COURSE OF THE LOWER RIVER MURRAY IN SOUTH AUSTRALIA: EFFECTS OF UNDERPRINTING AND NEOTECTONICS?

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The change in direction of the River Murray from westerly to southerly at North West Bend has been attributed to faulting or warping, but no appropriate structure has been located in the country rock coincident with the river course. Yet the angularity and the straightness of major sectors argue structural control. The plan course of the Murray downstream from Morgan is attributed to underprinting from basement fractures following the Middle Miocene but prior to the Late Pliocene. Uplift of the Marmon Jabuk structure superimposed on the effects of underprinting accounts for major departures from the SSW trend downstream from North West Bend, as well as the impounding of Lake Bungunnia. The upper shallow section of the valley-in-valley form was shaped at a time of higher baselevel in the Middle-Late Tertiary. The lower section is the present Gorge. The valley floor was lowered probably by subterranean solution and flow followed by collapse of the cavern roofs. Regression of the River at times of lower sea level caused the breach of the Marmon Jabuk blockage and the draining of Lake Bungunnia.

Key words: River Murray Gorge, underprinting, Lake Bungunnia, side-channels, Marmon Jabuk structure.

'From Overland Corner to the lakes and islands of the mouth there is a gorge, determined in its directions by structural features, averaging a mile in width, cutting through level-bedded marine Miocene limestones' (Fenner 1934: 86).

THE RIVER MURRAY may be regarded as consisting of two parts. The upper or inland river consists of its headwaters and various major tributaries that converged and coalesced during the later Tertiary to form the endoreic, meandrine river flowing through western Victoria and New South Wales and into South Australia as far downstream as Overland Corner. There its character changes as it enters a gorge bounded by colourful cliffs. This is the exoreic or lower Murray that leads to the sea. Moreover, as noted by Charles Sturt during his epic boat journey of 1829, after many days and weeks flowing generally westwards the River turned 'suddenly to the south … in a great NW angle' (Sturt 1849, I: 10).

This is but one of the problems posed by the course of the lower River Murray (Fig. 1) and discussed in this paper:

Why, following the withdrawal of the sea in the Middle Miocene and prior to the Late Pliocene, did the River turn abruptly from a westerly to a southerly course at North West Bend, near the present site of Morgan?

Why are the River course and valley essentially straight between North West Bend and Swan Reach?

What is the explanation for the prominent easterly loops south of Swan Reach, namely the Nildottie Loop downstream from Big Bend, Chucka Bend near Bowhill, and particularly, the pronounced westerly deviation between Chucka Bend and Tailem Bend, referred to here as the Mannum Loop?

Did the inland waters overflow southwards and erode a valley, or was there an ancestral separate lower Murray that regressed northward from the then coast to capture the inland waters?

Bearing in mind the calcareous nature of the country rock, was the Murray Gorge formed wholly by river erosion or did subterranean solution and collapse play a significant role in its formation?

STRUCTURE AND STRATIGRAPHY

The Murray Basin is a framed basin, i.e. a polygonal basin 'framed' by outcrops of basement rocks but un-

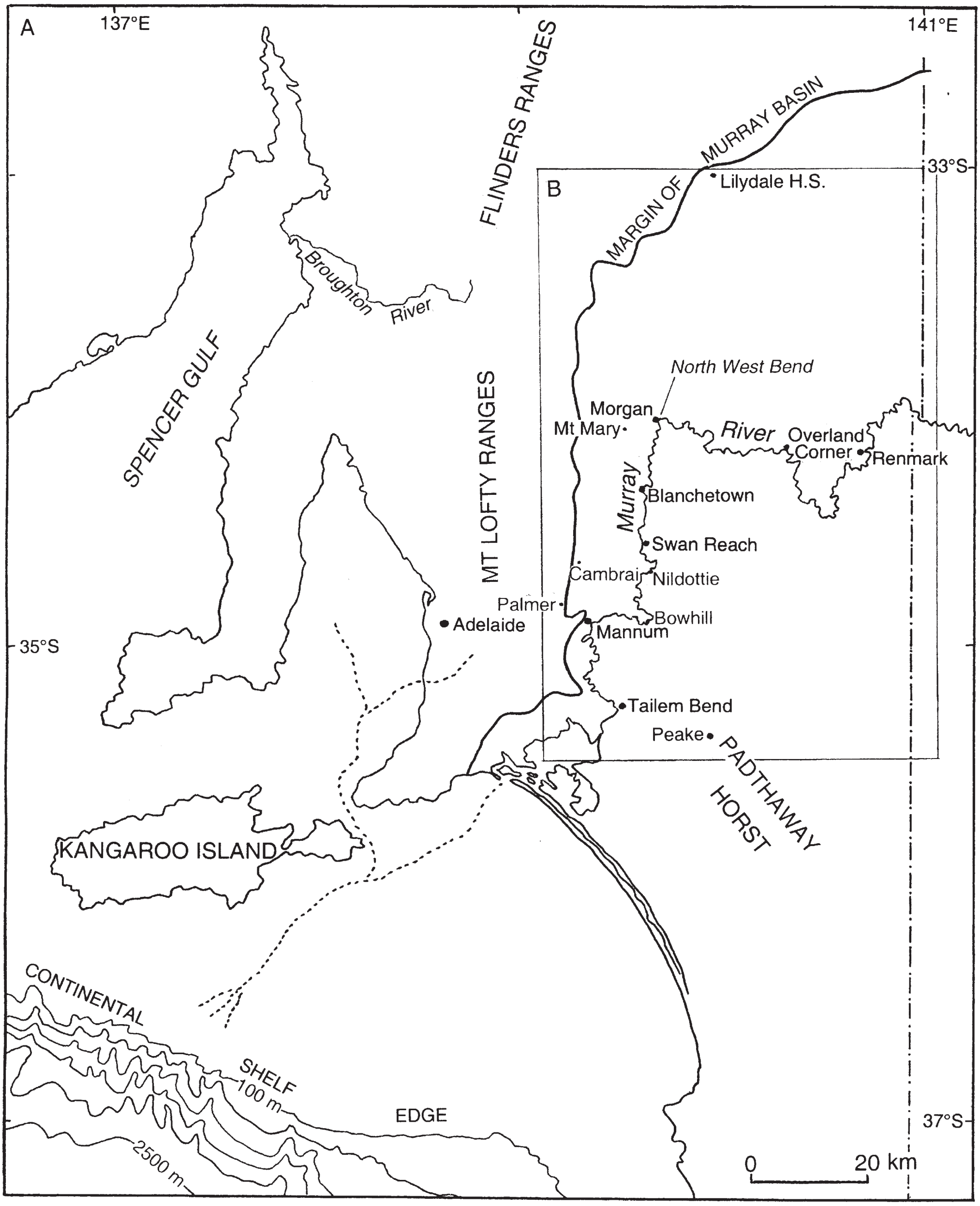


Fig. 1. (A) Location map. Extent of Murray River during glacial periods of low sea level shown by dotted lines (after Von der Borch 1968).

derlain by depressed blocks (Hills 1963: 336; see also Fenner 1934: 83; Fig. 2A). In the west the Basin is dominated by outcrops of the flat-lying Mannum Limestone. Essentially of Early-Middle Miocene age, it was deposited in a marine embayment overlying an Early Palaeozoic basement, the surface of which took the form of an undulating inselberg landscape developed in a variety of igneous and metamorphic rocks. Some unweathered representatives are exposed in the inselbergs and other outcrops, particularly at the western margin of the Basin. Such basement rocks have also been encountered in bores (Barnett 1989). The

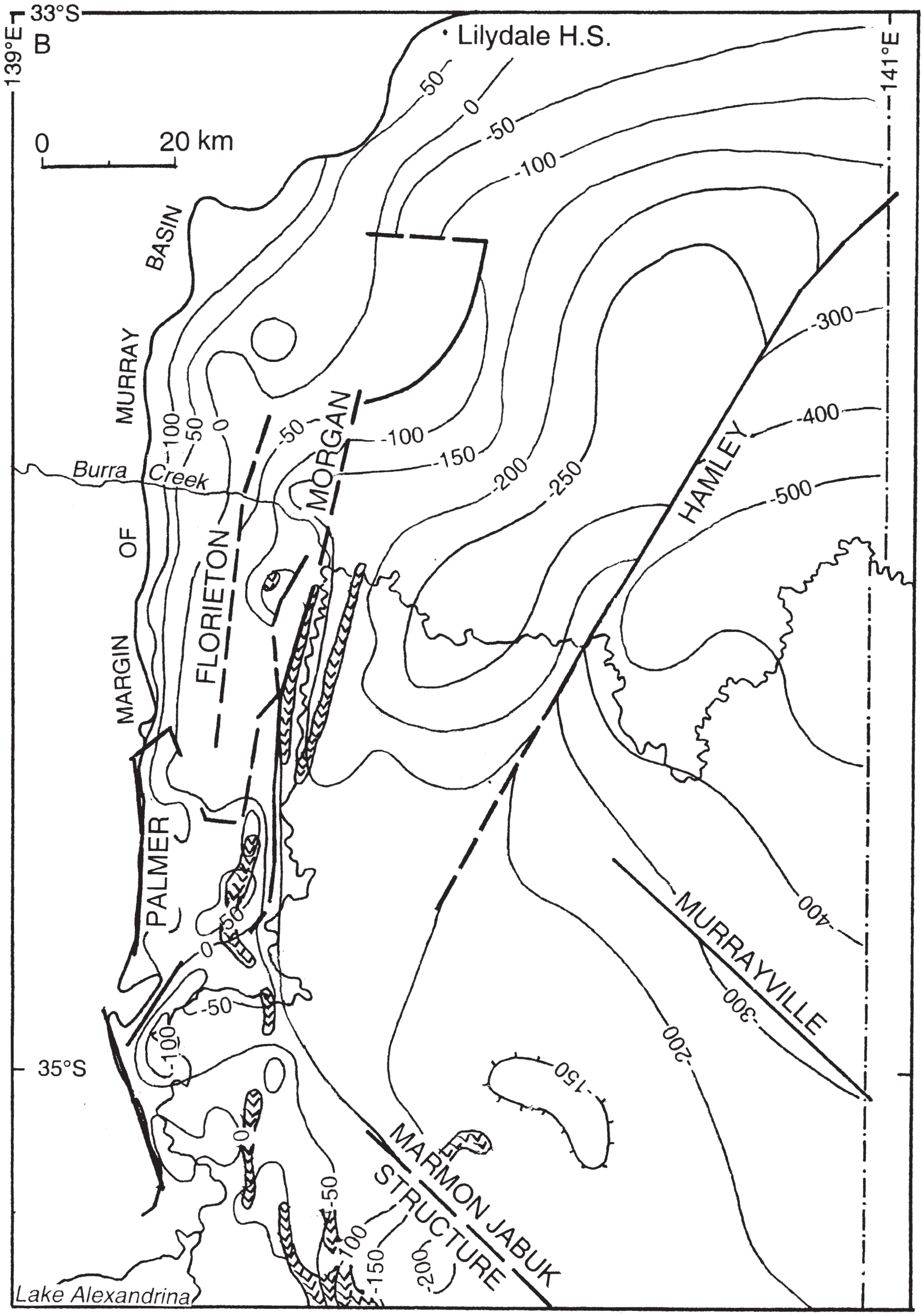


Fig. 1. (B) Elevation (in metres AHD) of preTertiary basement, and structure of western Murray Basin (after Barnett 1989). Faults in heavy lines, basic intrusions indicated by 'v's.

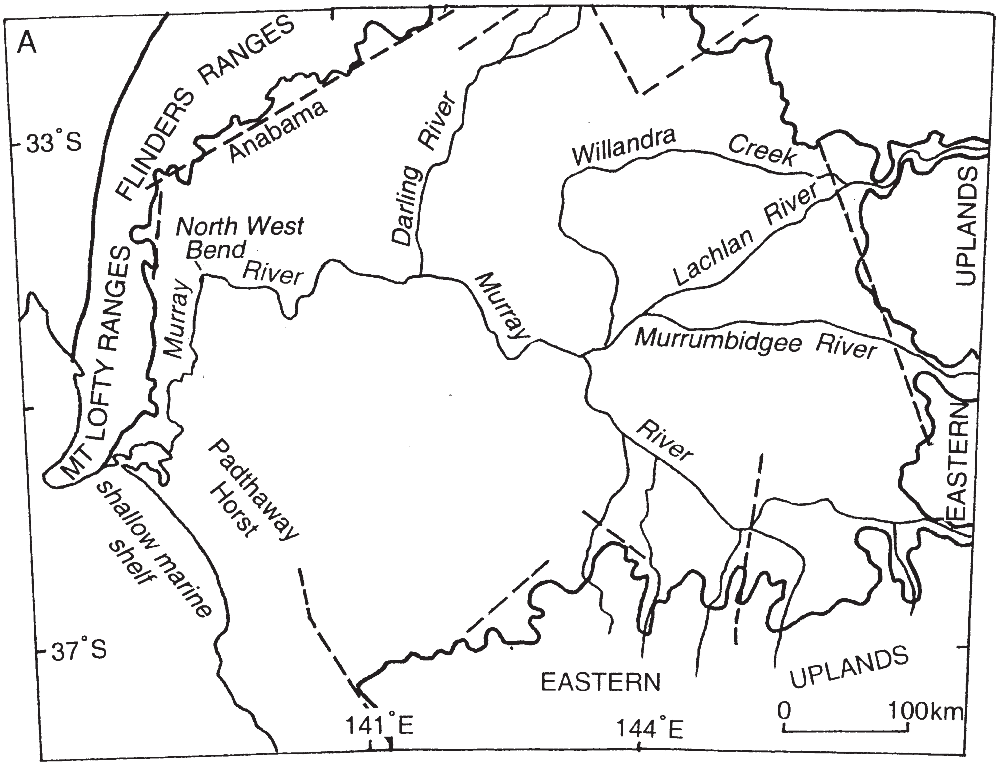


Fig. 2. (A) Framed Murray Basin (after Hills 1956). Dashed lines indicate faults.

crests of a few of the higher hills project from beneath the sedimentary cover in inliers such as Black Hill.

The post-Miocene chronology of the Basin reflects the global sea level changes of the later Cenozoic (Stephenson & Brown 1989; Brown & Stephenson 1991). At times of relatively high sea-stand various major inland rivers entered the Basin from the north-east, depositing shallow-water marine and marginal fluvial and lacustrine sediments (Fig. 2B). The present course of the River from Tailem Bend upstream was presaged prior to the later Pliocene by a valley that later became an estuary extending north as far as Morgan, on to Lilydale H.S. (homestead), and east to Overland Corner. In it was deposited the Norwest Bend Formation,[1] typically represented by a massive bed of oyster shells (*Ostrea sturtiana* Tate, 1884), but including clays and cross-bedded sands (Fig. 2C). The estuary appears to have been narrow between Tailem Bend and Walker Flat, some 110 kms upstream, in which sector its limits are still discernible in the landscape. To the north, however, it formed a broad but shallow body of water, extending to the west as far as the Florieton fault-line depression in the vicinity of Mt Mary. Shallow-water marine and estuarine sands (Loxton and Parilla sands, respectively) of equivalent age form a thin cover overlying and marginal to the Mannum Limestone. They form a Pliocene surface of low relief that extends into western Victoria (Wallace et al. 2005).

In South Australia, the western Basin is dominated by a riverless karst plain, which dates from the later Pliocene. Surface streams and shallow subsurface flows issuing from the Mt Lofty Ranges were graded to the Norwest Bend Formation estuary (Twidale & Bourne 1975; Twidale et al. 1978). Remnants of this Pliocene surface are preserved in the piedmont south of Palmer, where a ferruginous carapace is developed in the piedmont above Mannum Gorge (Twidale & Bourne 1975). The Pliocene surface is eroded mainly in Mannum Limestone and is the result of corrosion planation (Ford & Williams 1992: 443) involving dissolution and stream corrasion down to the water table. That such planation is effective is indicated in the southern sector of the Eucla

[1] North West Bend for the topographic feature, but Norwest Bend for the stratigraphic Formation.

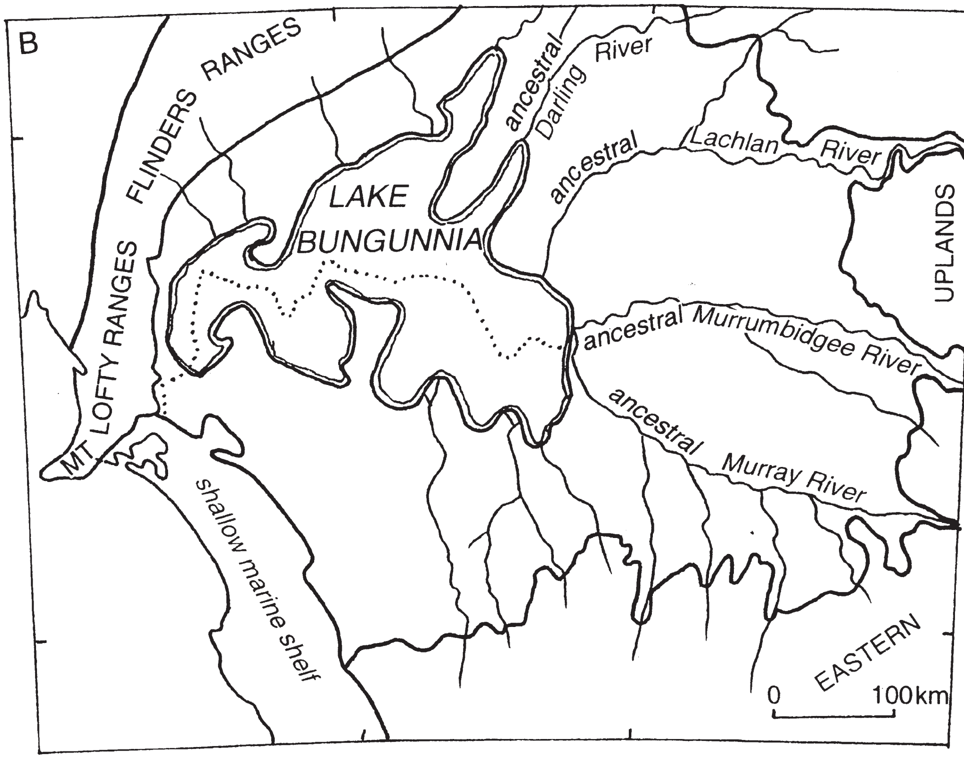


Fig. 2. (B) Position and former extent of Lake Bungunnia (after Stephenson 1986).

Basin where the Nullarbor Limestone, has been lowered by as much as 60 m (Lowry 1970), despite its being crystalline rather than clastic. The many cave systems detected in the Mannum Limestone (eg. Matthews 1985: 5-18–5-19; G. Pilkington pers. comm. 2006; cf. Trendall 1962) and the high carbonate content of the river waters – in the sector of the River under review carbonates of calcium and magnesium account for about one third of the load in solution (McKay et al. 1986; see also Livingstone 1963: table 57, p. G31) – suggest that the process continues.

The elevation of the Pliocene surface relative to the eastern Mt Lofty Ranges reflects the effects of Late Pleistocene or post Pleistocene faulting, as demonstrated by the exposure of the Palmer-Milendella Fault west of Cambrai (Bourman & Lindsay 1989) and the location of Miocene remnants high on the adjacent scarp (Mills 1965; Twidale & Bourne 1975).

Sediments deposited in the shallow Lake Bungunnia (Firman 1965; Stephenson 1986), which dates from the Late Pliocene to Middle Pleistocene (2.5–0.7 Ma), formed an extensive veneer over the northwestern part of the Basin in South Australia (Fig. 2B) and adja-

Fig. 2. (C) Remnant of oyster beds of Norwest Bend Formation, near Walker Flat.

Fig. 3. (A) Murray Gorge near Walker Flat showing bluffs in massive flat-lying Miocene calcarenite.

cent areas of northwestern Victoria (Lawrence & Goldberry 1973; Bowler 1980; Bowler et al. 2006). Though the Lake was probably impounded by uplift of the Marmon Jabuk structure (eg. Twidale et al. 1978) it may also indicate a more humid and/or cooler climate (Stephenson 1986). According to An et al. (1986) aridity set in about 500,000 years ago. In the north, linear east-west trending desert dunes developed between about 360,000 and 25,000 years ago (Twidale et al. 2007; Lomax et al. 2007, 2010).

During later Cenozoic periods of low (glacial) sea level the bed of the River Murray was incised in response to the lower baselevels, while the limestone plains to either side remained essentially intact. Thus was formed the present shallow but colourful and spectacular gorge (Fig. 3A). Between Tailem Bend and Swan Reach remnants of the shallow Norwest Bend estuarine valley were left perched as the upper components of a valley-in-valley form (Fig. 3B).

Alternations of cut-and-fill corresponding to glacial low sea levels and interglacial highs are recorded in the Late Pleistocene and Holocene valley-floor sediments (Sprigg 1952; Firman 1965; Rogers 1995). At times of low sea level the river extended

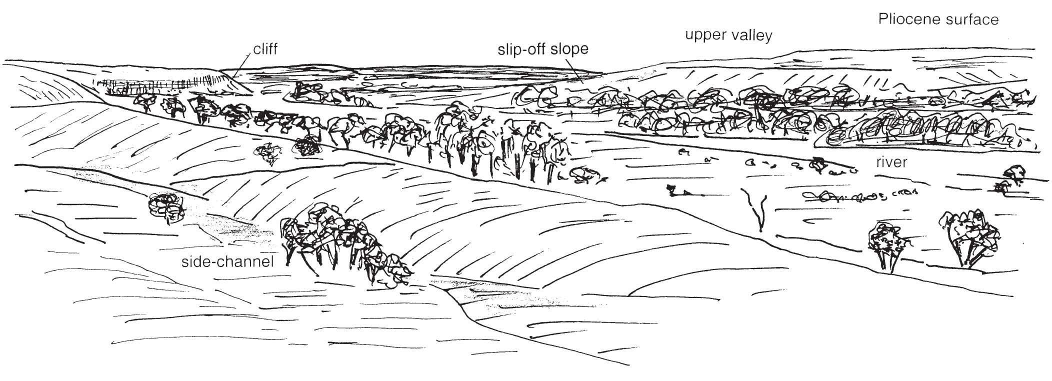


Fig. 3. (B) Sketch of valley-in-valley form of Murray Gorge a few kilometres upstream from Mannum, with simple side-channel in foreground.

across the continental shelf east of Kangaroo Island, until the mix of riverine waters and transported sediment tumbled over the edge of the continental slope and carved huge submarine canyons (Sprigg 1947; Von der Borch 1968; Stephenson & Brown 1989; Hill et al. 2005; Fig. 1A).

STRAIGHT COURSE OF THE LOWER MURRAY, MORGAN – SWAN REACH

Most workers are agreed that the overall straight sectors of the course of the Murray in South Australia, as well as some of its angular reaches, are structurally-controlled. Several possible reasons for these configurations have been suggested, but whatever the reason for its initiation, a major river like the Murray would have been self-perpetuating and self-enhancing: the intrusion and operation of reinforcement mechanisms (Logan 1851; Behrmann 1919; King 1970; Twidale et al. 1974) would have ensured that once initiated the River and valley would persist.

Warping

Fenner (1931: 85) noted a 5° dip of the limestone exposed in the gorge walls at Morgan and suggested that it signified the presence of a warp, which he believed '…marked the present course of the Murray between Morgan and Chucka Bend.' The origin of such dips is debatable. They could be tectonic and associated with warping, as Fenner assumed, but equally they could be original depositional dips or due to camber (eg. Hollingworth et al. 1944), the latter implying that topography preceded displacement, rather than the converse.

Faulting

O'Driscoll (1960: 126) referred to the 'deflection point' of the River at Morgan, implying that the westerly-flowing Murray was there diverted to the south. He noted that the northwestern part of the Murray Basin is underlain by a system of step faults downthrowing to the east 'which probably have been recurrently active through the Cenozoic' (O'Driscoll 1960: 20). He cited in particular the Morgan Fault, the recent activity of which is indicated 'by its influence on the direction of flow of the River Murray, which indubitably owes its sudden change of course at Morgan, and subsequent almost straight-line flow as far south as Blanchetown … to the presence of a fault.' Unfortunately this reasoning is circular for O'Driscoll assumed the presence of a fault on the basis of the course and character of the River and its valley.

O'Driscoll was but the first of several workers who have ascribed the change of course at North West Bend to fault deflection (eg. Firman 1972; Barnett 1989: 50; Stephenson & Brown 1989: 392; Brown & Stephenson 1991: 30) and the downstream straight course to fault control. Ludbrook (1961: 86) was of that mind and, moreover, claimed that the oyster beds of the Norwest Bend Formation 'on the western side of the river [stand] at a higher elevation than those on the east' (Ludbrook 1980: 91–92). The statement is open to misinterpretation, depending on the scale Ludbrook had in mind, for whereas modern maps suggest that the Pliocene estuarine beds preserved within the present gorge have not been disturbed, there is no doubt that the Morgan Fault has been active since the Pliocene for the oyster beds stand higher to the west of it than to the east (Firman 1971a; Barnett 1989). The Morgan Fault, however, lies west of the river course. Thus, the lack of spatial coincidence between the Murray and any known surface fault rules out any direct connection between the channel and a known structure.

No fault zone has been identified in the prominent cliffs in and around Morgan. Extrapolation of the structure as shown on the 1:250,000 geological map (Firman 1971a; Rogers 1977) carries it to the vicinity of North West Bend and beyond, into the valley of the Burra Creek. This stream takes an abrupt change of course from SSE to south, about three kilometres north of its junction with the Murray, suggesting structural control. Also the Miocene Pata Limestone stands 5–7 m lower to the east of the Creek than it does to the west. But apart from the implied dislocation in the Burra Creek valley, no appropriately positioned fault zone has been identified south of Morgan. Moreover, even if post-Miocene displacement of the Morgan Fault blocked and diverted the River Murray, it clearly has not influenced its course to the south for though the fault scarp increases in amplitude to the south, it also diverges from the River so that the two are some 5 km apart in the latitude of Blanchetown. It may be argued that the exogenic Murray was diverted at Morgan and flowed along the base of a debris slope deposited against the base of the tectonic scarp (Fig. 4A): but no remnants of such features, if ever they existed, have been observed. Similarly, drag may have created a break of

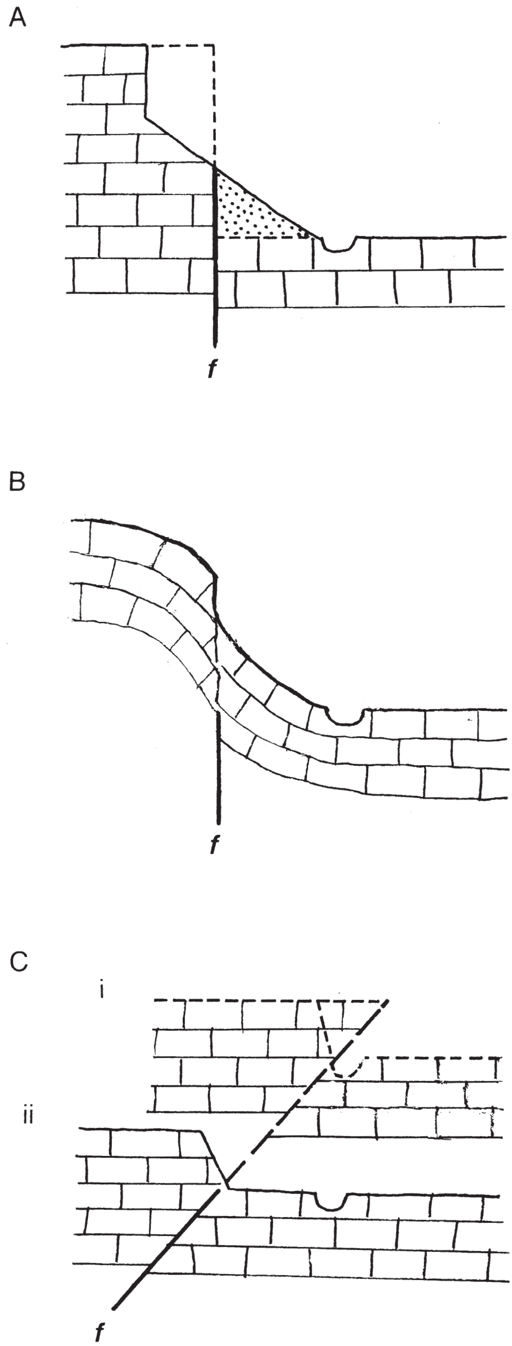


Fig. 4. Position of River Murray channel determined by (A) debris slope (B) drag slope, and (C) referral.

slope adjacent to the scarp (Fig. 4B), but again such features have not been recognised in the field.

Referral

Referral is the transmission or imposition of the structural effect at a lower level and spatially offset from the original. Thus a fault-line river and valley may through reinforcement effects persist in the same location, while the plan position of the dipping fracture zone that determined its initial development migrates laterally as the land surface is lowered. As applied to the lower Murray, if the Morgan Fault had determined the position of the River and was gently dipping and of reverse or thrust type, and if the land surface had been sufficiently lowered it can be deduced that the spatial locations of the two would separate but that the river channel would persist in its initial location (Fig. 4C). However, geological sections based on borelog information show that the Morgan Fault is steeply dipping (Barnett 1989). This precludes the mechanism as a possible explanation of the alignment and position of the River between Morgan and Swan Reach.

Capture or piracy

Williams and Goode (1978; see also Goode & Williams 1980) proposed that during the Eocene and/or the Late Middle to Upper Miocene the 'ancestral' River Murray in South Australia debouched into Spencer Gulf, near the present mouth of the River Broughton. Implicit in this suggestion is the diversion of the inland Murray by an exogenic Murray which regressed northward from the then coast and effected the capture of the inland river at Morgan. In these terms the North West Bend would be an elbow of capture.

Though the courses of the Broughton and its tributaries are largely controlled by structure, and the alignment of the inland Murray and of the Broughton is suggestive, the Mt Lofty-Flinders ranges originated in the Early Palaeozoic Delamerian Orogeny and were again uplifted in latest Cretaceous or Early Eocene times (eg. Miles 1952; Campana 1958). Uplift also occurred in the later Cenozoic and continues (Glaessner & Wade 1958; Williams 1973; Bourman & Lindsay 1989; Love et al. 1995; Quigley et al. 2006). Contrary to some earlier reconstructions and recent revivals, although the Miocene seas occupied marginal embayments on both its flanks, during the Tertiary 'The Mt Lofty Ranges were not covered by the sea.' (Glaessner & Wade 1958: 124): it was an upland barrier blocking the supposed course of the upper

Murray toward Spencer Gulf throughout the Cenozoic era. Moreover, the Broughton sediments are not consistent with a Murray Basin provenance (Harris et al. 1980; Gostin & Jenkins 1980; Stephenson & Brown 1989). The hypothesis suggested by Williams and Goode (1978) also begs the question of why having turned south, the River Murray follows a linear southern course for some 60–70 km. Later in the discussion, however, it will be suggested such piracy cannot be ruled out, though not as earlier conceived.

Underprinting

No suitable structure has been identified in the Cenozoic strata in which the River has incised its channel and valley, but the course of the River may have been determined by underprinting, that is, have been imposed from below by deep basement structures acting on overlying strata.

Wopfner (1960) attributed the open folds developed in silcreted Cretaceous strata in southwest Queensland and adjacent areas to basement shearing transmitted to and through the overlying strata. The spectacular 700 km-long straight course of the Darling was attributed to basement joggling along major fault zones and the resultant development in the Quaternary alluvia, in which the Darling mainly flows, of shallow linear depressions and half-grabens (Hills 1961: 83). In the western Murray Basin, Firman (1974) attributed to underprinting the angular pattern of the River between Renmark and Morgan.

Opinions as to the nature of the underprinting mechanism vary. As demonstrated the River is not coincident with a fault zone. It could, however, have exploited a weathered zone associated with a basic intrusion comparable to those plotted by Barnett (1989; Fig. 1) and proven by drilling. But the subchannel zone has not been drilled, so that the question remains open. On the other hand, geophysical evidence of meridional trends additional to the fractures implied by the linear basic intrusions has been noted at both local and regional scales (Hills 1953; O'Driscoll 1960: 20).

Some have suggested direct transmission of stress from deep structures (Hills 1961; Saul 1978; O'Driscoll & Campbell 1997). Twidale and Bourne (2000), however, offered an alternative underprinting mechanism that is germane to the Murray Basin environment. They attributed aligned and topographically anomalous dolines developed in the Pleistocene dune calcarenite of western Eyre Peninsula to the concentration of groundwaters above basement fractures, followed by site-specific solution, collapse and subsidence (Twidale & Bourne 2000). Such an underprinting mechanism is appropriate in the context of a terrane dominated by calcareous strata (Fig. 5). A structure that would concentrate water, solution and erosion is required.

The exploited zone may not be a fracture zone, however, but one of strain. That disturbs crystal lattices, so that minerals are rendered more susceptible to water entry and alteration (Russell 1935; Turner & Verhoogen 1960: 476; Nabarro 1967: 4). This could create a zone that induces underprinting and could account for the present linear course of the Murray south of Morgan in terms of local evidence.

Such a zone of strain would be difficult to detect geophysically but even a slight preferential permeability would be enough to produce solution at the base of the Mannum Limestone. Reinforcement would ensure that this slight weakness was enhanced to favour groundwater circulation and concentration in the zone above the basement zone of strain.

Ironically, after considering his geological sections Barnett (1989: 51) suggested that resurgent or recurrent movements on known faults 'has transmitted

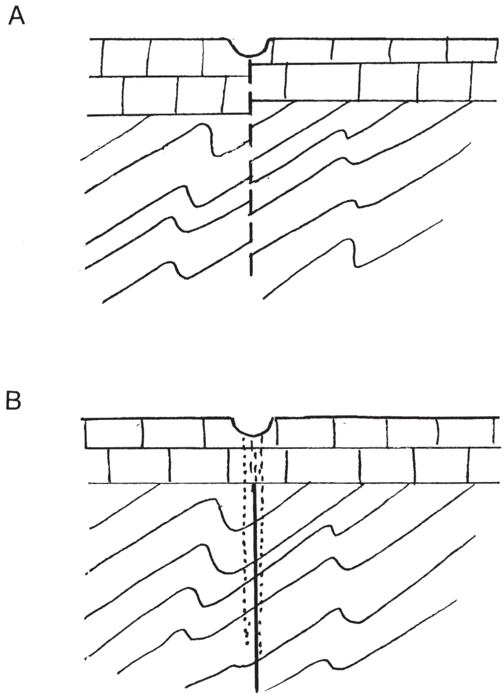


Fig. 5. Underprinting (A) by joggling, and (B) by solution.

basement structures up through the Cainozoic sediments to the ground surface' and Brown and Stephenson (1991: 308) also mentioned a possible link between major bends in the river course and concealed basement faults and ridges. However, as has been pointed out, these authors set aside the idea and attributed diversion of the Murray at Morgan to the Morgan Fault.

MARMON JABUK STRUCTURE

The course of the Murray between Morgan and Swan Reach appears to be determined by a submeridional basement zone of en echelon or zig-zag shears of predominantly NW-SE and NE-SW orientations (O'Driscoll 1960: 19 & 21). These shears could be of conjugate type and be associated with the Morgan Fault to the west but incorporated in the strain zone that, it is suggested here, has been exploited by weathering and subsequently by the River. Between Swan Reach and Tailem Bend the structure responsible for the linearity of the Murray south of Morgan is, however, overridden by the Marmon Jabuk uplift.[2] Only south of Tailem Bend is the Morgan–Swan Reach line resumed.

The Marmon Jabuk uplift (Fenner 1930: 36; Twidale et al. 1978; Stephenson 1986) is represented by a scarp to the southeast, in the vicinity of Peake. It is construed as the uplifted northeastern edge of the Padthaway Horst. The structure may be dated from the Early Palaeozoic Delamerian Orogeny (Preiss 1987), but have been subsequently revived. It has affected the Early to Middle Miocene Mannum Limestone and arguably caused the westerly diversion of the Murray in the Mannum Loop prior to the Late Pliocene (eg. Ludbrook 1980). The northerly inclination of beds at Chucka Bend and noted by Fenner (1931: 85) may be an expression of the Marmon Jabuk uplift in this area.

An uplift and northeast-up-tilting of the SE-NW trending Marmon Jabuk structure could have locked the meridional 'river' strain zone, inducing the relief of stresses by movement on the Morgan Fault. Because shearing produces both tension and compression along different stress axes, some joints could have been opened but others sheared causing crumbling of the adjacent country rock. Both conditions later could have been exploited by solution. The linear lower Marne River and various other minor tributary streams, and the elongate depressions or dolines ESE of Chucka Bend are also suggestive of structural (fracture) control (Fig. 6).

LATE PLIOCENE ESTUARY

The valley of the Murray has been incised into the Pliocene surface, but the ancestral river is thought to predate the Late Pliocene (Ludbrook 1961: 85), though no outcrops of the Formation have been recognised in the Mannum Loop. This does not necessarily imply than none exists in that sector. Outcrops occur above Fromms Landing, just downstream from Walker Flat (Fig. 2C), but possibly because they are too small are not shown on the 1:250,000 map of the area (Firman 1971a). There may be other remnants of limited areal extent, but in any event occurrences are scarce or absent in the Loop sector, yet there must have been a connecting channel in order for the estuary to have extended northward from the sea and north from Chucka Bend.

The apparent absence of the Norwest Bend Formation in the Mannum Loop could be due to the River having eroded an alternative course in the Late Pliocene. The present course of the River in the Mannum Loop could be a Quaternary development, with the earlier Murray flowing more directly between Bowhill and Tailem Bend. But if the River had flowed across the base of the Mannum Loop no obvious evidence remains. The perviousness of the Mannum Limestone and consequent lack of surface drainage suggests that the high plain surface is relatively stable and enduring. Yet there is no sign of an abandoned valley comparable to Green Gully preserved on the backslope of the Cadell Fault Block, New South Wales (cf. Harris 1939). There is no broad shallow depression similar to the shallow valley in which the Norwest Bend Formation was deposited and that can be construed as representing the former river course. No deposits of oyster beds have been found in crucial locations distant from the present valley. No submeridionally-oriented caves or dolines suggestive of a subterranean course have been located along the base of the spur (Matthews 1985; G. Pilkington CEGSA, pers. comm. 2006):

[2] 'Jabuk' is an Afghan name possibly linked to an early cameleer attached to an early survey party. 'Marmon' may be a corruption of Madman's (Gap) a local topographic feature (Cockburn 1984). Fenner (1930) appears to be the first to have linked the topographic form to the now widely recognised structure. It is part of the same structure referred to elsewhere as the Padthaway high and the Pinnaroo Block (e.g. Bowler et al. 2006).

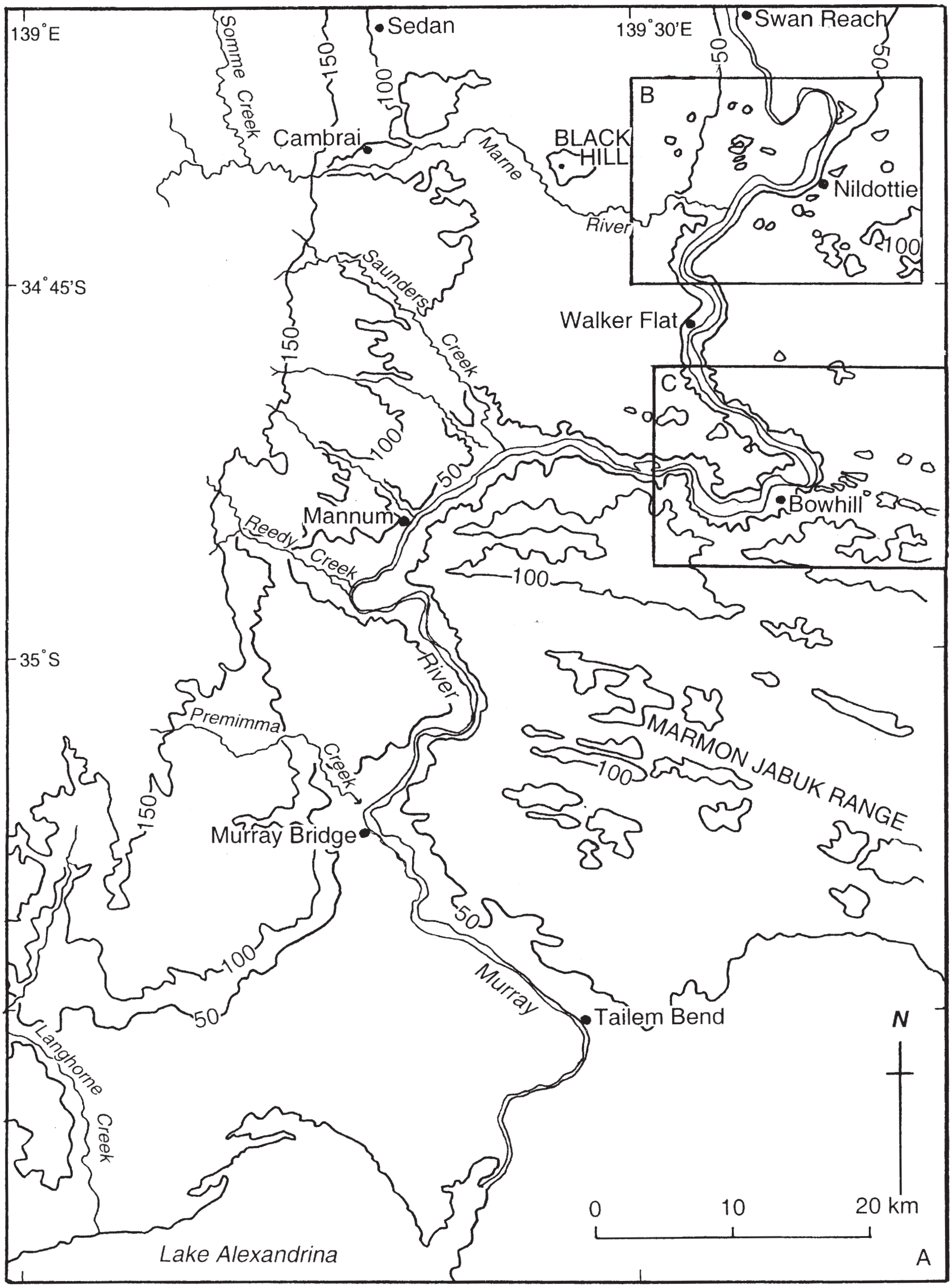
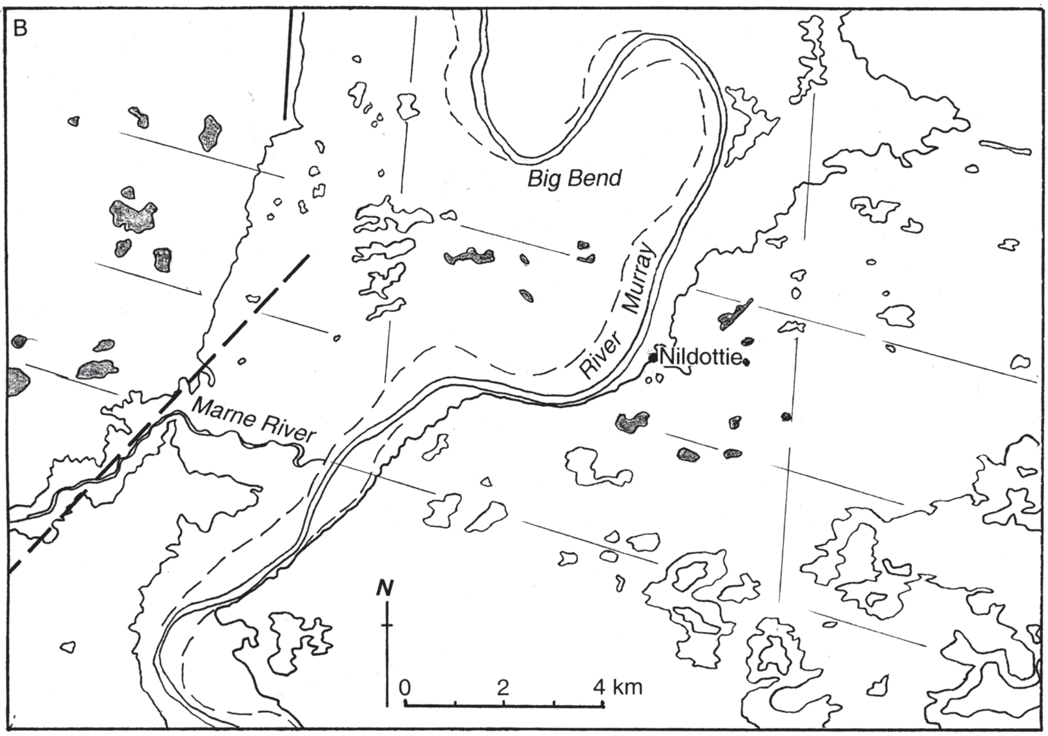


Fig. 6 (above and page 218). Map extract of (A) Mannum Loop, showing (B) the River Marne junction, and (C) Chucka Bend and E-W trending closed depressions. The Mt Lofty Ranges stand to the west of the 150 m contour line in A, Some of the contours identified in A are shown as form lines in B and C.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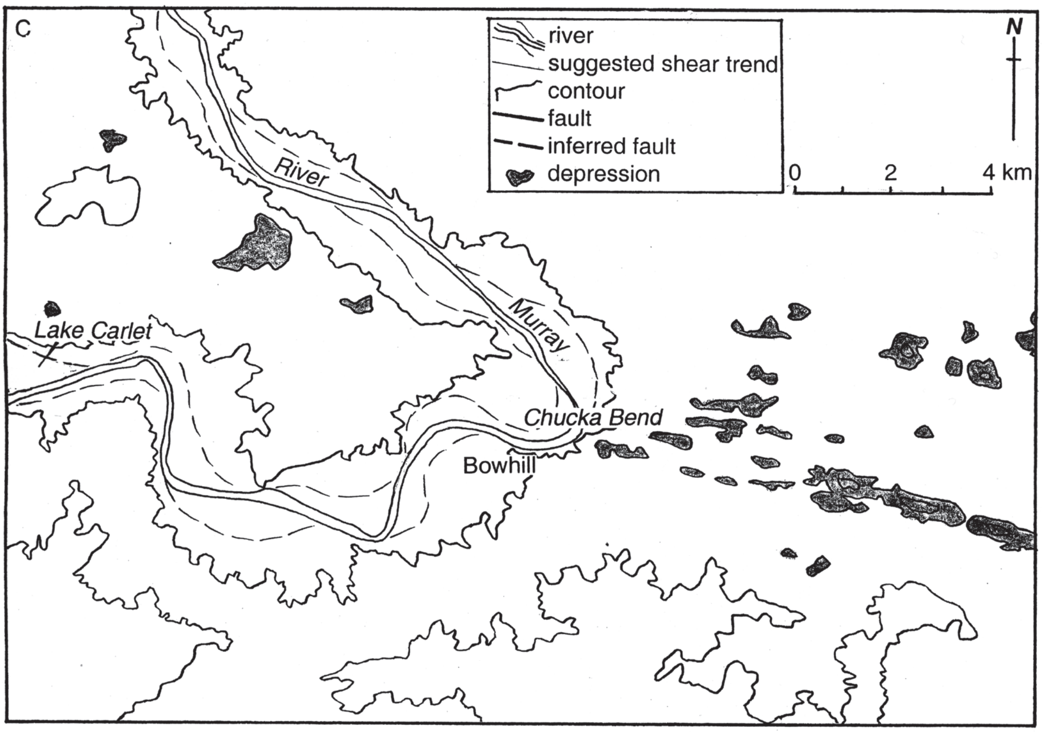
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shallow depressions caused by solution and collapse of the Mannum Limestone are developed in the area but they are elongated WNW-ESE and probably reflect the exploitation of fractures. That there would have been subterranean solution had the River formerly crossed the base of the Loop is suggested by the occurrence of many minor caves in the present valley sidewalls, mostly at or near water level (eg. Matthews 1985). Thus there is no morphological or sedimentological evidence to suggest that the Pliocene River Murray followed a course different from that it presently pursues.

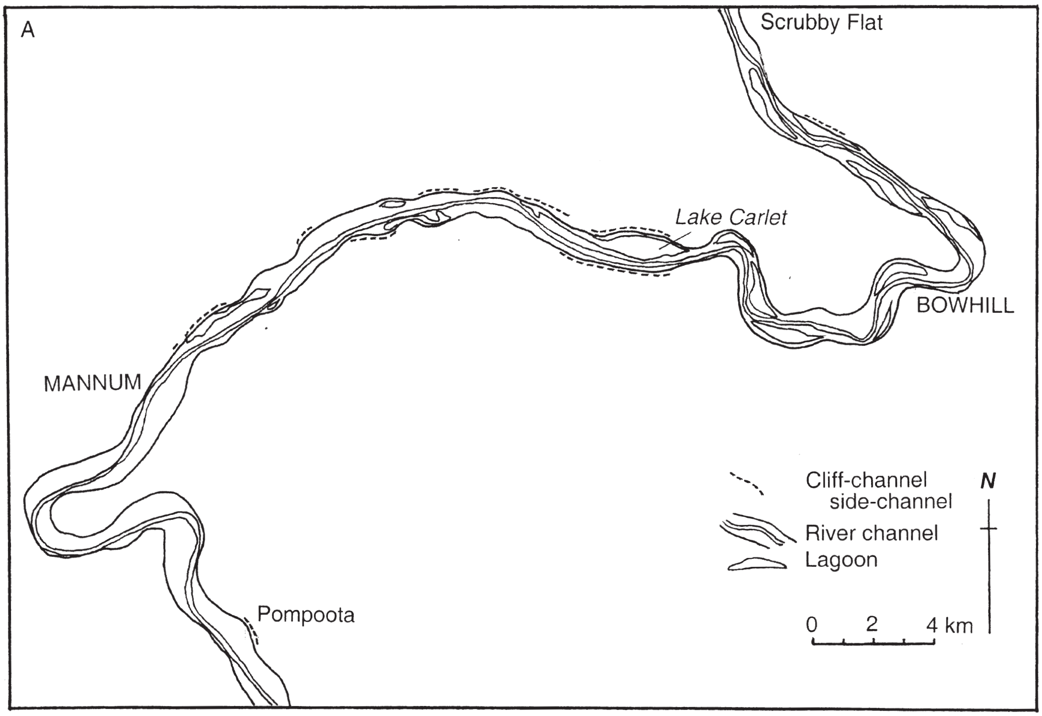
The valley-in-valley form, with the deeper steep-sided gorge incised into the floor of a broader shallow upper estuarine valley, is well preserved in the Mannum Loop section. If the Loop predates the Late Pliocene and the Norwest Bend Formation, and if the impounding of Lake Bungunnia was caused by renewed (post Late Pliocene–Early Pleistocene) uplift of the Marmon Jabuk structure, then the profile (thalweg) of the uppermost of the valley-in-valley forms ought to have been disrupted. In an undisturbed landscape its level would have declined gradually downstream but if uplifted it ought to be equal or higher in elevation in the Loop section than it is upstream. Such a hump in the profile of the estuary is represented in the contemporary landscape only by a possible rise of some 10 m in the height of the break of slope between estuary and high plain and by the dip in the Mannum Limestone noted by Fenner (1931); but with other variables (such as the heightening of a bluff as result of scarp recession) in play, this evidence is not convincing. The most that can be said is that it is not incompatible with the Marmon Jabuk structure having been active in post-Pliocene times.

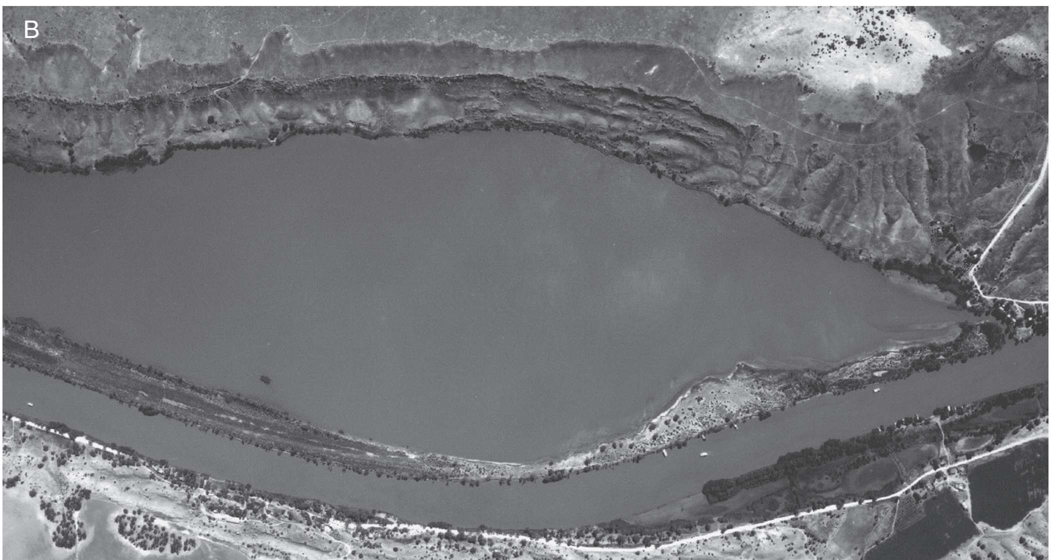
LAKE BUNGUNNIA

Some 3.0 – 2.5 million years ago (Bowler et al. 2006) renewed uplift of the Pinnaroo Block, the northwestern sector of the Padthaway Horst, here referred to as the Marmon Jabuk structure, caused the obstruction of the drainage of the western Murray Basin including the estuarine River Murray. A shallow but extensive lake now known as Lake Bungunnia (Firman 1965; Fig. 2B) was formed (also Twidale et al. 1978; Stephenson 1986; Stephenson & Brown 1989; Rogers 1995). At its greatest extent the Lake evidently overflowed to the south, via what is now the Wimmera River valley and the Douglas Depression, in southwestern Victoria (Bowler et al. 2006: eg. 182 & 203). At this stage the Lake must have inundated the shallow estuarine valley in which the Norwest Bend strata were deposited. But renewed uplift of the Marmon Jabuk structure caused this outlet to be blocked. Thereafter drainage to the sea was by way of an outlet at the southwestern margin of the water body, 'against Mount Lofty Ranges, just south of Nildottie' (Bowler et al. 2006: 203), which indicates a general location only, given that Nildottie is on the River and not close to the Ranges. This occurred 0.5–0.6 million years ago. Drainage was via a braided channel that coursed around the Mannum Loop, and carved its Gorge in response to a low (glacial age) sea level (Stephenson 1986; see also Tate 1884). As the River regressed northward through the Mannum Loop to the position of Walker Flat it breached the tectonic barrier that had impounded Lake Bungunnia. A flood of water would have been released.

Such an overflow would account for the side- or cliff-channels (Fig. 7A) standing 7–15 m above present river level and formed upstream from Pompoota as far north as Walker Flat (Thomson 1975; Twidale et al. 1978). At two sites, one on the right bank immediately upstream from Mannum (Fig. 3B), the other on the left bank opposite Lake Carlet and about 11 km downstream from Bowhill, the old valley side is scored by multiple interlaced channels (Fig. 7B & 7C). Cut in the Mannum Limestone, the channels are up to 10 m deep but are more commonly in the range 4-8 m. Some are simple channels that slope downstream, but others terminate abruptly, the water responsible for them presumably diverted into adjacent flows or sinking into the country rock. The channels are most likely relics of a braided sector of the River Murray (Thomson 1975).

A braided pattern is a typical response to high stream discharge (cf. Leopold & Wolman 1957) and the increase in depth downstream of the perched side channels is compatible with a flood rampaging through that section of the River. Braided streams are a response to flood discharges and are most readily and commonly developed in alluvia or unconsolidated detritus. Bedrock developments are, however, recorded. The Spokane Flood, for example, produced braiding in basaltic rocks and on a vast scale in the Channeled Scabland, northwestern USA (Baker 1973). In the case of Lake Bungunnia the flood breaching of the barrier near the present Mannum and that impounded Lake Bungunnia could have created a braided stream either in the unconsolidated Norwest Bend Formation and been imposed on the Mannum Formation limestone or it conceivably could have developed directly in the relatively weak calcarenite.


A
Scrubby Flat
Lake Carlet
BOWHILL
MANNUM
Pompoota
Cliff-channel
side-channel
River channel
Lagoon
N
0 2 4 km


B

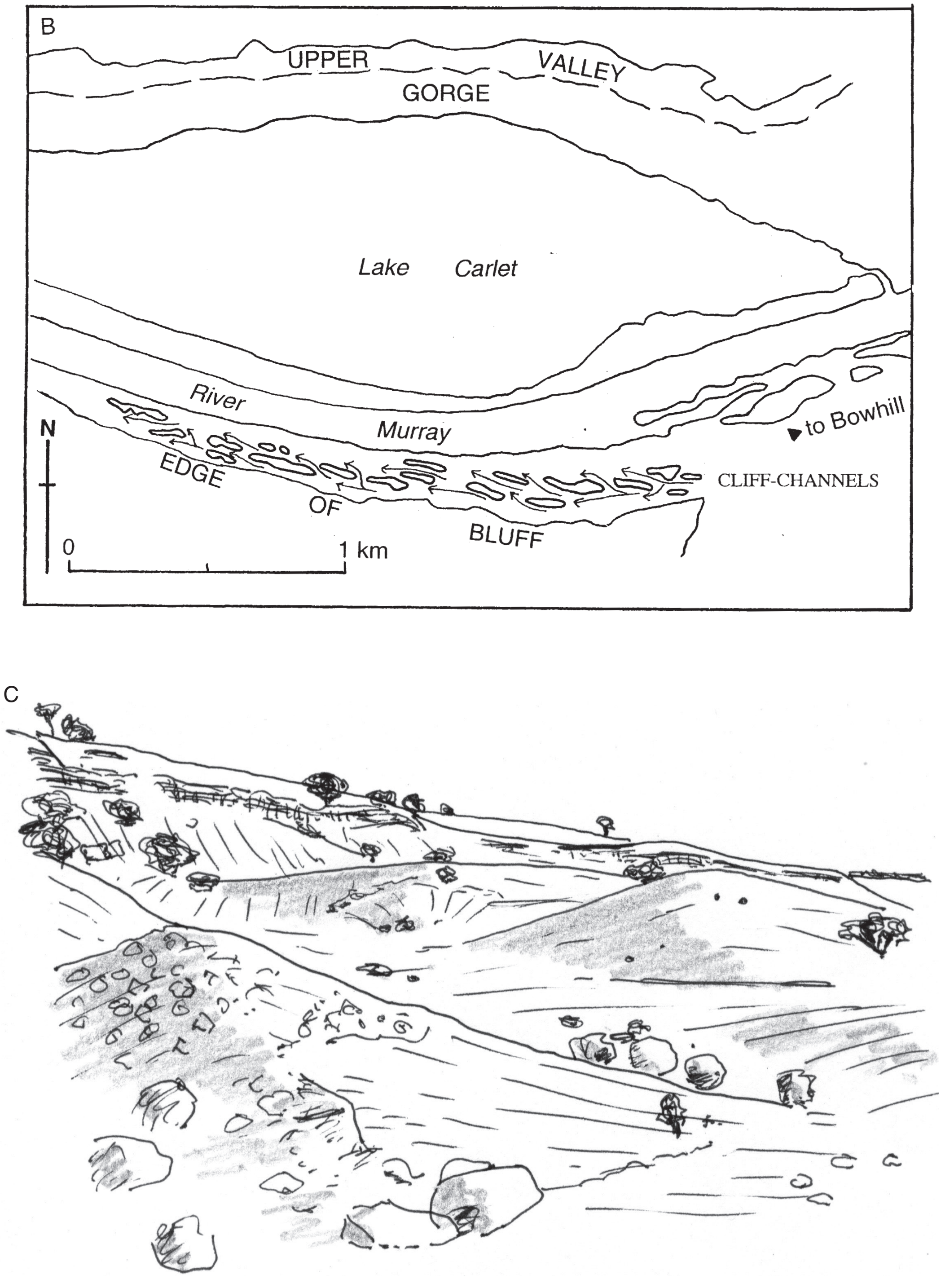


Fig. 7 (page 220 and above). (A) Distribution of side- or cliff-channels between Scrubby Flat and Pompoota (after Thomson 1975, fig. 2-49). (B) Vertical air photograph and explanatory diagram of side-channels and divides, left bank and downstream from Bowhill, opposite Lake Carlet. (C) Sketch of part of the complex.

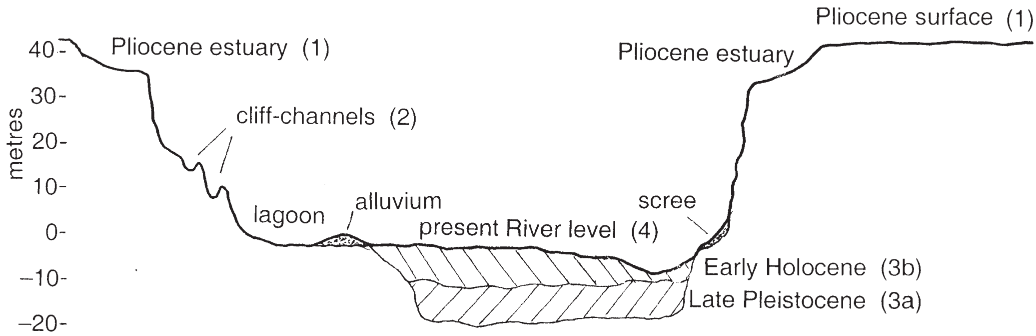


Fig. 8. Diagrammatic cross-section of the Murray Gorge in the Mannum Loop sector showing erosional and depositional chronology.

The braided section lies downstream from the confluence of the Marne River with the Murray. The Marne rises in the eastern Mt Lofty Ranges where it drains an area of granite and gneiss with abundant quartz. The river delivers sand to the Murray, thus increasing the abrasive capacity of the flow. Erosion of the sandy facies of the Norwest Bend Formation would further have enhanced its erosional capability. It is suggested that a flood of water so armed, scoured the channel and adjacent areas, and washed away most of the lightly lithified Norwest Bend Formation in the Loop sector.

Dissection of slip off slopes has also contributed, as has the rapid recent development of short streams tributary to the main river. They possibly originated as subsurface flows followed by sapping and roof collapse. This is suggested by their development across the chaotic topography found in the areas of multiple side channels near Mannum and Younghusband. The position of the cliff-channels shows that the lower Murray had already cut a deep channel when the overflow began, for they stand well below the level of the estuarine channel, several metres above the present valley floor, and some tens of metres above the deepest but now partly-filled valley (Fig. 8).

Firman (1973: 39) reported remnants of old stream channels beneath Ripon Calcrete and located high in the walls of the Gorge from various sites between Morgan and Murray Bridge. According to Brown and Stephenson (1991) the Ripon Calcrete is about half a million years old. If so, streams probably cut the then recently exposed bed of Lake Bungunnia. Assuming that the dating of the calcrete is valid, the Gorge sector upstream from Tailem Bend is less than 500,000 years old.

ORIGIN OF THE GORGE

At times of low sea level (baselevel; Fig. 9A) regional water table would have been lowered and drainage would have gone underground: a gorge could have developed, in part at least, as a result of solution and collapse of the roof of the caverns so formed in the pervious, permeable and soluble calcarenite. There may have been a transitional period when the inland waters maintained the channel developed in relation to higher baselevel, before tumbling into a deeper channel which was partly exposed, and partly underground (Fig. 9B). Gradually, however, the nick point migrated inland from the then coast and eventually broke through to the area near Overland Corner where the Miocene limestone outcrop gave way to alluvia. The gorge became the entity it now is, and the exoreic Murray captured the inland waters.

The meandering River eroded undercut bluffs where it impinged on the sidewalls of the Gorge. Slip-off slopes developed on the opposite side of the valley, but as the meander belt migrated laterally and simultaneously moved downstream, the valley floor and the Gorge were widened. The present valley floor with its meandrine channel, flood plains and lagoons dates from some 4000 years ago (Firman 1971b). The flood plain includes lagoons and arcuate remnants of earlier channels (ox bows) as well as the present river channel. Most of the meanders are smoothly curved but some are angular. These may have developed by the River in flood, when the meanders migrated rapidly downstream cutting across part of the next loop downstream. The highest flood since European settlement occurred in 1956 when the River stood some 7 m above its usual level, but a

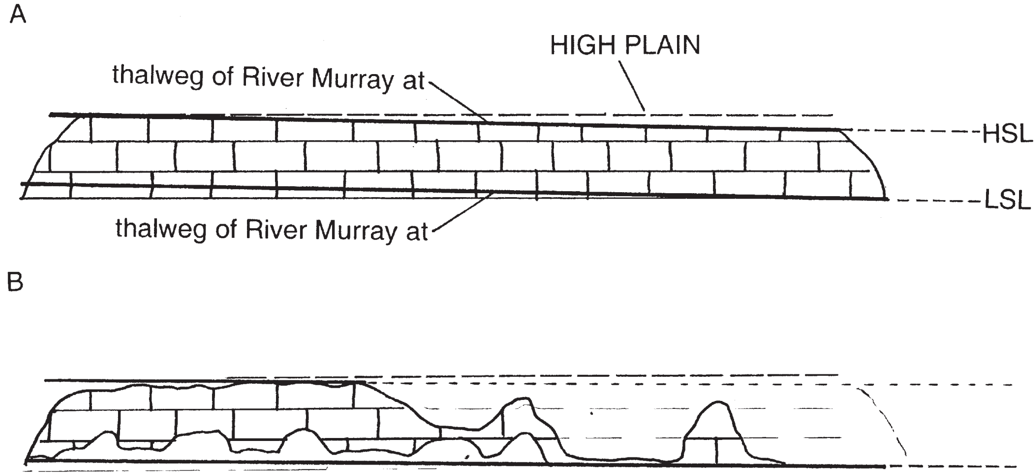


Fig. 9. Gorge development (A) by river erosion in relation to high baselevel, and (B) by solution and collapse when baselevel low.

slightly higher flood dating from some 3000 years ago is recorded in sediments exposed in an archaeological excavation near Walker Flat (Lawton et al. 1963; Mulvaney et al. 1964; Twidale 1964).

CONCLUSIONS

Previous explanations of the change in direction of the Murray from east-west to north-south in its gorge section have involved diversion by the Morgan Fault. This explanation is at odds with the field evidence. The change of course of the River is not coincident with the trace of the Morgan Fault, for the channel and valley lie up to 5 km to the east of the structure.

Of the various possibilities that can be suggested in explanation of the diversion and linearity of the River Murray and its valley below Morgan, underprinting determined primarily by the exploitation of basement fractures seems the most likely. Joggling of the basement, and concentration of groundwater and resultant dissolution over basement fractures or other structural weaknesses, provide possible explanations for the linear stream sectors. Given the calcareous nature of the country rock the latter is the most likely. Whatever the precise mechanism in any given sector of the river, underprinting provides a solution for the paradox presented by structural control that is not visible at the surface.

This analysis appears to be based in the Holmesian maxim that when one has excluded the impossible, whatever remains, however improbable, must be the truth (Doyle 1928 [1892]: 273). Rather is it a case of nothing being sure and thus everything possible. But the underprinting hypothesis is more than last chance. It is compatible with the salient field data. It accounts for the development of an ancestral exogenic River Murray that, as implied by Williams and Goode (1978), captured the inland drainage entering the region from the east, causing this runoff to be diverted to the SSW and the ocean. Pleistocene rejuvenation and gorge development extended upstream beyond North West Bend to the vicinity of Overland Corner, capturing the inland drainage.

Underprinting accounts for the linear sectors of the River between Morgan and Swan Reach and from Tailem Bend southwards. The Nildottie and Bowhill easterly diversions referred to earlier can be explained in terms of underprinting from fractures revived and opened by recurrent uplift of the Marmon Jabuk structure, which diverted the River to form the Mannum Loop. Reactivation of the Marmon Jabuk structure accounts also for the formation of Lake Bungunnia, the draining of which is attributed to incision and regression of the River at times of low sea level. These interpretations are consistent with the known relative ages of various landscape elements.

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