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Ancestral Murray River on the Lacepede Shelf, southern Australia: Late Quaternary migrations of a major river outlet and strandline development

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The Murray River drains the 1.06×10^6 km^2 Murray–Darling Basin and discharges into the sea at the Murray mouth in southeast South Australia. The outlet faces the 180 km-wide Lacepede Shelf and forms part of a wave-dominated beach barrier/lagoon complex, the largest of its type on the Australian coast. Global glacial cycles during the Pleistocene produced lowered sea-levels and exposure of much of the Lacepede Shelf, with the paleoshoreline advancing out to the present edge of the continental shelf during glacial maxima. Mapping and sediment sampling of the Lacepede Shelf in 2006 and 2007 allowed the ancient course of the Murray River on the shelf to be traced and studied for the first time, revealing a 200 km-long system of ancient infilled channels and lagoons. The main system of anastomosing Pleistocene channels begins southeast of the present Murray mouth, off Lakes Alexandrina and Albert, runs southward initially but then veers west-southwest across the central Lacepede Shelf before heading southwest directly south of central Kangaroo Island, and splaying into the head of Sprigg Canyon at the shelf edge. The Last Glacial Maximum channel starts near the current Murray mouth and forms part of this channel system. An earlier channel system ran a more direct, shorter 150 km south-southwest path from off Lakes Alexandrina and Albert to the shelf edge. The Lacepede Shelf is founded on a platform of gently folded, shallow-marine Miocene carbonates. The top of the platform is a prominent regional flat-lying erosional unconformity with local karstic relief in the order of 10 m. Unconsolidated sediment cover (?Pliocene–Quaternary) is mostly relatively thin or absent. However, a depocentre (Lacepede Basin), commonly 6–10 m thick, underlies the central Lacepede Shelf and that part of the shelf directly south of Lakes Alexandrina and Albert. This basin comprises estuarine, lagoonal/lacustrine and fluvial facies of the paleo Murray River, including channel-fill and point-bar deposits. Sediment drifts and residual paleo dunefields are common components of the young sediments on the shelf. A Holocene yellow/red fine quartz sand less than a metre thick, likely to have formed from reworked Last Glacial Maximum eolian sheets/dunes as well as lagoonal/lacustrine sediments, is the predominant sediment type at the surface of the central and northern Lacepede Basin. Paleochannels or paleovalleys of the Murray River incised into the Miocene carbonate platform are typically 10–20 m deep, 450–1000 m wide and contain up to 25 m of sedimentary fill and cover.

KEY WORDS: continental shelf, Gambier Limestone, Lacepede Shelf, Lacepede Basin, Quaternary, Murray canyons, Murray River, Sprigg Canyon.

INTRODUCTION

The outlet of the Murray River in southeast South Australia is an example of a wave-dominated estuary unmatched in scale anywhere along the Australian coastline. The Murray River drains one of Australia's largest inland river catchments, the 1.06×10^6 km^2 Murray–Darling Basin (Figure 1), before debouching onto the Lacepede Shelf—a 180 km-wide embayment in the continental shelf (Figures 2, 3). Global glacial cycles in the Pleistocene and associated increases in ice volume resulted in sea-level falling as much as 120–130 m below the current level (Figure 4). Such falls produced regressions that periodically fully or partially exposed the Lacepede Shelf, at times transforming it into a vast coastal plain. As the shoreline migrated back and forth across the shelf, the position of the mouth of the Murray River also changed. Contemporaneous neotectonic activity manifested as regional upwarping further significantly influenced the geomorphic development of the area and led to the preservation of a remarkable series of Pleistocene strandlines on the

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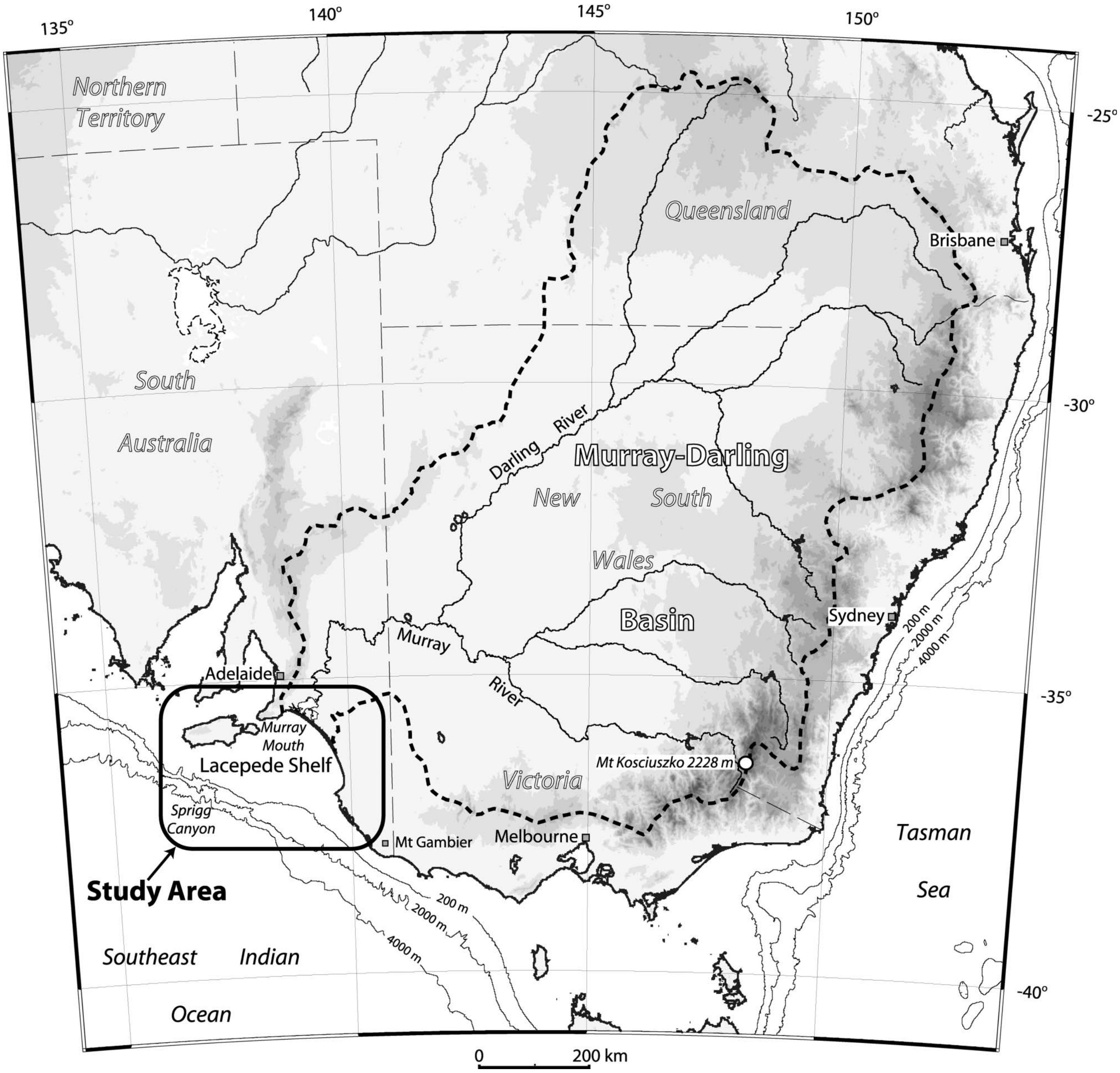


Figure 1 Location of the Lacepede Shelf at the outlet of one of Australia's largest river systems, the Murray–Darling Basin. The Murray River flowed across the Lacepede Shelf during glacial periods of the Pleistocene as sea-level fell, and the shoreline advanced towards the edge of the continental shelf, shedding sediment into canyons on the continental slope. Onshore topography is shown in grey-scale, with darker shades representing higher elevations in 200 m increments and culminating in Australia's highest mainland peak (Mt Kosciuszko) at 2228 m.

Coorong coastal plain (Sprigg 1952, 1979; Belperio 1995; Murray-Wallace *et al.* 1998).

Although studies have been made of the modern Murray River estuary (Harvey 1996; Bourman *et al.* 2000), and surficial sediments on the Lacepede Shelf have been sampled and analysed (James *et al.* 1992), very little was known of the Quaternary history of the region including sedimentary fill successions on the shelf, the antecedent land surface, and its geology. Indeed, many important questions regarding the mid–Late Quaternary geological evolution of the area, its paleogeography and sedimentology remained unanswered or have been the subject of speculation. In particular, what was the course of the ancient Murray River on the shelf and how did it change over time, what was the influence of local and regional neotectonics and climate change, and where did the sediments from the Murray–Darling Basin end up? In addition, what were the sedimentary processes operating on the shelf, and what were the nature and extent of the Murray estuary, coastal landforms and fluvial systems in the hinterland? Are there any links between the deep-sea canyons off the Lacepede Shelf and ancient courses of the Murray River?

Two scientific expeditions to the Lacepede Shelf on RV *Southern Surveyor* designed to answer some of these questions were undertaken in 2006 (Voyage SS02/06) and

2007 (Voyage SST02/07). Specific aims were to find evidence of the ancient Murray River, to map associated fluvial and lacustrine sedimentary systems, to investigate possible links with some of the deep-sea canyons nearby, and to obtain more information on the geology of the underlying bedrock platform. The initial results of these geophysical mapping and geological sampling investigations are the subject of this paper. In it, we integrate our new data and findings with earlier studies to develop a better understanding of the structural and stratigraphic framework of the Lacepede Shelf, and in particular, the ancestral Murray River that flowed across it during most of the Quaternary.

PHYSIOGRAPHIC SETTING

The Lacepede Shelf is a large, 30 000 km^2, embayment within the continental shelf off southeast South Australia (Figures 1, 3). It is bounded to the northwest by Kangaroo Island, with hills to 307 m high, and the mainland Fleurieu Peninsula, which is the southern extension of the 710 m-high Mt Lofty Ranges that overlook Adelaide. East of the Lacepede Shelf lies the relatively flat southwestern part of the Murray–Darling Basin, an extensive Tertiary–Quaternary epicratonic basin that occupies a large part of inland southeast Australia. The modern shoreline here is a beach barrier/lagoon complex, arcuate in shape and almost 200 km long. Dunes of the narrow Younghusband Peninsula (Figure 2) separate the brackish to hypersaline lagoons of the Coorong from the sea. Towards the northern end of the complex is the Murray mouth, the channel that is the ocean outlet of the Murray River, which drains the vast Murray–Darling Basin. Just inland are the two large but shallow (mainly <4 m deep) Lakes Alexandrina and Albert. The coastal plain inland of the southern Coorong is characterised by a series of ridges (Figure 3)—ancient strandlines, typically 20–30 m high and aligned roughly subparallel to the modern coastline, that are preserved remnants of former similar coastline complexes (Cook *et al*. 1977).

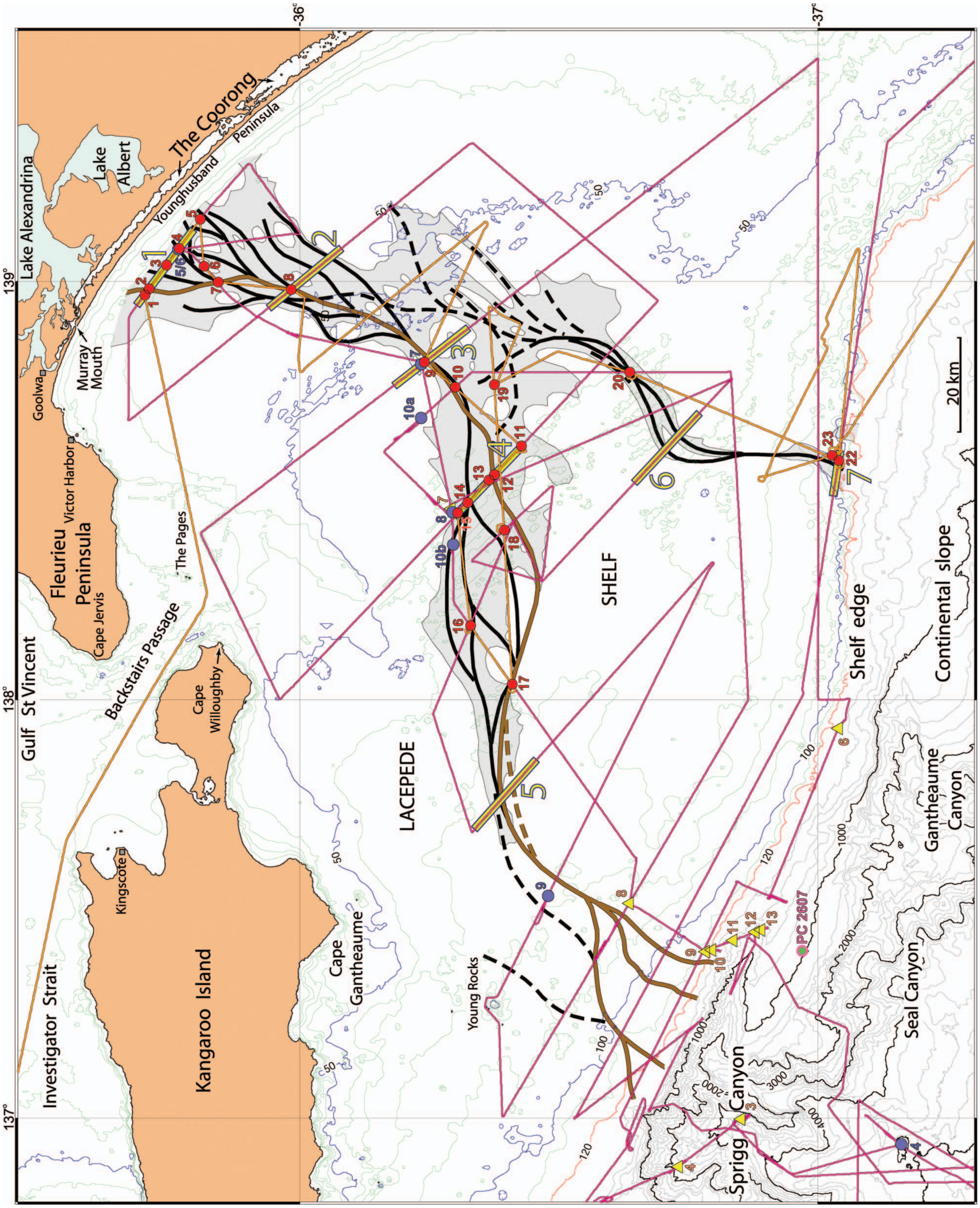
Mostly flat-lying, the sea bed of the Lacepede Shelf generally dips very gently seawards and is about 60 m deep in its middle shelf setting (Figure 2); 60% lies within a depth range of 40–70 m (Figure 4). Some small islets are located south of Kangaroo Island and at the entrance to Backstairs Passage. The outer, southwest-facing edge of the Lacepede Shelf is 100–200 m deep and drops off rapidly to meet the steep continental slope. The continental slope, about 80 km wide, is deeply dissected by the Murray canyons (Hill *et al.* 2005). One of the largest of these is Sprigg Canyon (Figures 2, 3), located directly south of Kangaroo Island. It has walls up to 2 km high and an upper thalweg slope of 20°. The flat abyssal plain seaward of the continental slope is 5000–5300 m deep.

BEDROCK GEOLOGY

Basement in the region comprises metamorphosed sediments of the Cambrian Stansbury Basin (Gravestock & Gatehouse 1995), intruded by granites of the Delamerian (Late Cambrian–Ordovician) Orogeny. Kangaroo Island and Fleurieu Peninsula are underpinned by these basement rocks and form part of the Kanmantoo Trough. Granites outcrop on both their southern coasts, which border the Lacepede Shelf. Rocky islets well south of Kangaroo Island such as Young Rocks (Figure 2) are related granites, while The Pages (Figure 2) near Backstairs Passage are composed of Cambrian metasediments. Numerous small scattered basement outcrops also occur on the coastal plain inland of the Coorong (Cowley & Freeman 1993), particularly along the Padthaway Ridge about 30–60 km inland. The outcrops include Stansbury Basin metasediments and Delamerian granitoids, acid volcanics and basic intrusives. Permian glacigene sediments (such as clay-rich till with erratic boulders) up to several hundred metres thick are preserved in ice-scoured depressions on Kangaroo Island and Fleurieu Peninsula. Thicker deposits may occur in nearby offshore areas such as Backstairs Passage (Daily *et al.* 1979), and a borehole on Hindmarsh Island near the Murray Mouth intersected Permian glacially-derived sediments at a depth of 230 m (Bourman *et al.* 2000).

The southwest and southern margins of the Lacepede Shelf are underlain by mid-Jurassic–Cretaceous rift basins of the Southern Rift System (Willcox & Stagg 1990). A major arcuate basin-bounding fault extends eastward from the western tip of Kangaroo Island, along the upper continental slope south of the Lacepede Shelf, and across to the coast at Robe (Hill *et al.* 2005 figure 2). This fault separates the area of shallow basement beneath the Lacepede Shelf from the Bight Basin to the west and the Otway Basin to the southeast. Seismic data suggest that supra-basement sediments beneath the shelf are about 600 m thick (Willcox 1974).

Extensive parts of the region, including the Lacepede Shelf, are underlain by Tertiary strata. They include the intracratonic Murray Basin (Brown & Stephenson 1991; Rogers *et al.* 1995) to the northeast, the Gambier Basin (Smith *et al.* 1995) in the southeast, and the St Vincent Basin to the north. Having evolved together as part of one large interconnected Tertiary depositional system, these basins share similar stratigraphy and lithology (Alley & Lindsay 1995), and because of this, the boundaries between them are diffuse. The succession passes upwards and seawards from Lower Tertiary deltaic clastic sediments into temperate shelfal carbonates in the Miocene. The Gambier Limestone (equivalent of the Mannum Limestone in the Murray Basin) is a major fossiliferous unit of the Upper Oligocene–Middle Miocene Heytesbury Group up to 400 m thick with a strong erosional unconformity at its top. It underlies the shelf and onshore parts of far southeast of South Australia and probably much of the Lacepede Shelf. Off Robe, deep exploration wells Trumpet 1 and Troas 1 intersected 300 m of Gambier Limestone (Krassay *et al.* 2004). A thin Lower Pliocene shallow-water marine transgressive sand overlies the Gambier Limestone in places. The southern coast of Kangaroo Island has Pleistocene dune rock (eolianite) cliffs, headlands, shore-platforms and reefs.



Lake Alexandrina
Lake Albert
The Coorong
Younghusband Peninsula
Goolwa
Murray Mouth
Victor Harbor
Fleurieu Peninsula
Cape Jervis
The Pages
Backstairs Passage
Gulf St Vincent
Cape Willoughby
Investigator Strait
Kingscote
Kangaroo Island
Cape Gantheaume
Young Rocks
LACEPEDE
SHELF
Shelf edge
Continental slope
Gantheaume Canyon
Seal Canyon
Sprigg Canyon
PC 2607
20 km
36°
37°
137°
138°
139°

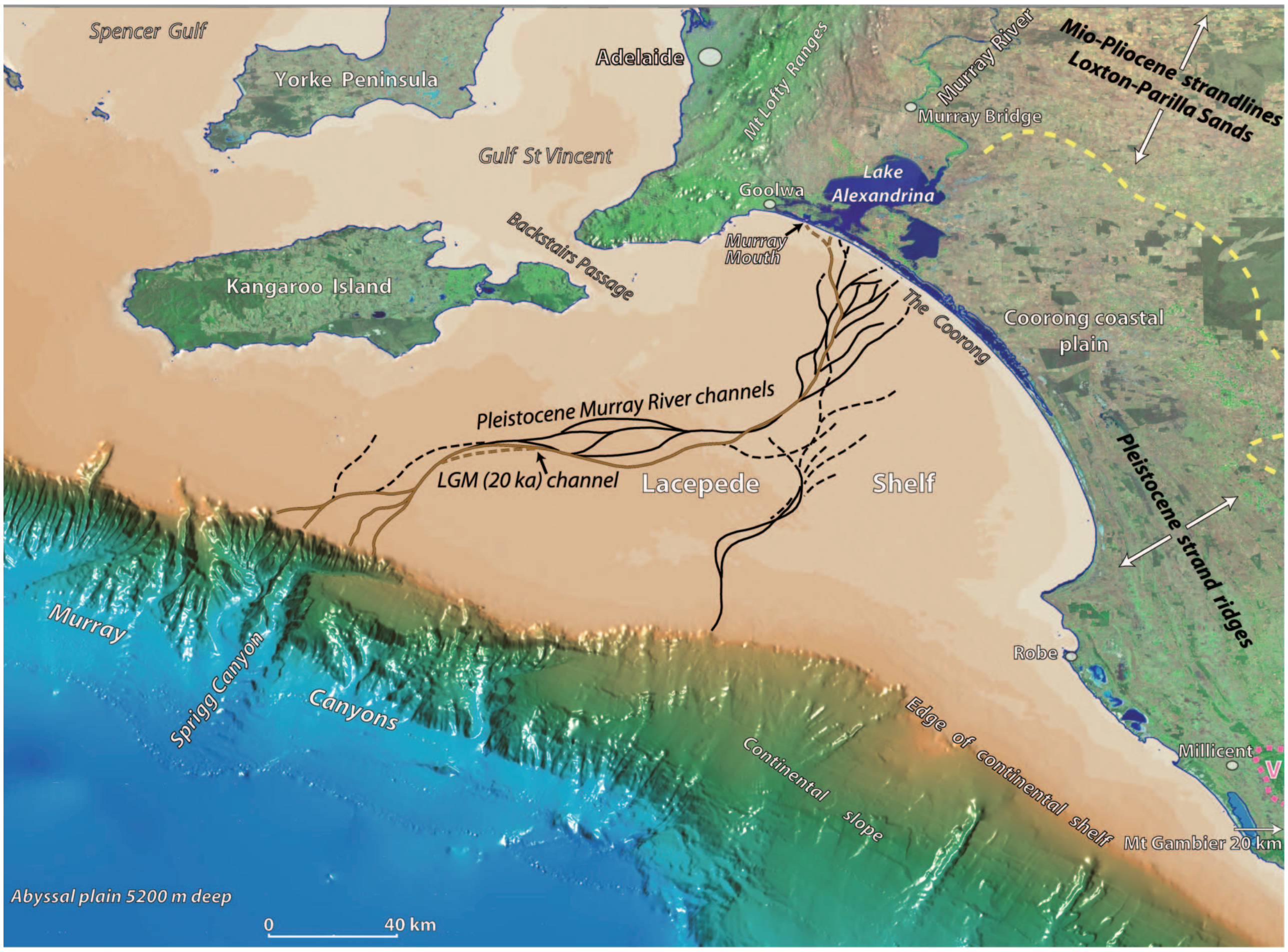


Figure 3 3-D oblique view, looking north, over the Lacepede Shelf region and mapped Murray River paleochannels (Last Glacial Maximum channel in brown). Onshore topography is draped by Landsat 7 imagery. The area marked by a V (in the southeast corner) contains outcrops of Newer Volcanics that were active around Mt Gambier during the Quaternary, and possibly were responsible for the semi-regional uplift that led to the preservation of the Pleistocene strandlines on the Coorong–Mt Gambier coastal plain to the north-northwest. The dashed yellow line separates the Mio-Pliocene and Pleistocene strandlines and marks the northwest extension of the Kanawinka escarpment. The wide continental shelf (light brown/fawn area) dips very gently seaward to a depth of about 200 m at the shelf edge, beyond which the continental slope, deeply incised by canyons, descends steeply to a flat abyssal plain at 5200 m. During major glaciations in the Pleistocene, the Lacepede Shelf was an expansive coastal plain across which the Murray River flowed southward from the present Lakes Alexandrina and Albert, then roughly west-southwest and into the head of Sprigg Canyon. The river flowed almost directly south at times during early lowstands.

CRETACEOUS–EARLY PLEISTOCENE TECTONICS AND GEOLOGICAL EVOLUTION

The gross Late Phanerozoic geological and geomorphic architecture of this part of the Australian margin was established when Australia split from Antarctica in the Late Cretaceous (Norvick & Smith 2001), following protracted rifting that began in the mid-Jurassic. Remnants of the Mesozoic rift basins are preserved in the margin as the Bight Basin to the west and the Otway Basin to the southeast. Oceanic basalts, formed by seafloor spreading that began locally in the Campanian, underlie the abyssal plain south of the Lacepede Shelf. The northern rift shoulder, which includes the

Figure 2 Paleodrainage and detailed bathymetry of the Lacepede Shelf and adjacent continental slope, based on track-line and swath data, including new multibeam data collected during the 2006 *Southern Surveyor* SS02/06 expedition and earlier multibeam surveys (Hill *et al.* 2001; Hill & De Deckker 2004). Isobaths down to the 120 m isobath (in red) are at 10 m intervals, while deeper isobaths are at 200 m intervals. The 120 m isobath approximates the shoreline at the Last Glacial Maximum (LGM). The survey lines are those of SS02/06 (magenta) and SST02/07 (orange), along which multibeam sonar and sub-bottom profiler data were collected. The blue-grey dots are SS02/06 gravity core stations and the yellow triangles are SS02/06 dredge sites; the red dots are SST02/07 vibrocore stations. The grey-shaded area has >6 m of Quaternary sediment cover. The thick black and brown (LGM) lines denote Pleistocene channels of the paleo Murray River. Locations of sub-bottom profiles 1–7 (Figures 6–8) are represented by the numbered thick yellow lines.

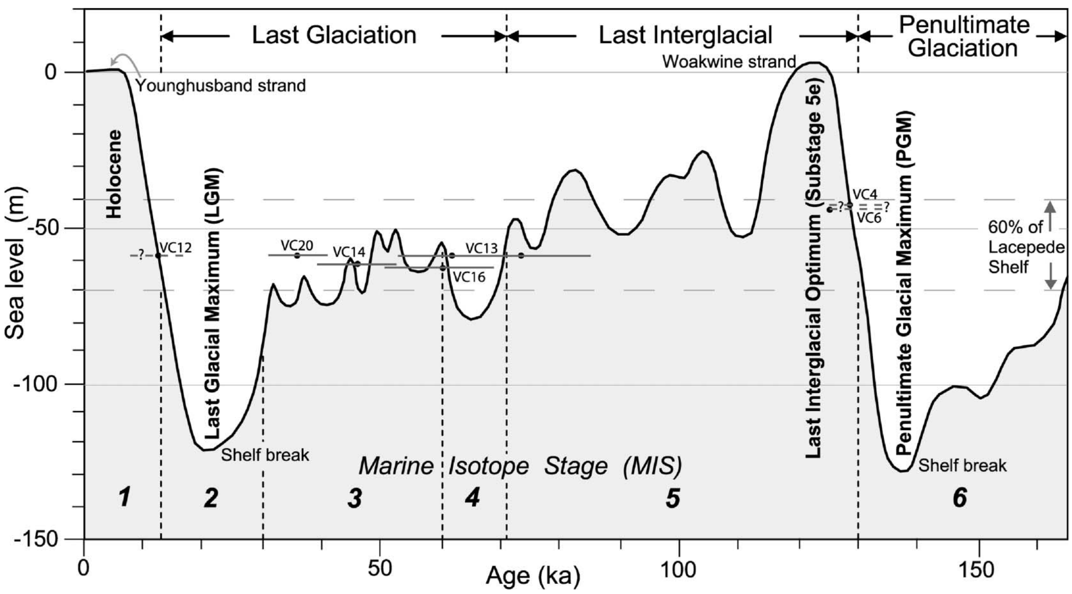


Figure 4 Global relative sea-level curve for the past 165 000 years (later Quaternary), showing relationship to glacial events and Marine Isotope Stages. The curve was compiled from various sources, including Lambeck & Chappell (2001) and plots presented in Siddall *et al.* (2006). The Younghusband and Woakwine strands (Belperio *et al.* 1995) are expressions of the Holocene (MIS 1) and MIS 5e highstands, respectively. The shoreline at the glacial maxima was located at the present shelf break (120–130 m bsl). Mean sea-level during the Late Quaternary (and probably during most of the Quaternary) was about 55 m below present sea-level, and this is reflected in the fact that 60% of the Lacepede Shelf lies within 15 m of this level. Plots of vibrocore sample depth against AAR age (with error bars) (Table 4) mostly show good correlation with the sea-level curve.

Kangaroo Island/Lacepede Shelf area, appears to have remained elevated during the Late Cretaceous following breakup.

In the Paleocene, downwarp in the interior of the continent led to the formation of the Murray Basin, now filled with up to 600 m of Cenozoic fluviolacustrine and marine deposits, while subsidence of the margin, at least along the Otway coast, produced deltas. Marine transgression continued into the mid-Tertiary, peaking in the Middle Miocene as shallow seas in the Murray Basin flooded inland as far as 350–400 km from the present coast (Langford *et al.* 1995). During this time, ice sheets had formed on Antarctica and southern Australia became cooler and drier, reducing siliciclastic sediment supply and resulting in progressive dominance of temperate biogenic carbonate sedimentation on the margin (McGowran *et al.* 1997), the shelfal Gambier Limestone being an example.

Onset of intraplate compressional stress in the mid-Miocene (Hill *et al.* 1995; Perincek & Cockshell 1995) led to folding and uplift which, accentuated by glacioeustatic drop in sea-level, resulted in a depositional hiatus during most of the Late Miocene, particularly 10–6 Ma (Dickinson *et al.* 2002). The Gambier Limestone shelf was bevelled, with up to several hundred metres of section eroded, and its surface sculptured by karst formation.

Renewed marine transgression in the latest Miocene–Early Pliocene deposited a thin sheet of sand, leaving an extensive system of arcuate strandlines, the Loxton–Parilla Sands (Figure 3), in the central and southern Murray Basin 60–250 km from the present coastline (Ludbrook 1961) as the region was gently uplifted. At the same time, neotectonic activity initiated faulting and uplift of the Mt Lofty Ranges (Twidale *et al.* 1978; Sandiford 2003). At about 3.2 Ma (An-Zhisheng *et al.* 1986) the Murray River was tectonically dammed near Swan Reach (~60 km upstream of present Lake Alexandrina) resulting in the formation of Lake Bungunnia (Stephenson 1986; Bowler *et al.* 2006), a huge freshwater lake covering 40 000 km^2 of the Murray Basin. Towards the end of the Early Pleistocene, *ca* 1.0–0.7 Ma, the lake had completely drained due to erosional downcutting of the Murray River Gorge (Twidale *et al.* 1978), and the sea had re-entered the area from the south, eroding the fault-controlled Kanawinka escarpment (Figure 3) on the inner Coorong coastal plain.

QUATERNARY SEDIMENTATION, TECTONICS AND SEA-LEVEL CYCLES

Throughout the Quaternary, the dominant influence on sedimentation patterns on and adjacent to the Lacepede Shelf was relative sea-level change (Figure 4), brought about by a combination of glacioeustatic cycles and vertical movements associated with neotectonism (Belperio 1995; Sandiford 2007). Compelling evidence of this is the remarkable system of Pleistocene raised calcarenite strandlines on the coastal plain southeast of the Coorong (Sprigg 1952, 1979; Brown & Stephenson 1991; Murray-Wallace *et al.* 1998). These marooned strandlines, which extend 100 km inland (Figure 3), represent interglacial highstands and *de facto* Milankovitch cycles, as the area was uplifted at a steady 7 cm/ka for the past 800 ka (Huntley *et al.* 1993; Harvey *et al.* 2001). This uplift also constricted the Murray River to the west, against the Mt Lofty Ranges. Whether the uplift is related to regional intraplate compression and warping or doming by basaltic volcanism (Newer Volcanics: Sheard 1978) active in the Mt Gambier area (Figure 3) through the Quaternary is not clear. Murray-Wallace *et al.* (1998) and Murray-Wallace (2002) suggested the latter, while Wallace *et al.* (2005) proposed that the local uplift is along a west-southwest-trending axis (Gambier Axis) that is the western part of a more extensive Western Highlands Uplift Axis in western Victoria. More recently, Sandiford (2007) discussed the uplift of this part of the Australian continent since mid-Tertiary times.

The oxygen isotope record from the deep ocean is a high-resolution proxy for global ice volume in glaciers and ice sheets, and hence climate change and relative sea-level going back at least as far as the beginning of the Cenozoic (Zachos *et al.* 2001). Over the past one million years, the isotopic record shows strong oscillations with a period of about 100 ka suggesting that orbitally driven insolation changes have been eccentricity dominated. This cyclicity is evident in the Pleistocene strandlines of the Coorong coastal plain (Figure 3), each of which represents an interglacial highstand. The sequence of strandlines indicates that the past 11 interglacial highstands did not deviate by more than +6 m from present sea-level (Murray-Wallace 2002). During the Last Interglacial Optimum *ca* 123 ka [Marine Isotope Stage (MIS) 5e: Figure 4], sea-level was ~2–4 m above present sea-level (APSL) (Murray-Wallace & Belperio 1991; Belperio *et al.* 1995; Lambeck & Chappell 2001). During the current interglacial (MIS 1), sea-level rose rapidly at first and then plateaued about 7000 years ago at its present level, leading to the formation of the Holocene Younghusband Peninsula beach-dune barrier. The Last Glacial Maximum lowstand (*ca* 20 ka) was about 120 m (possibly as much as 125 m: Yokoyama *et al.* 2000, 2001) below present sea-level, while the Penultimate Glacial Maximum (*ca* 138 ka in MIS 6) was probably several metres lower than this (Figure 4) (Chappell *et al.* 1996; Lambeck & Chappell 2001).

The period 123–30 ka, covering MIS 3–4 and most of MIS 5, saw sea-level gradually fall from about +3 to –70 m, but fluctuating about 20–30 m peak-to-peak as it did so. Between 30 ka and the Last Glacial Maximum, sea-level dropped rapidly from –70 m to about –120 m. Mean sea-level during the Last Interglacial/Glacial cycle (*ca* 130–13 ka) was about –55 m (Figure 4), as it probably was over most of the mid–Late Quaternary since about 800 ka (Siddall *et al.* 2006).

On Kangaroo Island, major transgressive dune complexes associated with the Last Interglacial highstand are developed along the south and west coasts. The large-scale cross-bedded, weakly cemented calcarenites cannot be easily distinguished from earlier multiple episodes of Pleistocene and later Holocene dune transgression, and dune and beach calcarenite facies merge imperceptibly (Murray-Wallace & Belperio 1991). During times of lowered sea-level in the Pleistocene, when climatic conditions would have been more arid (Bowler 1976), wind-blown sand (commonly carbonate) may have accumulated locally in drifts and dunes on the Lacepede plain forming eolianites that became indurated on subsequent subaerial weathering.

Spatial variations in elevation of the Last Interglacial shoreline (Murray-Wallace & Belperio 1991; Bourman *et al.* 2000) illustrate differential, ongoing mild neotectonism of the region. Since the Last Interglacial Optimum (*ca* 123 ka) the Mt Lofty Ranges/Fleurieu Peninsula have been uplifted about 8 m, while to the south-southeast upwarp has elevated the Mt Gambier area about 16 m. The Murray mouth area has remained at about the same elevation or undergone slight subsidence, facilitating the formation of Lakes Alexandrina and Albert.

SEA BED SEDIMENTS AND MODERN PROCESSES ON THE SHELF

The Lacepede Shelf is part of a temperate cool-water carbonate depositional province and 'carbonate factory' on the Australian southern margin 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 by storms 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 offshelf transport as the major physical process.

The sedimentary facies on the Lacepede Shelf are a product of its high-energy setting, carbonate production (particularly bryozoan 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 Murray mouth and beneath the central part of the shelf, the sea bed 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 (Gingele *et al.* 2004; Gingele & De Deckker 2004). At the top of several cores and in dredges taken on the continental slope, iron-stained quartz grains were found, and these would characteristically have had an eolian origin.

RESEARCH VOYAGES SS02/06 AND SST02/07

The 2006 *Southern Surveyor* SS02/06 investigation of the Lacepede Shelf acquired 2000 km of sub-bottom seismic profiles and multibeam sonar sea bed data along a network of lines extending from near the Murray Mouth to the shelf edge (Figure 2). Sediment samples were recovered at eight stations by gravity corer (Figure 2; Table 1), but penetration was mostly very limited due to the sandy nature of the surface sediments and only one reasonably long core (GC5: 210 cm) was recovered. A number of dredge hauls using a chain-bag rock

Table 1 Gravity cores taken on and adjacent to the Lacepede Shelf, Voyage SS02/06.

Gravity core	Lat/long (°)	Water depth (m)	Core length (cm)	Sample description
GC4	−37.1602 136.9373	5040	69	Fine, well-sorted carbonate sand
GC5/ GC6	−35.7629 139.0767	42	210/26	Red fine sand over estuarine mud
GC7	−36.2352 138.8024	55	3	Medium sand
GC8	−36.2955 138.4481	62	Core-catcher only	Yellow/brown fine-medium sand with shell fragments
GC9	−36.4808 −137.5313	79	Core-catcher only	Calcareous sand with shell fragments
GC10a	−36.2349 138.6737	57	Core-catcher only	Brown calcareous medium sand
GC10b	−36.2970 138.3705	54	Core-catcher only	Brown calcareous medium sand

dredge, with small pipe dredges attached, were also made on the outer margin of the shelf. Very little rock was recovered (mainly because sites with rugged outcrop were avoided to minimise potential dredge loss), though various amounts of mollusc/gastropod shells, sand, mud and modern benthic biological material were collected. Useful sea bed geological samples were recovered at 10 dredge sites (Figure 2; Table 2).

The Kongsberg TOPAS PS18 parametric sub-bottom profiler provided high-quality data on the shelf, to sub-bottom depths of about 40 m. The 32 kW system, with narrow $\sim 3.5^\circ$ beamwidth, was operated in Ricker transmit mode within a frequency range of 1–6 kHz. The 30 kHz multibeam echo sounder, a 135 beam Kongsberg-Simrad EM300, has its transducers mounted on a gondola beneath the hull and provided high-resolution images of the seafloor. Swath width is about five times water depth in relatively shallow areas (<1 km deep) such as on and adjacent to the Lacepede Shelf.

The Lacepede Shelf was revisited in 2007 by *Southern Surveyor* Voyage SST02/07, this time equipped with a 6 m barrel hydraulic vibrocorer to try to get a series of long sediment cores from the Lacepede Basin. The vibrocorer was more successful than the gravity corer used previously, and sediment samples were recovered at 22 sites (Figure 2; Table 3). The longest core was 392 cm (VC9) and nine cores were 200 cm or more. Despite various trials, including driving the vibrocorer hard at maximum power for extended periods, penetration approaching the potential 6 m could not be achieved. Because recovered cores commonly contained mollusc shells, some several centimetres across, it is thought that large individual shells or shell beds have obstructed the corer and reduced penetration. During this voyage, an additional 700 km of sub-bottom profile and multibeam data were acquired (Figure 2).

SURVEY RESULTS

Sea bed morphology and surficial sediment distribution

Bathymetric contours of the Lacepede Shelf and adjacent continental slope (Figure 2) show that the seafloor of the shelf is mostly relatively flat. Where blanketed by a layer of young sediment, the sea bed is generally smooth and of flat to gently undulating relief. In areas of bedrock or basement outcrop, the bottom can be rough and jagged and of significant relief, commonly as much as 5–10 m. A surprising finding of the survey is how little surficial sediment there is on the shelf. About half of the shelf surface has less than 0.5 m of Quaternary unconsolidated/weakly cemented sediment cover (Figure 5). Almost the entire outer shelf, across a width of 30–50 km, is a marine hardground with scattered thin patches of carbonate sand and gravel, on a rough limestone surface that is host to epifaunal communities such as sponges and bryozoans.

Sediment on the bedrock platform is thickest in the middle of the shelf, in a depocentre aligned roughly west–east, and along a north-northeast-trending depocentre that links the Lakes Alexandrina and Albert area with the eastern end of the central depocentre. The combined depocentre, which we have named the Lacepede Basin (Figure 5), is mainly 6–10 m thick, but locally attains a thickness of up to about 25 m where channels and river valleys of the paleo Murray River have been cut into the bedrock platform.

Structure and channels in the Lacepede Basin

Sedimentary facies in the Lacepede Basin include flat-lying lacustrine/lagoonal beds, infilled channels and point-bar deposits (Figures 6–10). Channelling occurs at

Table 2 Dredge stations on and adjacent to the Lacepede Shelf, Voyage SS02/06.

Dredge	Lat/long (°)	Water depth (m)	Sample description
DR3	−36.8530 136.9979	3268	Sediment with pteropod shells
DR4	−36.7328 136.8838	2480	Sediment (both soft and consolidated samples) with pteropod shells
DR6	−37.0403 137.9314	133	Bryozoal sand
DR7	−36.2937 138.4571	63	Yellow/brown fine-medium sand; molluscs, beach rock
DR8	−36.6387 137.5132	84	Fine-coarse sandy material
DR9	−36.7848 137.3983	115	Bryozoal sand
DR10	−36.7970 137.4023	124	Bryozoal sand
DR11	−36.8378 137.4248	360	Mud with shells/shell fragments
DR12	−36.8802 137.4444	720	Mud with shell fragments
DR13	−36.8915 137.4498	762	Mud with shell fragments (including small gastropods)

Table 3 Vibrocores taken on the Lacepede Shelf, Voyage SST02/07.

Vibrocore	Lat/long (°)	Water depth (m)	Core length (cm)	Sample description
VC1	−35.6978 138.9678	39.5	183	Top: grey clay & fine sand; clean quartz & shell debris. Bottom: dark grey sand.
VC2	−35.7063 138.9820	39.3	88	Top: clean subangular quartz sand, *Elphidium* spp., shell debris & iron-stained quartz grains.
VC3	−35.7407 139.0390	40.0	65	Top: clean subangular quartz sand, foraminifera, shell debris & iron-stained quartz grains. Bottom: grey sand/clay.
VC4	−35.7645 139.0787	39.7	200	Top: clean subrounded quartz sand + some clay, foraminifera, shell debris, bivalve mollusc & bryozoan fragments & iron-stained quartz grains. Bottom: clay with shell grit.
VC5	−35.8060 139.1483	39.8	110	Top: subangular quartz sand; ostracods, foraminifera & iron-stained quartz grains. Bottom: grey-brown clay and medium sand.
VC6	−35.8131 139.0363	41.3	202	Brown sand with shell hash (mainly bivalves) at base.
VC7	−35.8408 138.9986	42.0	77	Top: subangular quartz sand, foraminifera, shell debris & iron-stained quartz grains. Bottom: very fine grey sand.
VC8	−35.9830 138.9806	46.2	360	Top: clean subangular-subrounded quartz sand, foraminifera & shell fragments. Bottom: dark grey silt.
VC9	−36.2412 138.8068	51.7	392	Top: clean subrounded quartz sand, orange-stained shell fragments. Bottom: dark grey silty clay.
VC10	−36.3013 138.7472	52.3	110	Top: subrounded quartz sand, numerous orange-stained shell fragments & foraminifera. Bottom: mottled sand.
VC11	−36.4291 138.6067	55.3	131	Top: clean subangular-subrounded quartz sand, foraminifera & orange-stained shell fragments.
VC12	−36.3771 138.5383	56.8	252	Top: clear angular quartz & rounded iron-stained quartz grains + brown stained, rounded carbonate fragments. 1 m: grey sand/clay. 2 m: shell hash and grey clay. Bottom: grey clay.
VC13	−36.3667 138.5254	57.5	88	Top: angular-subangular quartz sand, numerous orange-stained shell fragments & foraminifera. Bottom: shell hash including gastropods.
VC14	−36.3255 138.4715	58.5	233	Top: subangular quartz sand, many white & orange-stained shell fragments including foraminifera, ostracods, bivalve molluscs & bryozoans. 1 m: red clay. Bottom: shell hash.
VC15	−36.3057 138.4461	58.0	217	Top: subangular quartz sand, many white & orange-stained shell fragments including foraminifera, ostracods and bryozoan fragments. 1m: dark grey clay. Bottom: grey clay with shells.
VC16	−36.3309 138.1772	60.7	213	Top: subangular quartz sand, shell fragments including foraminifera & bryozoans, mostly stained. 1 m: grey sand. Bottom: very coarse grey sand with few shells.
VC17	−36.4116 138.0376	67.5	342	Top: subangular quartz sand, fragments of bivalve molluscs & bryozoans, and foraminifera, all mostly stained. 1 m: grey/green silt. 2 m: grey silt. 3 m: grey silt. Bottom: grey sand with small shell fragments.
VC18	−36.3963 138.4059	57.9	183	Top: subangular-subrounded quartz sand, foraminifera & stained carbonate fragments. 1 m: grey/green clay. Bottom: shell grit.
VC19	−36.3772 138.7528	53.5	159	Top: subangular-subrounded quartz sand, foraminifera & stained carbonate fragments.
VC20	−36.6381 138.7837	57.8	130	Top: subrounded-angular clear quartz grains & some rounded iron-stained quartz grains, stained carbonate fragments. Bottom: sand & shell grit + oyster shell.
VC22	−37.0401 138.5719	110.6	Core-catcher only	Small amount of grey sand.
VC23	−37.0276 138.5838	101.7	134	Top: beige carbonate sand, little quartz plus foraminifera. 1 m: fine grey sand. Bottom: fine grey sand.

a number of different levels in the basin sequence, reflecting at least six downcutting episodes probably related to major regressions, including that leading to the Last Glacial Maximum lowstand. The fill of the main Pleistocene channel or valley contains a stacked series of channels, indicating that channel re-incision commonly occurred at roughly the same place during multiple sea-level cycles. Paleochannels or paleovalleys of the Murray River are typically 450–1000 m wide and incised into the Miocene carbonate platform to depths of 10–20 m.

On the shelf, the channels (Figures 2, 3, 5) begin off Lakes Alexandrina and Albert, roughly follow the depocentre south-southwest, then veer west-southwest in the middle of the shelf and finally bend southwest across the outer shelf directly south of Kangaroo Island.

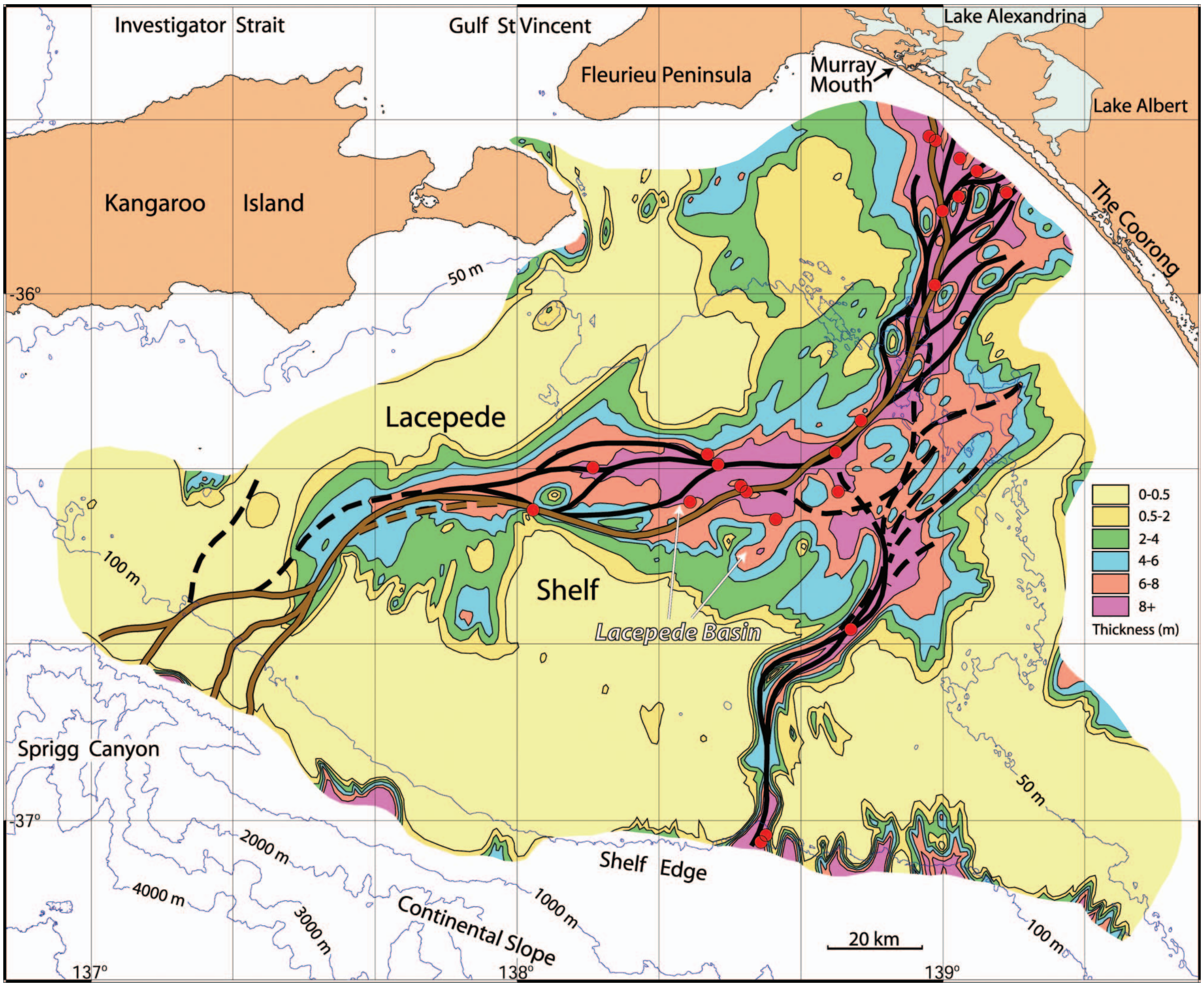


Figure 5 Isopach map of Quaternary sediment (plus possible Plio-Pleistocene basal sand) on the Lacepede Shelf with locations of Murray River paleochannels (Last Glacial Maximum channel in brown). The depocentre in the central and northwest Lacepede Shelf, here named the Lacepede Basin, unconformably overlies Miocene Gambier Limestone and is commonly >6 m thick, and up to about 25 m thick in the deeper paleochannels. The red dots indicate the vibrocore station locations.

The channels splay into the broad head of Sprigg Canyon on the continental slope. An older set of channels cuts across the outer shelf in a south-southwest direction from the centre of the basin, suggesting that an early course of the Murray River ran an almost direct route south-southwest from Lakes Alexandrina and Albert to the edge of the shelf. Downslope gullies and slope valleys 50–100 m deep are present on the upper continental slope downslope of this paleoriver outlet, but no major modern canyons are evident in the bathymetry (Figures 2, 3). The slope here is sediment-draped, with slump structures common (von der Borch & Hughes Clarke 1993).

Bedrock platform

Bedrock beneath the Lacepede Shelf, as observed in the sub-bottom profiles, mainly consists of a well-stratified, gently folded sequence, truncated at its top by a near-horizontal erosional unconformity. Several Otway Basin exploration wells, including Trumpet 1 and Troas 1 (Krassay *et al.* 2004) drilled on the far southeast of the shelf, off Robe, intersected this sequence. Logged as the Upper Oligocene–Miocene Gambier Limestone, it extends from the sea bed to a depth of about 300 m in this area. Consistency of seismic character suggests that Gambier Limestone forms the bedrock platform under most of the Lacepede Shelf. Basement rocks, probably Delamerian granites or possibly Early Paleozoic metasediments, outcrop or subcrop in several areas of the western Lacepede Shelf south of Kangaroo Island, including a 10 km-wide area around Young Rocks.

Folding in the Gambier Limestone is mostly gentle, with dips $<1^{\circ}$. However, in some places the beds are more tightly folded, and include structures such as open synforms with dips on the limbs up to 4° or possibly more. Deformation of the beds is usually more intense adjacent to basement subcrop. Individual fold structures (synclines/anticlines) beneath the Lacepede Shelf appear to be of relatively short extent since they can rarely be correlated from one profile to the next, though the relatively wide line spacing of the survey lines does not allow detailed mapping of the structures in most cases. Perhaps the pattern of folding was complicated by multiple phases of deformation acting in different directions. Though there appears to be no shelf-wide pattern in fold axis orientation, a roughly north–south trend appears to be present beneath the central south-west of the shelf, perhaps due to local east–west compression in the Late Miocene.

Results of coring and dredging programs

Our sampling provides information on the sediments of the Lacepede Shelf and adjacent continental slope from the sea bed to a sub-bottom depth of almost 4 m (Tables 1–3). The northern and central parts of the Lacepede Shelf are mostly floored by a fine–medium quartz-rich sand, usually red but in places of brown or yellow tones. The sand is up to about 0.5 m thick, and is generally underlain by a grey clay or silt commonly bearing shells or shell fragments—shell grit, hash or whole shells, including molluscs such as oysters and gastropods. Examination of the vibrocores reveals no evidence of freshwater fauna in any of them. The presence of benthic foraminifera such as *Ammonia beccarii, Triloculina* spp. and *Elphidium*, ostracods (e.g. *Cytherella*), reworked echinoid spines and mollusc shells indicates an estuarine or shallow-marine environment. Restricted environments, perhaps akin to the lagoons of the Coorong or Lakes Alexandrina and Albert before the barrages were built, are indicated at VC4, VC6 and VC14 due to prevalence of *Ammonia beccarii* and evidence of anoxic staining/coatings on grains and microfauna. A detailed analysis of GC5 near the Murray mouth (Figures 2, 9) suggests periods of subaerial exposure following sedimentation in a restricted environment (G. Nash pers. comm. 2007). Mottling seen as orange stains in this core is evidence of periods of pedogenesis.

Samples recovered on the outer shelf, near the shelf edge and on the continental slope are all dominantly carbonates. On the outer shelf and near the shelf break the sediments are relatively coarse and winnowed, reflecting the high-energy supra-storm/wave-base environment, and comprise bryozoan sand, shells and shell fragments. Downslope the sediments become muddy but contain occasional shell fragments. Pteropod shells in sediment dredged from channels in the upper–middle Sprigg Canyon suggest active transport from the shelf edge. The well-sorted nature of the fine carbonate sand cored in the lower Sprigg Canyon at a depth of 5040 m (GC4) is further evidence of active sediment flow down the thalweg of the canyon.

Amino acid racemisation (AAR)

The extent of racemisation of amino acids, a measure of fossil age based on the increasing ratio of D to L-amino acids, was determined by one of us (CVM-W) in fossil molluscs from the Lacepede Shelf by reverse-phase, high-performance liquid chromatography following the methods of Kaufman & Manley (1998). Analyses were undertaken on the total hydrolysable amino acids after hydrolysis for 22 h at 110°C in 8 mol HCl. The analytical procedure involved the pre-column derivatisation of DL-amino acids with *o*-phthaldialdehyde (OPA) together with the chiral thiol, *N*-isobutyryl-L-cysteine (IBLC) to yield fluorescent diastereomeric derivatives of the chiral primary amino acids. Amino acid D/L ratio determinations were undertaken using an Agilent 1100 HPLC with a C-18 column and auto-injector. Results are reported for the amino acids glutamic acid and valine based on peak area calculations.

AAR RESULTS

The extent of racemisation of glutamic acid and valine determined in fossil molluscs from a number of our vibrocores taken on the Lacepede shelf is presented in Table 4. The data are also compared with the extent of racemisation previously determined in shells of mid-Holocene age (Cann *et al.* 2006) and for a specimen of *Katelysia rhytiphora* from an exposure of the Last Interglacial Glanville Formation from western Hindmarsh Island near the Murray mouth.

The results reveal that the fossil molluscs plot into three distinct age groups. Three specimens of *Nuculana (Scaeoleda) crassa illepida* from core VC12 are of Holocene age, based on the comparison of the extent of racemisation in a radiocarbon dated specimen of *Bassina* sp. from core SV23 from Gulf St Vincent (Cann *et al.* 2006). In contrast, the specimens from cores VC4 and VC6 all show a high extent of racemisation, consistent with shells of at least Last Interglacial age (*ca* 125 ka, MIS 5e: Murray-Wallace 2000) and in two cases possibly older (Table 4). The remaining fossils from cores VC13, VC14, VC16 and VC20 all show an extent of racemisation indicating that they are older than Holocene but younger than the Last Interglacial Maximum, and accordingly may relate to deposition during an interstadial of the Late Pleistocene.

Numeric ages were determined for the fossil molluscs of inferred interstadial age using a model of apparent parabolic racemisation kinetics (Mitterer & Kriausakul 1989; Clarke & Murray-Wallace 2006). The ages were calibrated based on the extent of racemisation measured in the shells from the Last Interglacial Glanville Formation, as well as the radiocarbon dated Holocene specimen of *Bassina* sp. from Gulf St Vincent (Table 4). In addition, a glutamic acid D/L value of 0.02 characteristic for modern shells was subtracted from the D/L values for the fossil molluscs in order to account for the small amount of racemisation that occurs in the hydrolysis procedure in sample preparation. The uncertainty terms for the numeric ages account for a 1°C uncertainty in the diagenetic temperature. Notwithstanding the large uncertainties, the AAR data indicate that the older fossil molluscs are correlatives of MIS 3 and possibly in the case of the *Placamen* from VC13, the latest stage of MIS 5a.

Table 4 Amino acid racemisation in fossil molluscs and their inferred ages.

Vibrocore	Depth in core (cm)	Laboratory code	Species	Amino acid D/L value GLU	VAL	APK age (ka) GLU
Lacepede Shelf vibrocores (see Figure 2 for location)						
VC4	200	UWGA-6325	*Placamen placida*	0.578 ± 0.025	0.576 ± 0.004	>125
VC6	202	UWGA-6324	*Mactra* sp. (fragment)	0.489 ± 0.018	0.405 ± 0.018	*ca* 125
VC6	202	UWGA-6324	*Mactra* sp. (fragment)	0.436 ± 0.041	0.334 ± 0.025	*ca* 125
VC6	202	UWGA-6326	*Tawera lagopus*	0.586	0.482	>125
VC12	200	UWGA-6328	*Nuculana* (*Scaeoleda*) *crassa illepida*	0.142 ± 0.001	0.099 ± 0.001	Holocene
VC12	252	UWGA-6329	*Nuculana* (*Scaeoleda*) *crassa illepida*	0.160	0.111	Holocene
VC12	252	UWGA-6330	*Nuculana* (*Scaeoleda*) *crassa illepida*	0.163	0.121	Holocene
VC13	88	UWGA-6331	*Placamen placida*	0.305 ± 0.001	0.236 ± 0.006	73.7 ± 11
VC13	88	UWGA-6332	*Irus crenatus*	0.280 ± 0.018	0.223 ± 0.018	62.1 ± 9.3
VC14	233	UWGA-6334	*Placamen placida*	0.197 ± 0.001	0.154	30.7 ± 4.6
VC14	233	UWGA-6335	*Tellina* sp. (fragment)	0.240	0.238	45.6 ± 6.8
VC16	100	UWGA-6336	*Irus crenatus*	0.274 ± 0.013	0.270 ± 0.006	59.5 ± 8.9
VC20	130	UWGA-6337	*Irus crenatus*	0.223 ± 0.002	0.183 ± 0.004	39.4 ± 5.9
VC20	130	UWGA-6338	*Nuculana* (*Scaeoleda*) *crassa illepida*	0.212 ± 0.009	0.182 ± 0.007	35.6 ± 5.3
Holocene: Gulf St Vincent marine core SV23 (6670 ± 240 a cal BP: OZF-049: Cann *et al.* 2006)						
SV23	22–24	UWGA-5197	*Bassina* sp.	0.157 ± 0.017	–	–
Last interglacial (MIS 5e; *ca* 125 ka): Glanville Formation, Hindmarsh Island, South Australia (C. V. Murray-Wallace unpubl. data)						
–	50	UWGA-5567A–C	*Katelysia rhytiphora*	0.431	–	–

GLU, glutamic acid; VAL, valine; APK, apparent parabolic kinetics.

The vibrocore samples selected for AAR analysis were all taken from near the bottom of the cores except VC16, where the sample was from 1.0 m depth. The estimated age data plot close to the sea-level curve of Figure 4, supporting the general validity of the curve and the interpretation that the samples are of shallow-marine origin. Some samples, such as in VC6 and possibly VC13 and VC16, may have been reworked into younger sediment, but it seems that the reworking has been local and that no significant change in water depth occurred. VC20 shows a paleo water depth about 10 m shallower than indicated by the curve, suggesting that water depths towards the end of MIS 3 may have been a little shallower than the curve shows and that a slight upward correction may be required here if supported by additional data. Local neotectonic uplift since 40 ka could also explain some or all of the apparent discrepancy.

Backstairs Passage and possible 'Vincent River' paleochannel

Backstairs Passage is well known for its strong tidal currents and races flowing at speeds of up to 5 knots (2.6 m/s). Sea bed trenches 60–80 m deep off the western tip of Fleurieu Peninsula (Cape Jervis) and the eastern tip of Kangaroo Island (Figure 2) support prolific and highly diverse sessile and mobile marine invertebrate assemblages, including large sponges >1 m high and wide, large erect 'basket' bryozoans covered with epizoic crinoids (feather stars) and ophiuroids (brittle stars), and dense brachiopod colonies in sediment drifts (Shepherd & Sprigg 1976). These trenches are presumably the result of scouring by strong currents, probably mostly by vigorous tidal flows such as those now active, but in the past some of the downcutting may have been fluvial. A SS02/06 sub-bottom profile was run across the southern entrance to Backstairs Passage, just south of Cape Willoughby and The Pages (Figure 2), to investigate whether there was any evidence of an ancient 'Vincent River' channel that may have drained the Gulf St Vincent depression via the Lacepede Shelf during major lowstands (Harvey *et al.* 2001; Gingele *et al.* 2004). This profile was subsequently complemented by a SST02/07 profile through Backstairs Passage across the northern part of the deeper southern trench (Figure 2).

The SS02/06 profile shows a tidal channel floored by a planated bedrock surface and bordered by large sediment drifts up to 8 m thick, but no deep incision into the bedrock surface or other evidence of a major paleo river channel. In contrast, the SST02/07 profile shows a rugged sea bed trough about 5 km wide and mostly 10–15 m deep (below adjacent sea bed). Its floor includes several chasms 200–250 m wide with steep walls 4–10 m high, the deepest being 58 m below sea-level. The trough is devoid of unconsolidated sediment apart from an occasional small drift in topographic lows. Erosionally dissected Pleistocene sediment wedges (?eolianites) up to 5 m thick overlie a relatively flat bedrock substrate on the western flank of the trough. Folded and faulted, well-stratified Miocene carbonate strata outcrop on the sea bed and underlie the eastern part of the trough, while seismic character suggests that Paleozoic rocks underlie the western side. The eastern flank of the trough, largely bare of surficial sediment, also appears to consist mainly of Paleozoic rocks, probably Cambrian metasediments as exposed on The Pages just to the north (Figure 2).

The north-northwest-trending trough beneath Backstairs Passage is structurally controlled, and probably developed through reactivation of existing Paleozoic structures during post mid-Miocene uplift of Fleurieu Peninsula/Kangaroo Island. Erosion by tidal currents appears to have been the main influence in excavating the trough and its two deep trenches in particular, and in keeping them largely free of loose surficial sediment. The Gulf St Vincent basin, fed by rivers such as the Onkaparinga and Torrens, is a dish-shaped depression 41 m deep with sills at about the 30 m level at both its Investigator Strait and Backstairs Passage outlets. Thus, drainage from this basin during lowstands may at times have been via Backstairs Passage. A reason why no evidence for a major incised paleochannel was found at the southern entrance to Backstairs Passage (southeast of Cape Willoughby) may be that flow volumes were comparatively low because of the relatively small catchment and low rainfall of the semiarid climate, especially during the drier glacial periods. This would have resulted in drainage being mostly internal, i.e. into a shallow lake within the central depression with little or no overflow to the ocean, particularly via Backstairs Passage.

Key sub-bottom profiles across the Murray River paleochannel system

The varying character and structure of the Lacepede Shelf sea bed, the Lacepede Basin and contained Murray River paleochannels, and the underlying bedrock platform are portrayed in a series of seven key interpreted profiles (Figures 6–8, detail in Figures 9, 10), starting from the area of the Murray mouth and working south. As an approximation for converting sub-bottom thicknesses from two-way time (TWT) in millisecond (ms) to metres (m), 1 ms=1 m.

PROFILE 1: OFF LAKES ALEXANDRINA/ALBERT

This nearshore profile (Figure 6) shows a relatively thick, 8–10 m, young sedimentary section overlying planated bedrock. The sediments are believed to be mainly Quaternary, but could include a Pliocene basal sand. Bedrock, comprising folded Miocene carbonates of the Gambier Limestone, is incised by Pleistocene channels to a depth of about 7 m. A system of Last Glaciation (including Last Glacial Maximum) channels up to 2 km wide (Figure 9 detail A) cuts through the Lacepede Basin section at the northwest end of the profile off Lake Alexandrina. Smaller Last Glaciation channels are present towards the southeast end of the profile (Figure 9 detail B). Two sets of channels appear to be present, one set emanating from Lake Alexandrina and the other from Lake Albert (Figures 2, 3, 11). Gloster (1996) identified a possible prior channel of the Murray River that lies below the present-day Lake Albert and is at least 7 m deep.

A prominent flat-lying horizon at about 45 m (57 ms TWT) probably represents the Penultimate Glacial Maximum lowstand unconformity. The well-bedded sequences above the unconformity are interpreted to be Last Interglacial deltaic or lagoonal deposits. Small-scale faulting (displacements mostly <0.5 m) in the Quaternary section is evidence of neotectonic activity.

PROFILE 2: NORTHEASTERN LACEPEDE SHELF

The Miocene erosion surface is cut by a number of channels incised to depths of 5–12 m (Figure 6). The main channel (Figure 9 detail C), active during the Last Glacial Maximum, is about 12 m deep and 650 m wide and contains well-bedded dipping channel-fill deposits, estuarine in the upper section and probably fluvial at depth. The Quaternary section adjacent to this channel is relatively thin (0.5–2 m), but thickens substantially to as much as 8 m farther east. The sediment pile is topped by several metres of acoustically transparent sand that may be a Holocene drift deposit, but probably consists of eolian sand blown from the main channel by prevailing westerly winds during the Last Glaciation (Bowler 1976) forming a source-bordering dunefield.

PROFILE 3: CENTRAL-NORTHEASTERN LACEPEDE SHELF

As in Profile 2, this profile (Figure 6) shows a similar pile of young sediment up to 8 m thick to the east of the main channel. This channel (Figure 10 detail D), the only such structure deeply incised into the Miocene platform in this profile, is about 17 m deep and 450 m wide. The Quaternary section (Lacepede Basin) is typically 6–7 m thick and much of it consists of a point-bar facies. The upper section of the main Pleistocene channel comprises 5–6 m of post-Last Glacial Maximum channel fill (Figure 10 detail D).

PROFILE 4: CENTRAL LACEPEDE SHELF

The Quaternary section in Profile 4 (Figure 7) is relatively thick and of uniform thickness, averaging 8 m. As in Profile 3, only one major channel is incised into Gambier Limestone bedrock. The incision is again about 17 m deep, but in this case the channel is about 1000 m wide (Figure 10 detail E). The bedrock valley is overlain by 20 m of Pleistocene channel fill, which is in turn overlain by 2–3 m of horizontally bedded lagoonal or shelfal sediments of the Last Interglacial. Some small channels 3–5 m deep and of Last Glacial age cut into the well-bedded sediments. Stacked channels within the main Pleistocene channel indicate re-incision at roughly the same place during multiple regressive cycles.

The sediment-filled Last Glacial Maximum channel, at least 500 m wide, and associated 6–8 m-thick point-bar deposits lie in the southeastern part of the profile (Figure 10 detail F). The local sea bed high near the southeastern end of the profile may be part of a Last Glaciation dunefield. Small-scale faulting (<0.5 m displacements) in the Lacepede Basin section is evidence of minor neotectonic movements.

PROFILE 5: WESTERN LACEPEDE SHELF

Profile 5 (Figure 7) south of Kangaroo Island shows a Quaternary section that is highly variable both in thickness and stratigraphic character, probably due to the superposition of numerous erosional/depositional cycles and preponderance of eolian facies (particularly

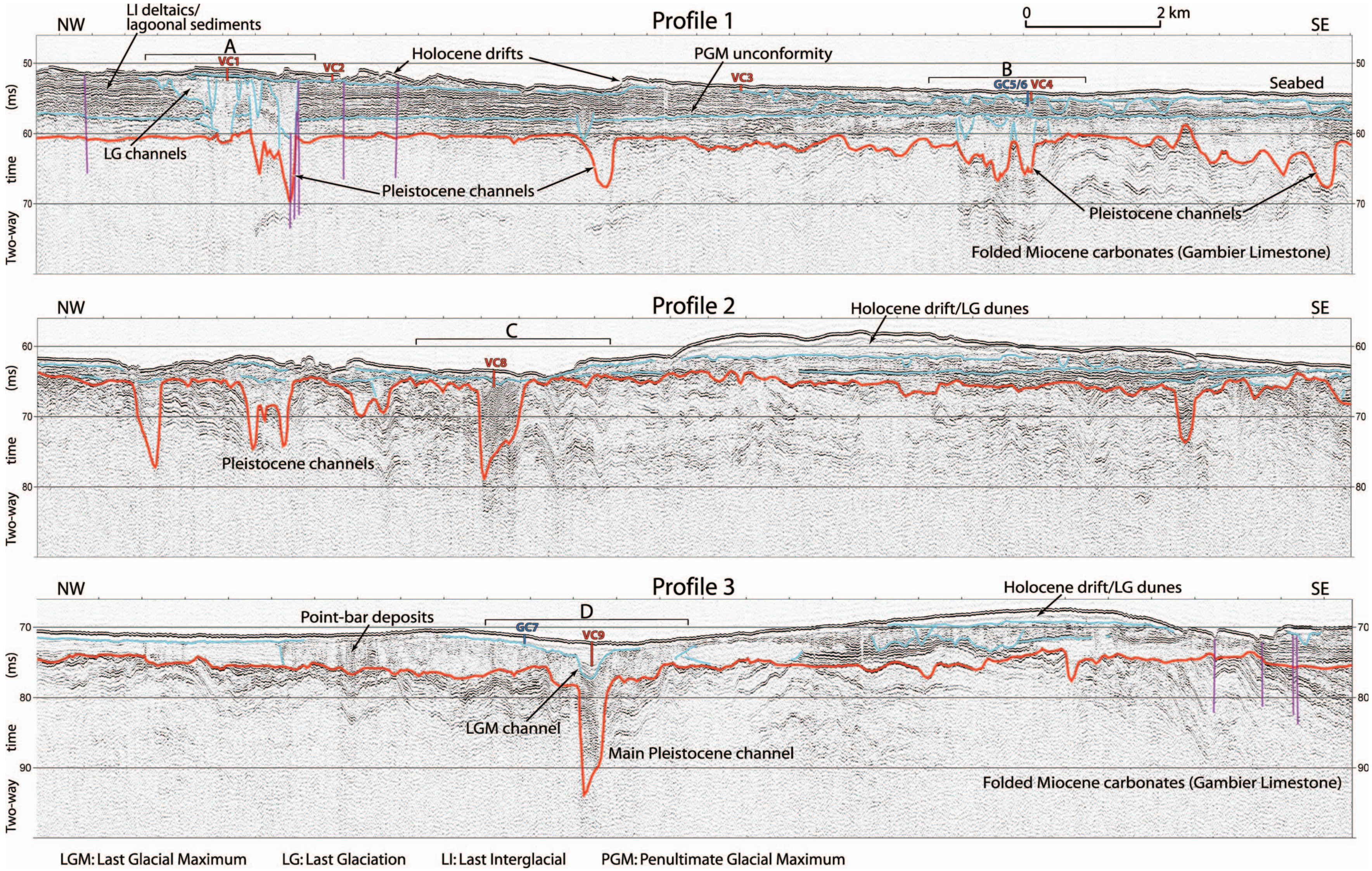


Figure 6 Sub-bottom Profiles 1–3 across the paleo Murray River, northern Lacepede Shelf (locations in Figure 2 and core details in Tables 1, 3). As an approximation for converting sub-bottom thicknesses from two-way time in millisecond (ms) to metres (m), 1 ms=1 m. Expected interval velocities are: water column, 1500 m/s; Quaternary sediment, 1700–2000 m/s; Miocene carbonate 'bedrock,' 2000–2400 m/s. The red horizon is top of bedrock (generally Miocene shelfal carbonates), the blue lines are Plio-Pleistocene horizons and channels, while small-scale faults are shown in purple.

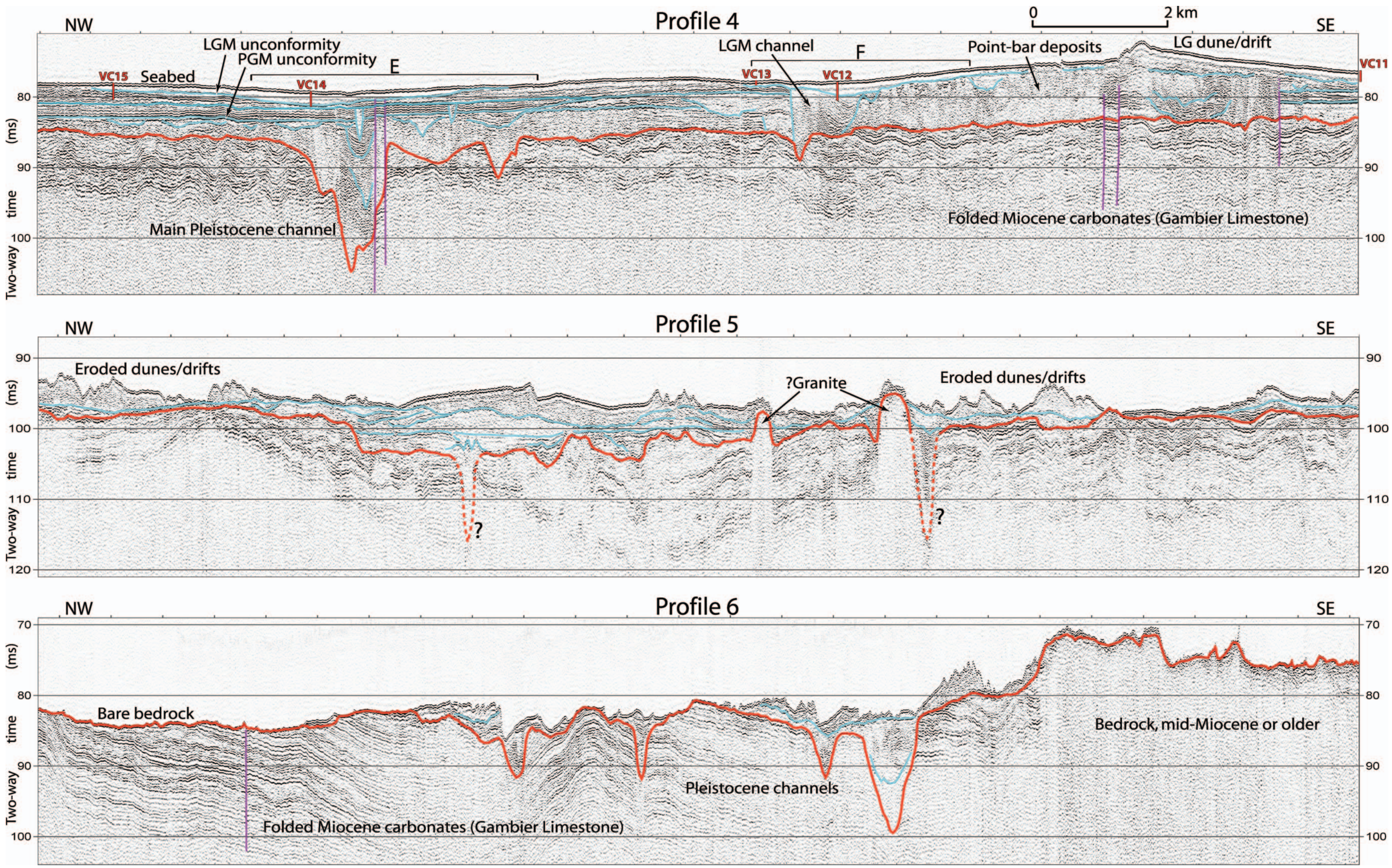


Figure 7 Sub-bottom Profiles 4, 5 across the paleo Murray River, central-western Lacepede Shelf, and Profile 6 across south-flowing paleochannels in the southern Lacepede Shelf (locations in Figure 2 and core details in Table 3). Explanation and colour scheme as for Figure 6.

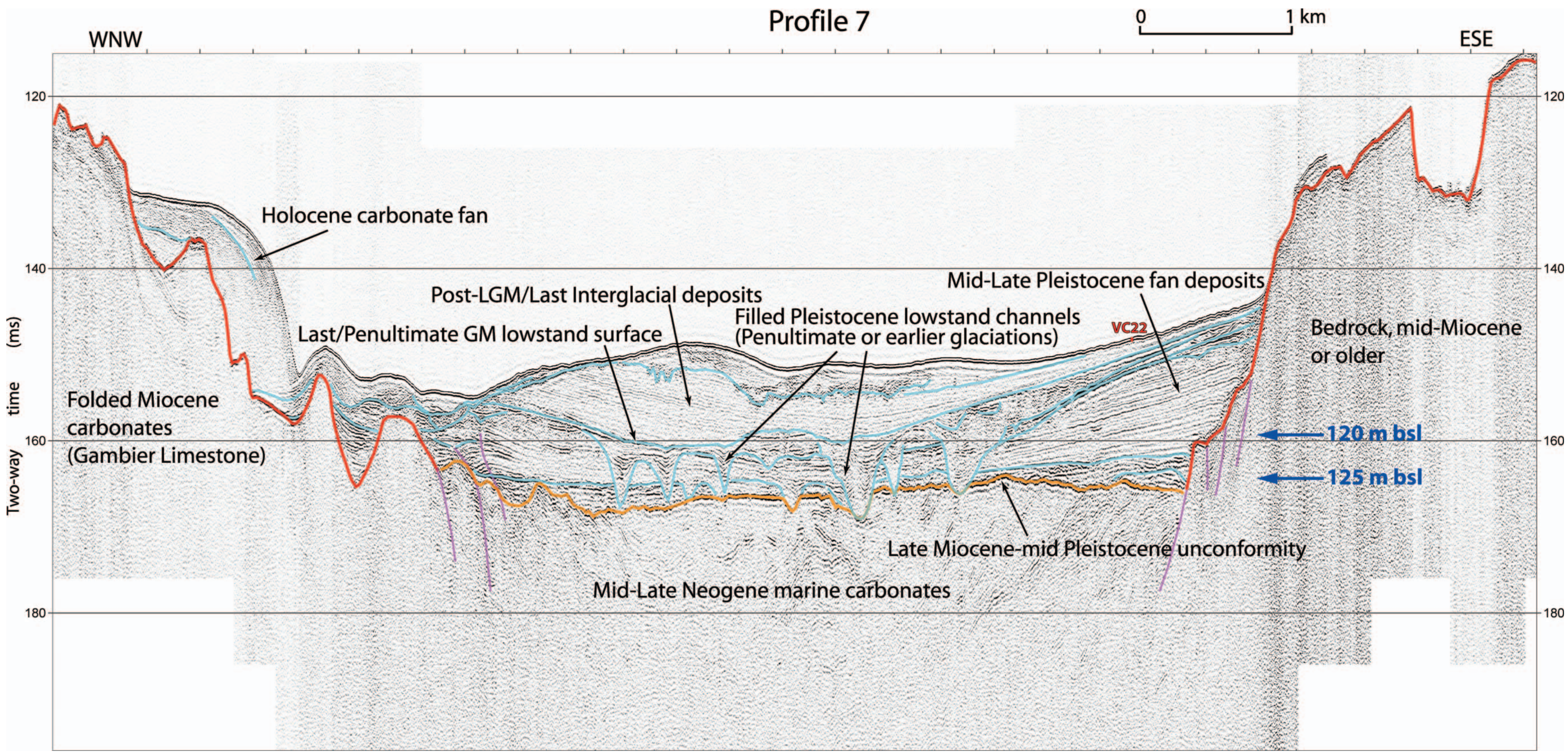


Figure 8 Sub-bottom Profile 7 across the outlet of south-flowing paleochannels, edge of southern Lacepede Shelf (location in Figure 2). Explanation and colour scheme as for Figure 6.

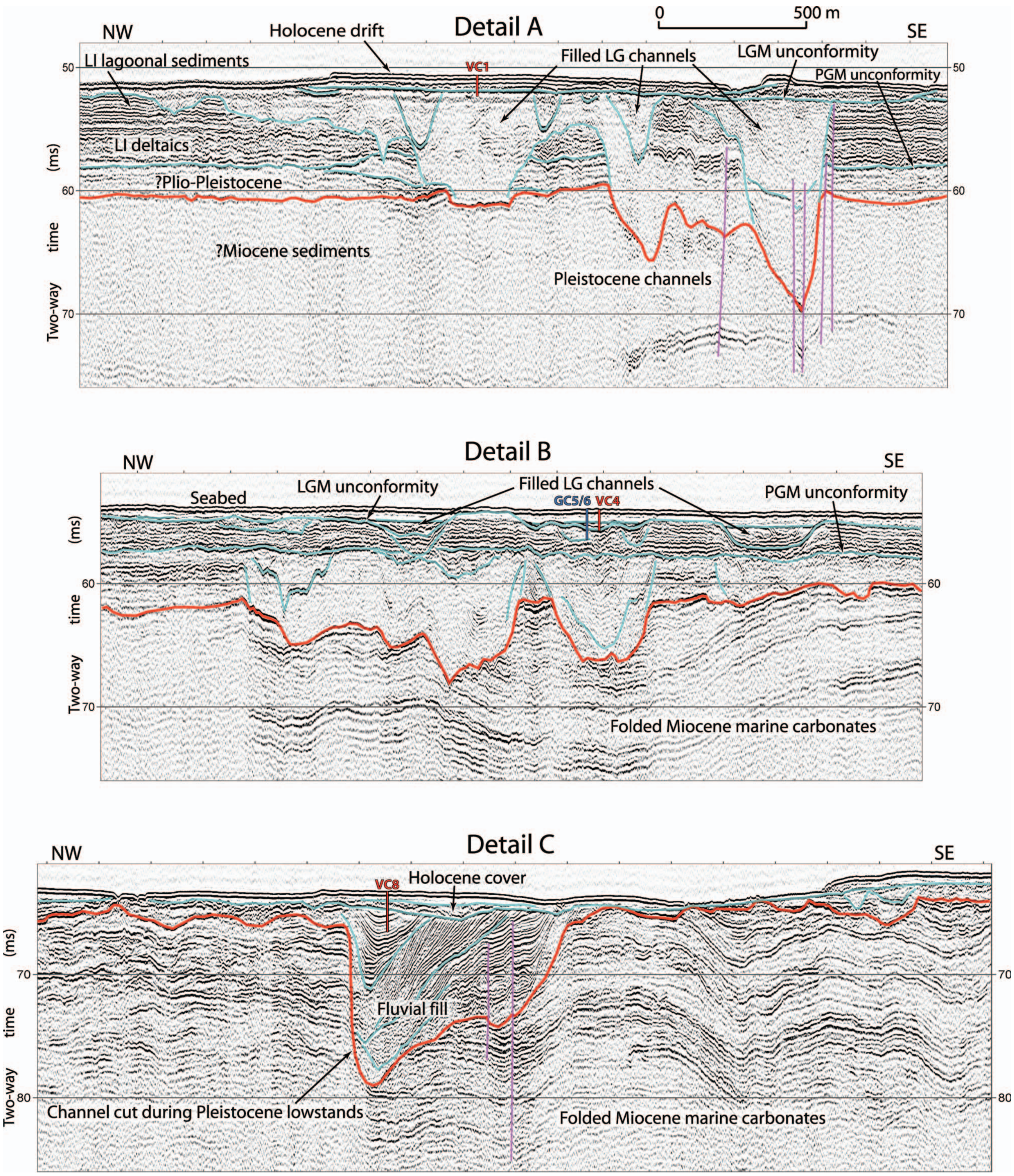


Figure 9 Detail of channels: A & B (Profile 1), C (Profile 2) (see Figure 6 for locations of detailed profiles). Explanation and colour scheme as for Figure 6.

carbonate-rich eolianites because of the mid–outer shelf location). The geological complexity is compounded by basement outcrop and subcrop on the section. Basement outcrop within the folded Miocene carbonates probably comprises Early Paleozoic granites as exposed on Kangaroo Island and nearby Young Rocks. Apart from two possible narrow channels incised 12–15 m into the Miocene carbonates, the lowest part of the bedrock surface is located beneath the mid-northwestern section of Profile 5. Local bedrock relief here is about –5 m and the depression is filled/overlain by 10 m of Quaternary sediments. The course of the paleo Murray River probably lay through this area many times during Pleistocene lowstands.

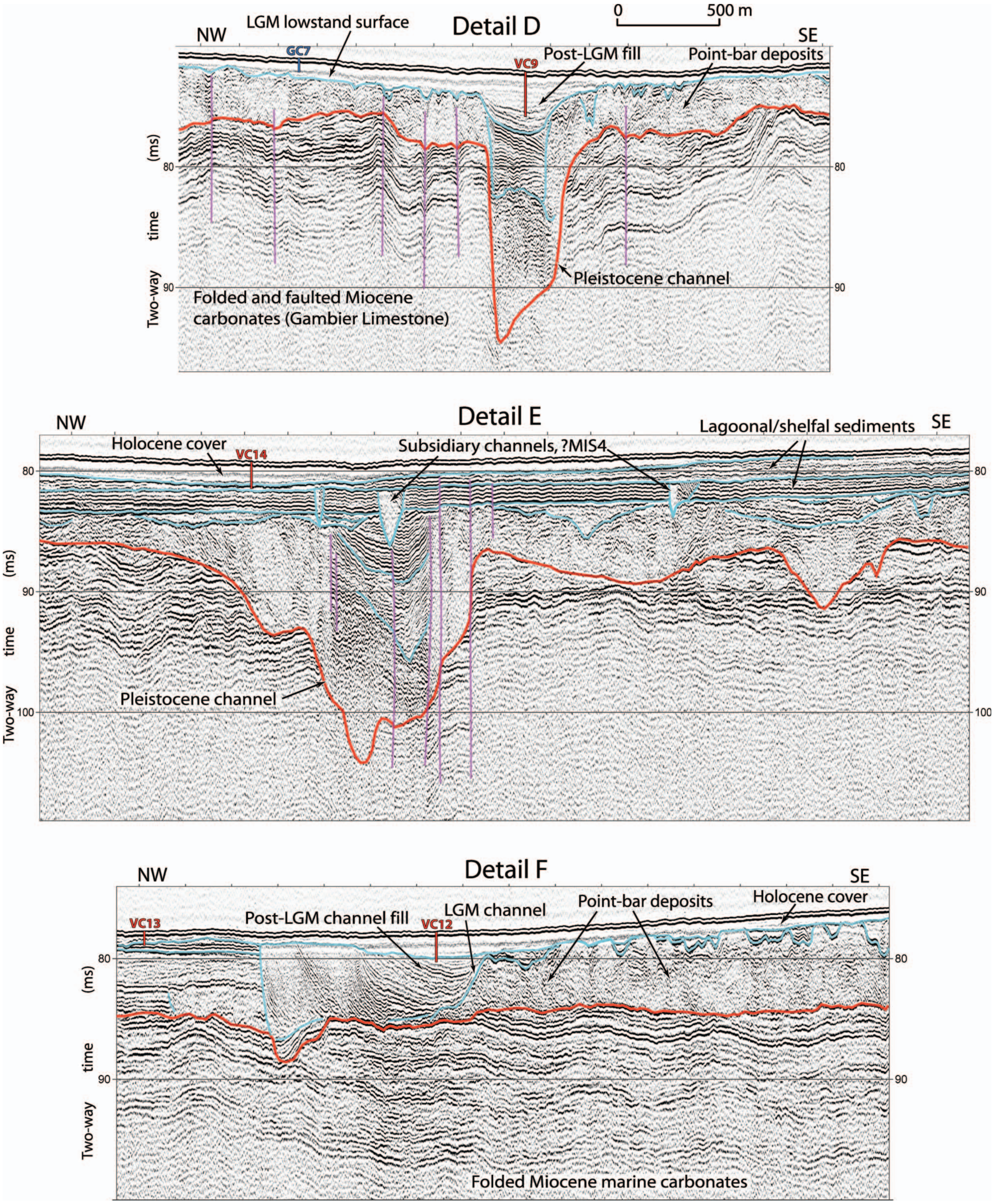


Figure 10 Detail of channels: D (Profile 3), E, F (Profile 4) (see Figures 6, 7 for locations of detailed profiles). Explanation and colour scheme as for Figure 6.

PROFILE 6: SOUTHERN LACEPEDE SHELF

Bedrock outcrops on much of Profile 6 (Figure 7) located on the central southern Lacepede Shelf. In general it appears to be folded and faulted Gambier Limestone, but at the southeastern end of the profile, where outcropping bedrock has positive sea bed relief of about 7 m, little if any stratification is evident suggesting the possibility of older basement rock. Several channels have been cut into the bedrock surface in the middle section of the profile where there is an overall dip in the bedrock surface. The ?Pleistocene sediment-filled incisions are mostly about 7 m deep, but the largest and most southeastern appears to be 15 m deep and 700 m wide.

PROFILE 7: EDGE OF SOUTHERN LACEPEDE SHELF

Profile 7 (Figure 8) is located across a canyon head at the edge of the continental shelf where the paleo Murray River may have discharged into the ocean at times during the Penultimate or earlier glaciations. The canyon head is about 7 km wide and is floored here by almost 20 m of Quaternary sediment of various facies including thick marine fans and drifts plus a series of filled channels commonly 6–9 m deep. The base of the Quaternary sedimentary section within the canyon head graben is a roughly planar, gently seaward-dipping, major angular unconformity about 125 m bsl (below sea-level) on the profile. Bedrock beneath the canyon head has a complex internal structure that includes dipping beds, folding and faulting. It probably largely comprises Miocene carbonates equivalent to the Gambier Limestone, as in the flanks of the graben, but may include truncated deposits as young as Pliocene. The series of channels and other major unconformities that lie at about 120–125 m bsl probably developed during lowstands associated with glacial maxima. The hiatuses they represent are possibly as young as the Last Glacial Maximum, but probably include glacial maxima of at least the last few glacial cycles.

DISCUSSION

Changes in channel/river valley morphology

Much of the fluvial geomorphology of the present lower Murray River, in particular the South Australian section, was controlled by Plio-Pleistocene faulting and vertical tectonic movements (Twidale *et al.* 1978). Here the modern course of the Murray River consists of meanders and abrupt changes in direction controlled by faults lines. The Murray flows in a valley typically 1500 m wide, but whose width can vary between 900 and 2100 m. It is commonly entrenched 40–130 m below the surrounding plain. The active river channel within the valley is mostly about 150 m across, but varies between 100 and 200 m.

In comparison, the paleo Murray River on the Lacepede Shelf excavated a smaller channel/valley typically 450–1000 m wide and 10–20 m deep. This downstream reduction in width and depth can be explained by: (i) the lower gradient on the shelf; (ii) relatively less vertical neotectonic activity; and (iii) the fact that the shelf was inundated by transgressions during much of the mid–Late Quaternary and so was not subject to fluvial erosion at such times. Despite some difference in scale, the Murray River paleovalleys on the Lacepede Shelf (Figures 9, 10) bear a striking resemblance in cross-section to the Murray River gorge upstream at Murray Bridge and Swan Reach (Twidale *et al.* 1978 figure 2).

Cyclical deposition of Murray Basin sediments off the shelf edge

The head of Sprigg Canyon is exceptionally broad, about 50 km across, and begins at the shelf break in water depths of 120–140 m. Thus, during most extreme lowstands (glacial maxima) of the mid–Late Pleistocene the Murray River would have discharged straight into the head of the Sprigg Canyon system, although Gingele *et al.* (2004) believed, on clay mineralogical evidence, that the river may have discharged elsewhere at times.

Several giant piston and gravity cores were taken on the mid–upper continental slope of the central Murray Canyons during the AUSCAN expedition (Hill & De Deckker 2004). 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 data from piston core PC 2607 (Figure 2) are particularly relevant to this study because of this core's location just east of Sprigg Canyon, adjacent to and downslope of the main Late Quaternary lowstand outlet of the Murray River. This 33 m-long core, taken from a water depth of 865 m, comprised foraminiferal silty fine sands with intercalated silty clay sections. PC 2607 underwent detailed geochemical analysis (Gingele *et al.* 2004), including charting the $\delta^{18}O$ record of *Globigerina bulloides*. The sedimentary record appears to be continuous, with no hiatuses evident. The bottom of PC 2607 coincides with MIS 6.5 (about 175 ka), and thus the core covers an age range close to that depicted in Figure 4.

Study of the core (Gingele *et al.* 2004) showed that during highstands (MIS 5 & 1), with the Murray mouth up to 200 km away, little terrigenous matter reached the site. Sedimentation was mainly pelagic, comprising mostly biogenic carbonate particles plus minor eolian dust. During lowstands (Penultimate Glacial Maximum & Last Glacial Maximum), when the Murray mouth was close to the present shelf edge and the shore was within 20 km of the core site, 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 these times. During the Penultimate Glacial Maximum carbonate content was $<5\%$ and sedimentation rates were as high as 60 cm/ka, while during the Last Glacial Maximum carbonate content was down to about 40% and sedimentation rate was up to 30 cm/ka. In comparison, interglacial background levels were 85% carbonate and 10 cm/ka deposition rate.

Mid–Late Quaternary paleogeography

Based on our mapping results, present-day detailed topographic models (offshore and onshore) and the paleo sea-level curve of Figure 4, we present in Figure 11 a series of maps of the Lacepede Shelf region showing paleogeography and Murray River paleodrainage at key times since the Penultimate Glacial Maximum (*ca* 138 ka).

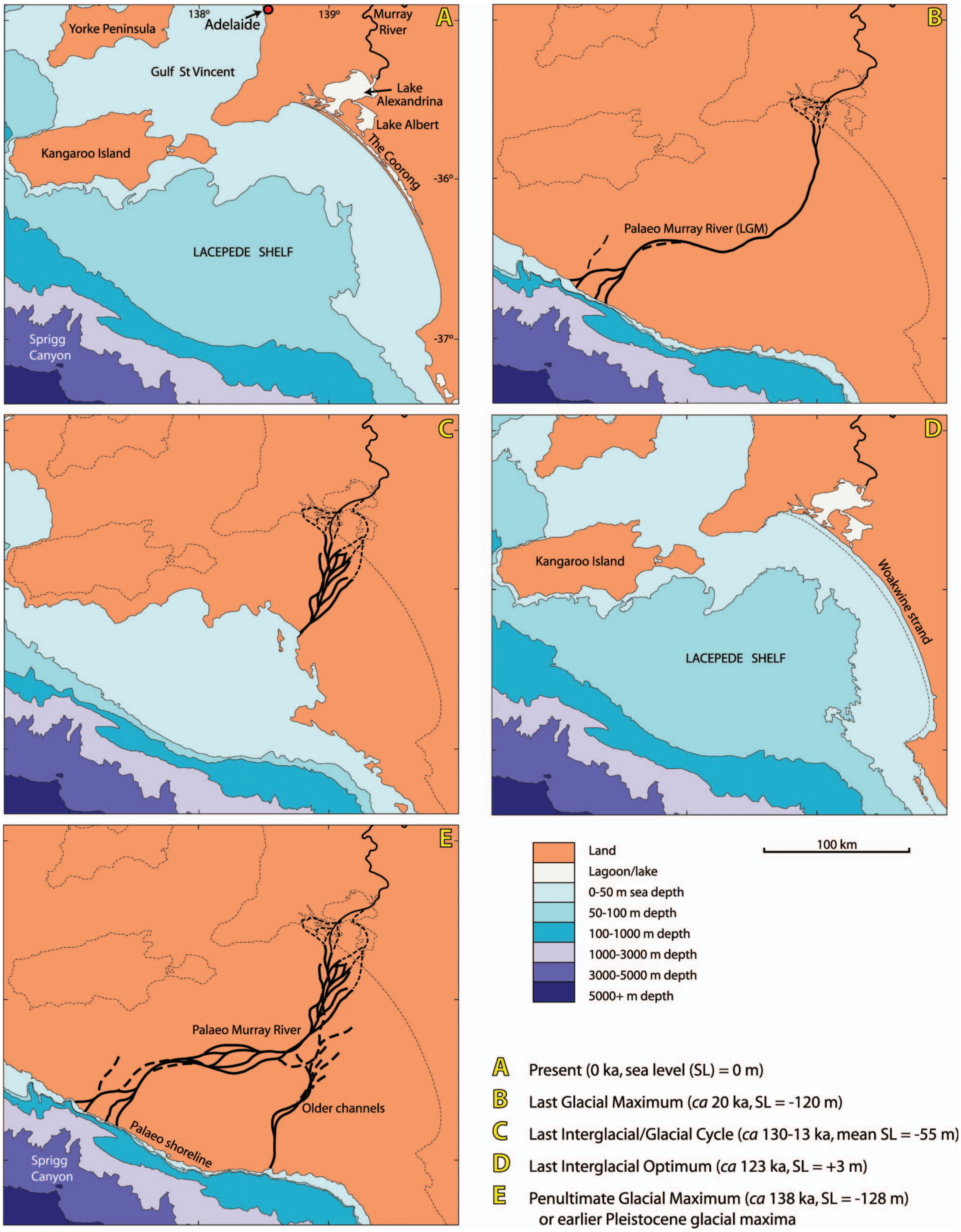


Figure 11 Paleogeographical snapshots of the Lacepede Shelf area for the Late Quaternary at key times (present-day, 20 ka, 130–13 ka, 123 ka and 138 ka) in the relative sea-level cycle illustrating the extent of successive exposure and inundation of the shelf and adjacent coast and the course of the Murray River at these times. The shoreline advanced and receded over distances of up to 200 km.

During the Last Glacial Maximum (*ca* 20 ka: Figure 11b) when sea-level was about 120 m lower, the Lacepede Shelf was a vast coastal plain, probably partly covered by eolian sand sheets and dunes (Bowler 1976; Sprigg 1979). The course of the Murray River across this plain is roughly similar to that postulated by earlier workers (Sprigg 1979; Hill *et al*. 2005), but is now much more precisely defined. The Murray River emptied into the sea above Sprigg Canyon via a radial series of channels. Humans arrived in Australia more than 40 000 years ago, and it is likely that people lived along the banks, lagoons and estuary of the paleo Murray River on the Lacepede coastal plain during the Last Glacial Maximum and later retreated as the sea rose to present levels (Figure 11a).

During the Penultimate Glacial Maximum (*ca* 138 ka: Figure 11e), and perhaps preceding glacial maxima, sea-level was possibly up to 8 m lower than during the Last Glacial Maximum. Though the paleogeography was much the same in terms of land area exposed, the Murray River drainage pattern on the Lacepede plain may have differed at times. Early drainage probably followed a more direct south-southwest course from the present Lakes Alexandrina and Albert area to the sea. Slight uplift associated with the nearby Mt Gambier Uplift (and suggested by the apparent anomalously shallow paleo water depth at VC20), or damming by barrier sands, may have diverted the lower Murray River to the west so that it emptied into the sea above Sprigg Canyon.

Following the Penultimate Glacial Maximum, the sea rapidly inundated the Lacepede Shelf, rising to about 3 m above present levels during the Last Interglacial Optimum (*ca* 123 ka: Figure 11d). Lakes Alexandrina and Albert would have been flooded and the coastline coincided with the present inner Coorong shore (Woakwine strand).

Figure 11c represents the most common paleogeographic scenario during the Last Interglacial/Glacial cycle (*ca* 130–13 ka) and indeed the entire mid–Late Quaternary. Mean sea-level during these periods was about 55 m below what it is today (Figure 4). Kangaroo Island was part of the mainland and the Murray River, with its sediment load, emptied into the sea at a point now the centre of the Lacepede Shelf. The Lacepede Shelf would have only been half its present size. Banks, shoals and barrier islands would have formed at the Murray mouth due to the shallowness of the sea, and marshes and other wetlands probably extended inland. Bathymetric contours in the central Lacepede Shelf (Figure 2) show a series of northwest-trending sea bed ridges 5–10 m high, which may represent former shallow banks, strandlines or dunes now drowned by the current transgression (i.e. interstadial equivalents of the modern coastal barrier landforms such as Younghusband Peninsula).

CONCLUSIONS

Our recent extensive marine surveys and research studies have revealed significant new information and detail on the course, character and associated depositional systems of the now-drowned ancestral Murray River that flowed from near the present Murray mouth to the edge of the continental shelf south of Kangaroo Island during Pleistocene lowstands. Our investigations have also shed more light on the stratigraphic and structural architecture of the 180 km-wide Lacepede Shelf and underlying Miocene carbonate platform, traversed by the paleo Murray River. Our main conclusions are as follows.

(1) The primary course of the lower Murray River during lowstands of the mid–Late Pleistocene ran south-southwest from the Lakes Alexandrina and Albert area to the central Lacepede Shelf, then veered west across the central shelf, and then southwest to empty into the upper Sprigg Canyon on the continental slope south of Kangaroo Island. At some stage during this period, the paleo Murray River followed a more direct south-southwest course from the area of Lakes Alexandrina and Albert across the Lacepede Shelf to a less spectacular unnamed canyon system on the continental slope.

(2) Bedrock beneath the Lacepede Shelf mostly comprises a platform of eroded Miocene shallow-water carbonates of Gambier Limestone. Some outcrop and inliers of basement rocks, probably Early Paleozoic granites and metasediments, are interpreted south of Kangaroo Island and around Backstairs Passage. The Gambier Limestone is folded throughout, with the folding being mostly gentle but locally open in places, including south of Kangaroo Island and beneath the central southern Lacepede Shelf.

(3) Surficial sediment cover on the Lacepede Shelf is relatively thin. It is believed to be mostly Quaternary in age, though Pliocene sediments may form a basal unit near the Murray mouth and off the Younghusband Peninsula to the southeast. A depocentre, the Lacepede Basin, extends south-southwest from the Lakes Alexandrina and Albert area and occupies the central Lacepede Shelf. It is commonly 6–10 m thick, but is locally up to 25 m thick where paleochannels of the Murray River are incised into the bedrock platform. Facies in the basin include filled paleochannels, point-bar deposits and well-stratified, flat-lying lagoonal/lacustrine sediments. Our sampling of the upper part of the basin indicates a surface layer up to 0.5 m thick of quartz sand, commonly reddish in colour, and believed to be of reworked Last Glacial eolian origin. Beneath this layer lie Late Quaternary estuarine muds and sands, often mollusc-rich. Minor neotectonic activity is indicated in places by small-scale faults (up to 0.5 m displacement) that extend partly or fully through the section.

(4) The outer Lacepede Shelf is a Miocene carbonate hardground largely devoid of surficial sediment cover because of its high-energy marine setting facing the Southern Ocean. Swell base along the edge of the Lacepede Shelf is at about 140 m depth (James *et al.* 1992). What little cover exists comprises thin patches ($<$0.5 m thick) of carbonate sand and gravel and some small pockets of winnowed carbonate drift in hollows and in the lee of local bedrock topographic highs. The surface of the carbonate platform is commonly rough and jagged, particularly on the outer shelf. Relief is typically 5–10 m, with pinnacles and steep-sided gullies

common sea bed features. Such sculpturing is the product of successive phases of erosion: karst formation during lowstand subaerial exposure and an energetic hydrodynamic environment when inundated.

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