightly convex or roughly linear. The gradient of the rise is about 1° and, in the case of the canyon thalwegs, this gradient continues well up the canyon valleys. On the mid slope, the thalwegs steepen to about 4° and then rise sharply on the upper slope where thalweg gradients are commonly as much as 15–30°. The spur profiles, on the other hand, have a uniform gradient down much of the continental slope of about 4.5–6°.

The mean difference in cross-sectional area between spur and thalweg sections across the continental slope is about 30 km^2. Applying this over the length of the Murray canyons margin, and correcting for the fact that this figure represents the larger canyons and that the canyons are approximately v-shaped in cross-section, the volume of sediment and rock in deficit due to canyon downcutting is estimated to be approximately 2500 km^3. Clearly, the amount of sediment deposited beneath the rise and abyssal plain would be far more than this volume because it includes sediment derived from the shelf 'carbonate factory' and the land.

Features of the canyons and adjacent shelf

The upper parts of both Sprigg and Du Couedic Canyons, the largest canyons on the central part of the margin, are broad fan-shaped or amphitheatre-like complexes of smaller canyons, winding channels and gullies that coalesce on the mid slope (Figures 4, 7). A 1000 m-high ridge divides Sprigg Canyon into two parts of almost equal size (West and East Sprigg Canyons: Figure 7). Du Couedic Canyon has a 20 km-long entrant on the outer continental shelf. This feature is much steeper on its eastern side, suggesting it was formed by erosive flow along its axis (from the north) or from the west, and empties into a deep narrow channel on the steep upper continental slope. Murray Canyon, which lies between Du Couedic and Sprigg Canyons, has a similar but slightly smaller entrant, while the adjacent West Sprigg Canyon also has an entrant but this is short and broad. These prominent entrants are located directly south of western Kangaroo Island, where the shelf is only about 50 km wide. The Du Couedic and Murray entrants may be conduits for seasonal saline bottom water outflows from Spencer Gulf (Lennon *et al.* 1987), as may the heads of the other canyons to the west.

Lacepede Shelf is relatively flat, with water depths mainly in the range 30 – 80 m (Figure 5). It has a broad depression immediately northeast of Sprigg Canyon, suggesting that the Murray River may have flowed this

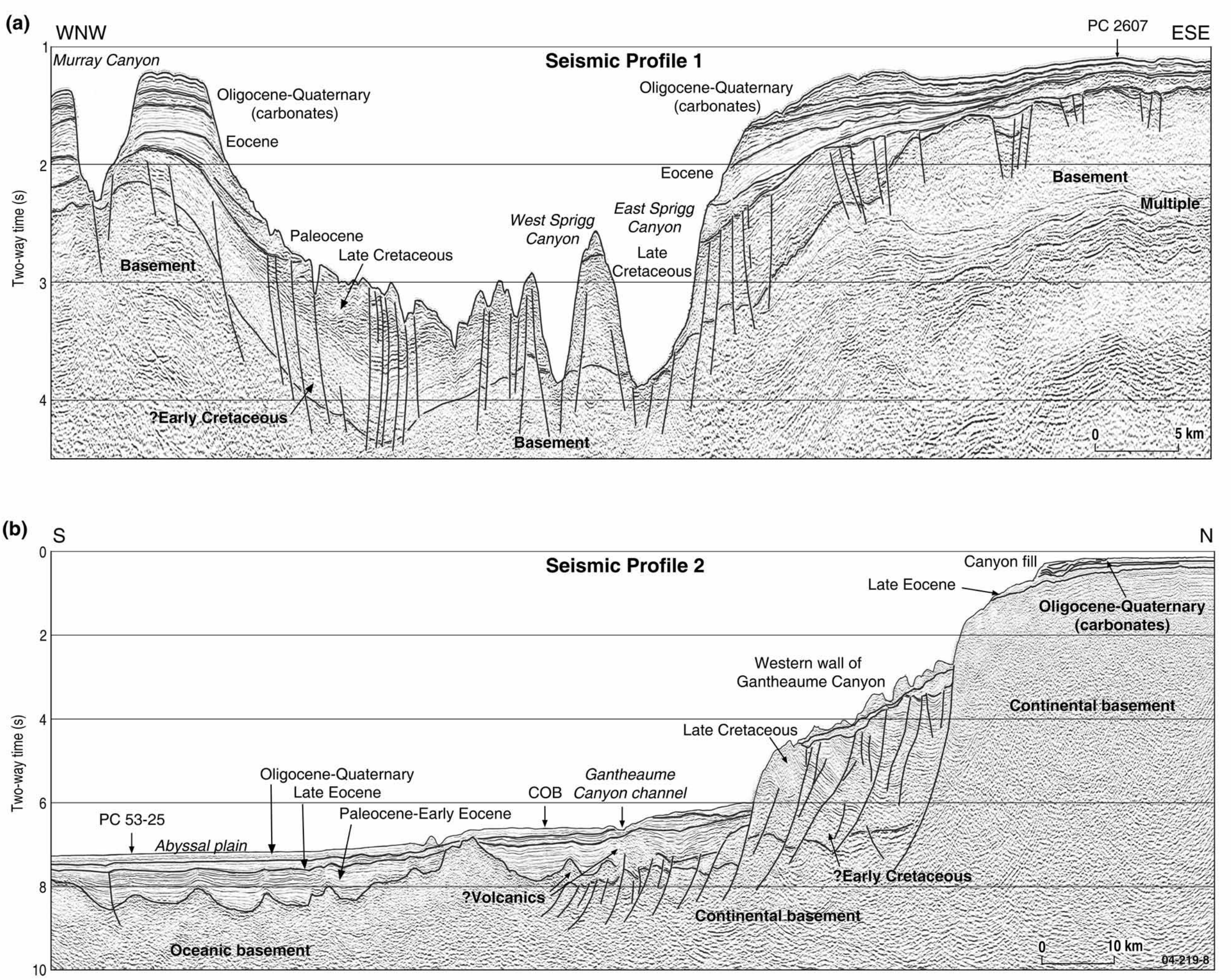

Figure 8 Seismic profiles 1 and 2 and interpretations (locations in Figure 5). Profile 1 is part of line AEA1028 of the AUSTREA-1 survey (Hill *et al.* 2000). Profile 2 is line 137-11 of Australian Geological Survey Organisation Survey 137 (Blevin *et al.* 1995); the interpretation of the latter is modified after Moore *et al.* (2000).

way across the shelf and into the head of Sprigg Canyon during the Last Glacial Maximum (20 ka: Yokoyama *et al.* 2000) when sea-level was 120–130 m lower (Clark & Mix 2002; Lambeck & Chappell 2001; Yokoyama *et al.* 2001) and during earlier Pleistocene lowstands (Figure 5). The entrants of Du Couedic, Murray and Sprigg Canyons start at the 120 m isobath, indicating that local rivers such as the Murray River emptied straight into the canyons during the extreme lowstands. Bathymetric contours in the central Lacepede Shelf (Figure 5) show a series of northwest-trending seabed ridges about 10 m high, which probably represent drowned beach ridges akin to those of the Coorong, and palaeo-strandlines further inland (Sprigg 1979). Similar low-amplitude ridges, but trending north-northwest, are seen in the bathymetry on the outer shelf west of Kangaroo Island in water depths of 120–150 m. Storm surges may have contributed to the development of these. Swell base along the edge of the Lacepede Shelf is at about 140 m depth (James *et al.* 1992).

Von der Borch and Hughes Clarke (1979) reported evidence of extensive mass-wasting in and around Gantheaume Canyon. Our images confirm their findings and show widespread deformation of the slopes throughout the Murray canyons. Arcuate structures, interpreted as slumps scars, are common on the continental slope and at the shelf edge (Figure 4), with some up to several kilometres wide. Many of the canyons were probably initiated by or at such slope failures.

Interesting features seen in the imagery are large holes, several kilometres across and several hundred

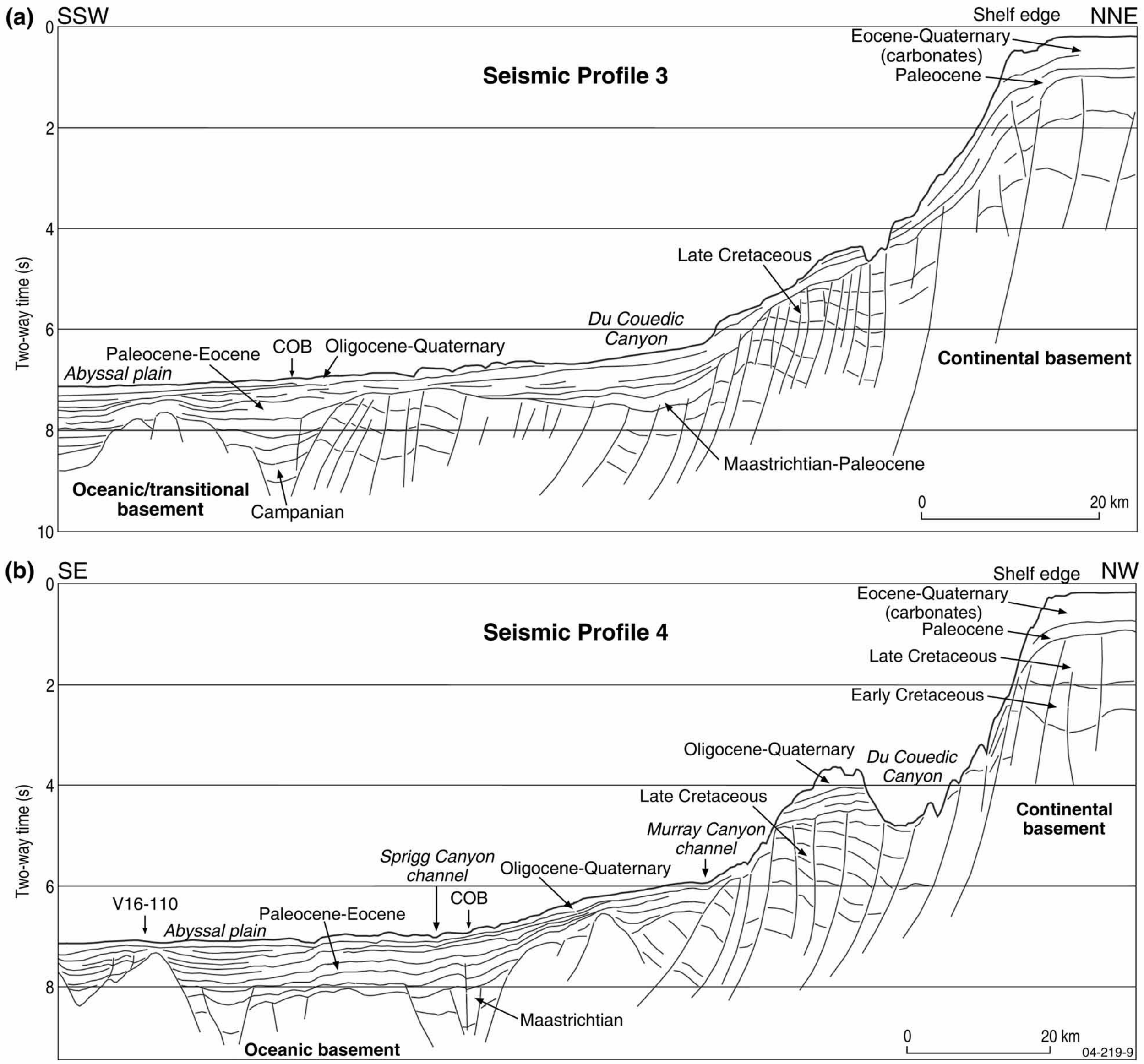

Figure 9 Line drawing interpretations of seismic profiles 3 and 4 (locations in Figure 5) shot as lines N407-6 and N408 of the 1972–73 Shell *Petrel* reconnaissance survey (Boeuf & Doust 1975).

metres deep, along the lower floors of some canyons where they debouch onto the lowermost slope and abyssal plain (Figure 4). These holes are spaced about 5 km apart and are steeper on their upslope sides (Figure 7a). They appear to be most pronounced at the base of the steeper and deeper canyons, such as Du Couedic (eastern side), Murray, and East Sprigg Canyons (Figures 3, 4). This suggests that the holes were gouged by surges of high-energy turbidity currents, which such steep canyons could generate. The turbulent surges were probably caused by episodic major slumping events at the canyon heads, particularly from unstable shelf-edge fans during sea-level lowstands. An alternate explanation for the holes is that they were formed by escape of fluids at the seabed, but this is less likely (see below).

The lower parts of the larger canyons, where they begin to merge with the continental rise, consist of broad, shallow outwash channels, mostly 50 – 100 m deep and 5 – 10 km across. The curved outwash channel of Du Couedic Canyon (Figures 4, 5) is the largest such feature and is 10 – 12 km wide and at least 75 km long. It is a relatively young feature that has cut a 100 – 200 m-deep swathe into the rise and leads upslope to the middle of the canyon headslope, suggesting that both it and this canyon's large entrant were cut at the same time. A series of holes on the continental rise east of the present channel (Figure 4) pre-date the cutting of the channel and may have formed by turbidity currents originating from the western head of the canyon.

The major complex of canyon systems at the western end of the Murray canyons and south of Eyre Peninsula, that includes Topgallant and Spencer Canyons, is located on a depocentre of the Ceduna Sub-basin (Figure 2) and is a thickly sedimented part of the margin. The canyons are typically box-shaped in cross-section, up to 10 km across and with very steep walls 800 – 1000 m high (Figure 5). They are slightly sinuous in plan, and in places appear to have captured adjacent canyons as they cut down into a thick and relatively unconsolidated sedimentary section. A network of feeder channels and gullies on the upper slope supplies sediment from the shelf edge to the main canyons lower down on the slope.

Information from backscatter imagery

12/13 kHz multibeam backscatter images acquired during the AUSCAN and AUSTREA-1 surveys (Figure 7b) provide additional information on the character of the seabed. In general, low backscatter was recorded from slopes covered by soft sediment drape, while canyon floors, slump scars and escarpments gave relatively high-strength returns. This was due to the presence of harder or rougher material, such as coarse sediments, debris flows, older more lithified sediments, or basement rocks, on the seabed or less than a few decimetres down.

The floors of the canyons in the west, those adjacent to the Ceduna Terrace, mostly produced higher than background backscatter, indicating coarser sediment (?sands) or older, more lithified sediments. The thalweg of Spencer Canyon gave a particularly strong and consistent return, perhaps due to inflow of coarse biogenic carbonates from the shelf edge. Backscatter images of the central canyons (Figure 7b) (Hill *et al.* 2001) were more complex because of the more complicated geomorphology. Canyon floors and thalwegs generally showed strong backscatter. The floors of East Sprigg and Seal Canyons, in particular, produced a high backscatter response, probably because their steep high walls are a source of coarse debris and talus. Slump scars and escarpments also show high backscatter, with basement rocks (Figure 8, ESE end of seismic profile 1) probably exposed on the 1000 m-high cliff face above Seal Canyon. The holes at the base of East Sprigg Canyon show low backscatter, suggesting that they may contain a layer of soft sediment. In the Gantheaume Canyon area, towards the eastern end of the Murray canyons, our new multibeam data show the same features observed by von der Borch and Hughes Clarke (1991) in their GLORIA sidescan and SeaBeam images, but in more detail. Here the rugged topography produces high levels of backscatter, particularly from the canyon floor and walls, and nearby escarpments and slump structures.

SEISMIC INTERPRETATION

Seismic data acquired in the area provide information on the depositional and structural history of the margin and associated canyon development. Very little good-quality seismic data exist over the Murray canyons, largely because of perceived poor petroleum prospectivity on this part of the margin, except west of Kangaroo Island in the Duntroon Sub-basin where seismic grids exist and several exploration wells have been drilled (Stagg *et al.* 1990). Nevertheless, several well-placed industry and scientific multichannel airgun lines do exist over the Murray canyons (Figure 5) and key lines are interpreted here (Figures 8, 9).

Seismic profile 1: across upper Sprigg Canyon

Seismic profile 1 (Figure 8a), paralleling the continental shelf, shows that the broad upper part of Sprigg Canyon lies within a Cretaceous graben containing about 1.6 s twt (seconds two-way time), or ~2 km, of sediment. Both main arms of the canyon have cut down through the entire Cretaceous – Cenozoic section to basement. The floor of the adjacent Murray Canyon, on a horst block, also lies at or close to the basement surface, with the canyon having cut through an 800 m-thick, well-stratified Cenozoic section and a thinner Cretaceous section. The Upper Cretaceous strata are wavy and contorted, partly due to Maastrichtian faulting which extends upwards to the Maastrichtian unconformity, but probably also due to syndepositional slumping. The Maastrichtian unconformity is strongly erosional on the slope east of Sprigg Canyon. The Cretaceous beds are angularly truncated and completely eroded off to the east. The overlying section comprises several hundred metres of Cenozoic deposits, which contain a mid-Eocene erosional surface. At core site PC 2607 (see next section), these deposits include about 100 m of Neogene – Quaternary carbonates and calcareous clays. The Paleocene sequence downlaps and thickens towards the middle of the canyon. However, it and any former overlying section, have now been almost completely removed by post-depositional downcutting. A series of channels 100 – 200 m deep on the lower western headwall incise Upper Cretaceous sediments.

Seismic profile 2: at Gantheaume Canyon

Seismic profile 2 (Figure 8b), across the margin near the eastern end of the Murray canyons, reveals a thin wedge of Upper Eocene and younger sediments beneath the outer shelf, basement exposure on the upper continental slope, and a thick block of faulted Cretaceous rift sediments beneath the mid-lower continental slope. A master normal fault beneath the upper slope separates this Cretaceous package from the continental headwall block. About 600 m of Maastrichtian and younger post-breakup deposits overlie highly extended Cretaceous rift section beneath the rise, while beneath the abyssal plain, outboard of an oceanic basement high, the section comprises up to 700 m of relatively flat-lying Cenozoic post-breakup deposits over oceanic basement.

The Upper Cenozoic wedge at the shelf edge contains a series of stacked buried channels. The upper surface of the Upper Cretaceous sequence is strongly eroded, implying that canyon cutting was probably occurring in the Maastrichtian – Paleocene. Gentle anticlinal folding and some faulting in the pre mid-Eocene section beneath the rise and abyssal plain appear to be related to more than compaction drape and suggest mild tectonic inversion and local intrusion of volcanics.

Seismic profile 3: at Du Couedic Canyon

In seismic profile 3 (Figure 9a), the section overlying continental basement beneath the outer shelf comprises about 1.3 s twt of Duntroon Sub-basin Lower Cretaceous sediments, 0.8 s twt of Upper Cretaceous sediments and 0.9 s twt (~1 km) of Cenozoic sediments. Beneath the continental slope the intensely faulted Cretaceous section, which is at least 2 s twt (~2.5 km) thick, steps down basinward through a series of normal faults of varying displacement. The upper surface of the Cretaceous section is erosional. The overlying Cenozoic sequence on the steep upper continental slope gradually thins downslope and appears to be mainly Palaeogene in age, with little Neogene present. On the mid slope, a small tributary canyon of Du Couedic Canyon cuts through to the Cretaceous surface. Farther down on the lower slope, the Cenozoic deposits average 500 m in thickness and probably include Neogene – Quaternary carbonates on local highs. At the base of slope, the very wide but shallow outflow channel of Du Couedic Canyon appears to be floored by Upper Eocene – Oligocene sediments and is underlain by a 1.2 s twt thick depocentre of Maastrichtian and younger post-breakup sediments. This depocentre was created by landward tilt of the underlying faulted rift block at the time of breakup. As a result, the post-breakup section is only about 500 m thick just north of the continent – ocean boundary and comprises relatively young sediments (Eocene and younger). Holes in the seabed just east of the channel appear to have formed in the Oligocene – Quaternary sequence. At the continent – ocean boundary, a graben that developed at the time of breakup contains a thick (2 s twt) fill of Campanian and younger deposits. Basinward, the post-breakup section thins to about 600 m over a large basement high of oceanic or transitional crust.

Seismic profile 4: Du Couedic to Seal Canyons

The northwest end of seismic profile 4 (Figure 9b) is close to the north-northeast end of profile 3, and the sub-shelf sections are similar, though the Lower Cretaceous is a little thinner. The slope below the shelf break is part of the Du Couedic Canyon headwall, is very steep due to erosion, and has little Cenozoic cover. The lower walls and thalweg of Du Couedic Canyon are cut into highly faulted Upper Cretaceous sediments. The Cretaceous section beneath the mid continental slope is at least 2.4 s twt (~3 km) thick. The ridge on the eastern flank of the canyon is topped by an erosional residual of Cenozoic sediments up to 1 km thick. At the mouth of Murray Canyon, the thalweg channel lies in the Oligocene – Quaternary sediments that blanket the continental rise. Beneath the rise, about 1 km of Cenozoic sediments overlie a jumble of continental fault blocks. Graben depocentres at the continent – ocean boundary, and nearby beneath the abyssal plain, contain about 2 km of Maastrichtian and younger post-breakup sediments. The basal post-breakup section up to the Eocene has been mildly deformed by some faulting and gentle folding. A small channel lies within the mid-Late Eocene section beneath the lower continental rise. The outlet channel of Sprigg Canyon is relatively narrow and shallow and lies within the Oligocene – Quaternary sequence.

QUATERNARY DEEP-SEA CORES

AUSCAN cores

The AUSCAN 'Calypso' cores (Hill & De Deckker 2004) were taken on the mid-upper continental slope of the central Murray canyons in water depths of 865 – 2427 m (Figure 5). Sites were chosen on local high features, not directly within the main canyons, with the aim of obtaining continuous pelagic, mostly biogenic, sequences influenced by finer sediments from rivers and the continental shelf, including fine sediment clouds associated with movement down the canyons, as well as occasional wind-blown material. The piston cores PC 2607, PC 2610 and PC 2612 were 33 m, 8 m and 35 m long, respectively, while the gravity core GC 2611 was 12 m in length. The sediments recovered were mainly foraminiferal silty fine sands with intercalated silty clay sections.

Two of the cores, PC 2607 (east of Sprigg Canyon) and GC 2611 (eastern Du Couedic Canyon) were analysed in detail (Gingele *et al.* 2004). Geochemical analysis included clay mineralogy, bulk mineralogy (quartz, aragonite, calcite), total and organic carbon, plus a range of major and trace elements. Oxygen and carbon isotopes were measured on the planktonic foraminifer *Globigerina bulloides*. Age models of the cores are based on the δ^{18}O-record of *Globigerina bulloides*, with individual isotope events identified and compared with the global SPECMAP-stack. The sedimentary record in both cores appears to be continuous, with no hiatuses evident. The bottom of core PC 2607 coincides with oxygen isotope stage 6.5 (*ca* 175 ka), and the bottom of the shorter core GC 2611 only reached stage 5.1 (*ca* 85 ka).

Analysis of the cores (Gingele *et al.* 2004) shows that the Murray canyons area experienced dramatic changes in the amount and composition of sedimentary material laid down over the last 175 000 years. The main influences on sedimentation mode and patterns have been changing sea-levels and associated shifts in the position of the Murray mouth. With the Murray mouth presently 200 km away from the Murray canyons, little terrigenous matter reaches the area and sedimentation is mainly pelagic. Sediments being deposited now consist almost entirely of carbonate particles plus minor aeolian dust. However, there is evidence of some fluvial clays reaching the core sites even during the latter periods of the Holocene (e.g. last 6000 years) when sea-level remained static (Gingele *et al.* 2004).

During sea-level lowstands, when the Murray mouth was close to the present shelf edge and the shore was within 15–30 km of the core sites (Figure 5), the sedimentation mode shifted to hemipelagic, strongly influenced by clays of fluvial origin, thus increasing the overall sedimentation rate by a factor of 3–6. Clay content and sedimentation rates peaked at *ca* 20 ka (oxygen isotope stage 2) and 140 ka (stage 6). At these times, carbonate content was down to about 40% and $< 5\%$, respectively, with corresponding sedimentation rates up to 30 cm per thousand years and a very high 60 cm per thousand years. In comparison, interglacial background levels were 85% carbonate and 10 cm per thousand years deposition rate. The composition of the terrigenous matter suggests that the Murray River was the major source of sediment during cold stages 4-2 and 6. However, during stage 6, the river load was more kaolinite-rich, possibly due to a tributary river from Gulf St Vincent that joined the Murray on the exposed shelf (Figure 5) (Gingele *et al.* 2004). There is some evidence in the clay record of core PC 2611 that this river may have reached the ocean independently during stage 2.

Vema and *Eltanin* cores

A number of deep-sea cores were taken in the Murray canyons area by US research vessels *Vema* and *Eltanin* in the early 1960s and 1970s, respectively. The *Vema* cores were described by Conolly and von der Borch (1967) and the *Eltanin* cores were documented by Frakes (1973). Cores located on the continental rise or adjacent abyssal plain (Figure 2) are *Vema* cores V16-110 (982 cm long), V18-220 (610 cm) and V18-221 (292 cm), and *Eltanin* cores PC 53-24 (155 cm) and PC 53-25 (1013 cm).

The *Vema* cores comprise graded beds of calcareous sand, silt and clay interbedded with olive carbonate-poor clays. Some of the coarser beds are clearly Bouma turbidite sequences, with coarse graded sands at the base overlain by upward-fining laminated and cross-stratified bands. All beds are at least broadly graded, even the apparently homogeneous clays. A poorly sorted sand in V18-220 at 160 cm core depth consists of fragments of foraminifers, molluscs, bryozoans, algae and much broken and reworked skeletal material. The coarse fraction ($>$ 1 mm) of a sand at 105 cm in V18-221 consists mainly of cheilostome and cyclostome bryozoans (Conolly & von der Borch 1967). The sediments are obviously turbidite deposits, with at least some units originating at the shelf edge. The *Eltanin* cores show similar structure and lithology, mainly sandy mud. The core sections comprise numerous beds varying in thickness but averaging 50 cm, with about half the beds having a sharp base. PC 53-25 contains several thin layers of sand and hash (shell fragments), probably swept down from the shelf by turbidity currents.

DISCUSSION

Some important questions to be answered in relation to the Murray canyons are: when were the canyons cut and what were the processes involved?

Firstly, we now know that most of the large canyons cut deeply into uppermost Cretaceous sediments, particularly on the upper slope, and as seen in seismic profile 1 across Sprigg Canyon (Figure 8a) relatively flat-lying Lower Palaeogene sequences are completely cut through. This suggests that maximum downcutting occurred since the Early Eocene. Evidence of mid-Eocene channelling beneath the rise (Figure 9b, and more obvious in the full-scale profiles) and stacked buried Oligocene–Miocene canyons beneath the outer shelf (Figure 8b) is compatible with this general deduction. Breakup at the Murray canyons margin occurred in the Campanian–Maastrichtian during the initial slow-spreading phase between Australia and Antarctica. Prior to that, sedimentation was terrestrial to shallow marine in a subsiding rift valley, without major topographic relief to allow deep canyon cutting. As oceanic rifts developed, relief of up to 2.5 km may have been generated, but the narrow rifts would have begun to fill rapidly with prodeltaic deposits, thus reducing this relief. Both fluvial and submarine canyons may have been initiated at this time. These and tectonic depressions created at the time may have acted as loci for canyon development during subsequent episodes of downcutting.

Secondly, canyon cutting requires mobile sediment for erosion. Periods when highest sediment volumes are likely to be available to canyons are: (i) during sea-level lowstands or tectonic uplift when adjacent shelves and deltas become exposed and are subaerially eroded; and (ii) during the early phase of transgressions when coastal deposits including beaches and aeolian dune-fields are eroded and reworked before substantial accommodation space develops with rising sea-level, and while the sediment source is still close to the canyon heads. An external sediment source is not strictly required since mobilisation of existing sediment by mass-wasting processes can also initiate downcutting, but such mobilisation requires an external driver such as tectonic steepening of a slope or scouring by an erosive bottom current.

Data from nearby parts of the margin provide a context to canyon evolution at the Murray canyons. These are discussed below.

Western Otway margin

To the southeast, between King Island and the Lacepede Shelf, numerous downslope channels and canyons (Hill & De Deckker 2004) dissect the thickly sedimented continental slope. The canyons are generally more deeply incised on the upper continental slope where the seabed gradient is higher, and a number of them are several hundred metres deep. As revealed in detail by the AUSCAN project, some of the largest canyons lie on the central margin, southwest of Portland. On the mid-continental slope, these canyons are up to 600 m deep and 12 km wide. In several cases, two or more branches on the upper slope join to form one large canyon on the mid-slope. Seismic mapping on the shelf has revealed systems of older buried canyon systems that were active throughout much of the Late Cenozoic, beginning in the Oligocene. Pollock *et al.* (2002) identified 20 successive canyon cut-and-fill events ranging from Late Oligocene to Middle Miocene in three palaeo-canyon systems beneath the outer shelf off Mt Gambier, and just east of the Lacepede Shelf. A little farther east, off Portland (Figure 1), Leach and Wallace (2001) mapped two distinct canyon systems within the shelf carbonates, a westward-migrating Miocene set and a largely symmetric Pliocene–Holocene set. Apart from minor slumping from canyon walls, the modern canyons on the slope appear to be inactive during the current highstand (Passlow 1997; Exon *et al.* 2002).

Ceduna Terrace area

The continental slope in the Ceduna Terrace region is of varying morphology and has been dissected by ubiquitous downslope gullies, channels and canyons (Rollet *et al.* 2001; Hill & De Deckker 2004). Tilbury and Fraser (1981) produced a bathymetric map of the Ceduna Terrace based on track-line data, and described the numerous submarine valleys on the upper slope that feed into canyons on the steeper mid-lower slope. The closely spaced, downslope channels and canyons are typical of erosion on a thickly sedimented slope. One of the largest canyons on the Ceduna Terrace is the Nullarbor Canyon, of which the lower section was swath-mapped in 2000 (Hill *et al.* 2001). This canyon is 250 km long, and has gouged a series of holes several hundred metres deep and up to 5 km across into deformed Upper Cretaceous sediments at the foot of the slope. The holes lining the canyon floor become smaller upslope; the larger ones are in water depths of 4000–5300 m. These holes are similar to those discovered in the lower sections of the central Murray canyons. It was suggested that the holes in the Nullarbor Canyon might be the sites of 'warm seeps', i.e. fluids from deep in the crust leaking out at the sea floor. Two marine investigations, by RV *Southern Surveyor* in 2000 (Harris *et al.* 2000) and RV *Franklin* in 2001 (Binns 2001) failed to find any evidence of active or fossil seeps. Sampling showed that the holes were formed in Upper Cretaceous mudstones covered by a veneer of pink Quaternary ooze. Because the investigations were not exhaustive, the possibility that the holes in the Nullarbor Canyon and Murray canyons are associated with fluid seeps cannot be ruled out until further studies are done.

The lower slope of the eastern Ceduna Terrace is the more intensely and deeply incised part of this large feature. Here narrow, downslope canyons are incised to depths of 500–700 m. Some of the canyon floors contain a series of holes similar to, but smaller than, those imaged in the lower Murray canyons to the east and in the Nullarbor Canyon to the west. Steps in the canyon floors (up to several hundred metres) suggest that some of the canyon development has progressed by headward erosion, and that the holes observed in the canyon floors could be residual 'plunge-pools' formed in less-resistant strata as canyon erosion advanced upslope (Hill & De Deckker 2004). The canyon floors show high backscatter, indicating coarser sediments (?sands) or older, more lithified, sediments at or just beneath the seabed.

Seismic profiles across the Ceduna Sub-basin show canyons and channels at a number of stratigraphic levels (Totterdell *et al.* 2000). The profiles indicate that: (i) the Santonian breakup unconformity is distinctly erosional in parts of the Ceduna Sub-basin, with broad channels 100–200 m-deep cut into this surface; (ii) a buried canyon about 15 km across and several hundred metres deep was cut into the Maastrichtian section and now is filled with Upper Paleocene–Lower Eocene sediments; and (iii) buried canyons and channels up to 200 m deep occur in the Middle Eocene and younger carbonate wedge. Boeuf and Doust (1975) noted Pliocene submarine erosion and associated deep canyon incision.

The area at the junction of the eastern Ceduna Terrace and the Murray canyons is characterised by a thick cover of Cenozoic sediments (largely carbonates). At the shelf edge, where the cover overlies the Duntroon Sub-basin, it is up to 2 km thick, and comprises a thick Middle Eocene and younger sequence of carbonates over a much thinner Upper Paleocene–Lower Eocene sequence of marine transgressive sands. It wedges out landward and thins down the continental slope. A seismic profile across the lower slope (Boeuf & Doust 1975) shows the Cenozoic unit to be up to 1 km thick and deeply incised by canyons, with some of the larger canyons floored in Upper Cretaceous sediments. This interpretation is consistent with the results of dredge haul 102DR07 (Feary 1993) from 3500–3700 m depth on the western wall of Topgallant Canyon; Campanian–Maastrichtian mudstones and carbonate rocks ranging in age from Middle Eocene to Late Oligocene were recovered. Ormerod (1993), using a dense grid of industry seismic lines, mapped a succession of Tertiary channels on the outer shelf above Spencer Canyon and identified channelling events at 65 Ma, 45 Ma, 36 Ma and 14 Ma, though some of the dating is not well-controlled. The incision depth of the 36 Ma channel system is about 250 m and trends north–northeast, in line with the modern canyons on the adjacent slope, suggesting that a major canyon system was active on the margin during the Late Eocene, possibly Early Oligocene.

Controls and processes

Von der Borch (1968) pointed out that the large canyons off southern mainland Australia appear to be associated with promontories of basement rocks jutting out from the coast, rather than modern or ancient drainage outlets. Hill *et al.* (2001), on the other hand, noted that the long linear canyons on the continental slope off west Tasmania appear to radiate from the mouths of major rivers along that high-rainfall coast, implying fluvial control on canyon distribution. Climate and onshore topography obviously influence canyon development. The environment of western Tasmania, with its mountains and high-discharge rivers (sourced by glaciers during parts of the Pleistocene) certainly contrasts with the generally arid conditions along the coast and mostly low-lying hinterland of southern Western and South Australia.

Kangaroo Island is a large landmass that juts into the Southern Ocean. In addition, several small rocky islets are located well out on the shelf south of Kangaroo Island, only about 30 km from Sprigg Canyon. The central Murray canyons thus fit the association advanced by von der Borch (1968). There could be two reasons for this basement promontory/large canyon association on arid coasts: (i) the basement profile across the margin is steeper and steeper slopes mean easier downcutting; or (ii) stream gradients are higher, so that during lowstands relatively energetic flows of water and sediment enter close to the shelf edge, cutting an incision; once established, such an incision traps carbonate or other sediment shed from the shelf and a canyon develops at this point. It should be noted that the large entrants of Sprigg, Murray, West Sprigg, and perhaps Althorpe Canyons all point towards the nearest land on Kangaroo Island, which supports the latter proposition. It could also be that the orientation of these entrants, and perhaps even the fact that they continue to exist, relates to high carbonate production in the eastern Great Australian Bight, and the funnelling of these sediments in this high-energy environment across the narrow shelf southwest of the island and over the shelf edge where the entrants remain open due to erosion. However, the development of Sprigg and Gantheaume Canyons is likely to have been influenced significantly by sediment input from the Murray River.

The shape and configuration of the canyons in the Murray canyons group are frequently controlled by faults and zones of structural weakness in the underlying older formations, mainly Cretaceous rift sediments and basement rocks, and the thickness of relatively unconsolidated sediments on the slopes. This explains the dramatic difference in nature of the central and western canyons (Figure 5), the former being controlled by shallow rift structures and the latter located on a slope thickly blanketed by Cenozoic sediments.

The main process involved in canyon formation in the Murray canyons appears to be slumping and other mass failures at the steep shelf edge and on the upper slope, generating turbidity currents that erode the continental slope below. The density flows have maximum energy and erosive power on the mid-slope, resulting in the observed deep incisions on this part of the margin. Many of the box canyons in the west have clearly developed by upslope advance of their steep headscarps, probably by a mechanism similar to that proposed by Pratson *et al.* (1994) and modelled by Pratson and Coakley (1996). In this model, pre-canyon downslope rills are developed by localised slope failures on the upper slope, sediment-flow erosion exploits local weaknesses at one or more sites on the middle to lower slope to start the downcutting process, which then leads to the development of a headward-eroding canyon by sediment-flow-induced upslope retrogressive failure. In the Murray canyons, particularly in the west, groundwater sapping at the canyon heads may contribute to headward erosion.

The pronounced downslope gully and ridge topography in the amphitheatre of the upper Du Couedic Canyon (Figure 3) is very similar to that observed along the northwest margin of the Bass Canyon (Hill *et al.* 1998), where sediment is continually being swept off the shelf edge by current action. The gullies probably initiated as a series of arcuate slumps that developed along the shelf edge due to buildup of carbonates, particularly during lowstands. The resultant fluted edge then evolved into a system of gullies deepened by continued downslope sediment movement.

We observe distinct, relatively narrow (about 1 km wide) meanders that incise the upper slopes of some canyon systems in the Murray canyons to depths of 100–200 m. The upper West Sprigg Canyon is a good example of a dendritic system of meandering channels (Figures 4, 7). Here, five or more tributary channels, each originating at the shelf edge, join on the mid-slope to form one channel 1.5 km wide. These channels are relatively young and may be active at present, transporting carbonates shed over the shelf edge to the lower continental slope and beyond.

Tectonic/eustatic influences on timing of downcutting

In the Otway Basin, the principal hiatuses since the beginning of the Late Cretaceous occurred in the Cenomanian, Santonian/Campanian transition, late Maastrichtian, mid-Middle Eocene, mid-Oligocene, and during latest Miocene–Pleistocene (Geary & Reid 1998; Krassay *et al.* 2004). In the Bight Basin, a major hiatus occurs in the Early Paleocene and sequence boundaries are located in the early Cenomanian, Turonian, late Santonian and early Middle Eocene (Totterdell *et al.*

2000). In the Duntroon Basin, Stagg *et al*. (1990) indicated a major sequence boundary at the Cenomanian/Turonian transition, and hiatuses in the Early Paleocene, late Early Eocene and Late Oligocene. There is broad correlation across the three basins. There is also some correlation with Haq's (1991) canyon-cutting events based on global lowstands, which he places in the Late Paleocene (*ca* 58 Ma), Middle Eocene (*ca* 48 Ma), Late Oligocene (*ca* 29 Ma), Early/Middle Miocene transition (*ca* 16 Ma) and Middle/Late Miocene transition (*ca* 10 Ma).

Eustasy is a powerful driver of canyon development, and detailed global deep-sea oxygen-isotope records, which reflect climate and sea-level change, are now available for the entire Cenozoic (Zachos *et al*. 2001). Post-Late Eocene variations in the isotope record are largely due to ice-volume changes. Based on the isotope record, lowstands are inferred in the Early Oligocene, Oligocene/Miocene transition (*ca* 24 Ma), Middle Miocene (*ca* 14 Ma) and latest Miocene – Pleistocene.

Combining the stratigraphic and glacioeustatic information, major changes in sedimentation patterns, including possible canyon cutting, are predicted for the Murray canyons area in the Cenomanian, Santonian/Campanian transition, Early Paleocene, Middle Eocene, Early Oligocene, Oligocene/Miocene transition (*ca* 24 Ma), Middle Miocene (*ca* 14 Ma) and latest Miocene – Pleistocene. Some fluvial channels may have been cut during the Cenomanian and Santonian/Campanian events, but these are not considered to have contributed significantly to canyon development in the Murray canyons apart from possibly acting as low points for later canyoning. The glacioeustatic-driven post-Late Eocene events are believed to have been the most important in cutting the Murray canyons.

CONCLUSIONS

Our recent multibeam swath surveys reveal the spectacular nature of the Murray canyons in detail for the first time. The new maps and images generated, and the results of geological and geophysical components of the investigations, have given us greater insight into the morphology of the canyons and the processes that created them. Though located less than 250 km south of Adelaide, the Murray canyons remain a mysterious undersea world with little known about their biology and oceanography. Our surveys and studies will assist environmental research and management of this pristine area. Our main conclusions are summarised below.

The Murray canyons are structurally controlled, with basement and Cretaceous rift sediment bedrock outcropping on canyon floors and parts of the deeply incised canyon walls, which are up to 2 km high. Structural trends are mainly west-northwest, reflecting underlying Jurassic – Cretaceous basin-forming faults of the Bight and Otway Basins.

The continental slope and canyon walls show evidence of considerable mass-wasting (slumps, sediment slides, turbidity currents). Extensive chutes and channel systems in the canyon heads convey sediment from the shelf edge into thalwegs of major canyons that debouch on the abyssal plain 5000 m below. We believe that some sediment movement and erosion is currently taking place.

Holes, up to 5 km across and several hundred metres deep, mapped along the outlets of the steeper and larger canyons, were probably eroded by high-energy turbidity currents generated by large slumps on the upper continental slope.

Cores taken on spurs between the Murray canyons show dramatic changes in sediment composition and sedimentation rates over the last 175 000 years. These variations in sediment deposition are due mainly to changing sea-levels and position of the Murray River mouth. During sea-level highstands (such as today), little terrigenous material reached the canyons, with sediments being mostly marine biogenic carbonates plus a minor aeolian component. During major lowstands, when the river mouth was located just off Sprigg Canyon, sediments deposited on the upper continental slope were hemipelagic and fluvial clays and the sedimentation rate increased by a factor of 3 – 6 to as high as 60 cm per thousand years.

Slumps and other mass failures at the steep shelf edge and on the upper continental slope generate turbidity currents that erode the continental slope below. Headward erosion is an important process in upslope migration and enlargement of canyons.

The canyons were cut episodically during the Cenozoic: we suggest that these events occurred in the Early Paleocene, Middle Eocene, Early Oligocene, Oligocene/Miocene transition (*ca* 24 Ma), Middle Miocene (*ca* 14 Ma) and during the latest Miocene – Pleistocene. The Early Oligocene and younger glacioeustatic-driven episodes are believed to have been the most important in carving the canyons.

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