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The Great Cumbung Swamp — terminus of the low-gradient Lachlan River, Eastern Australia

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The Lachlan River rises in the humid highlands of southeastern Australia and flows westward into the Murray Basin. The climate is sub-humid to semi-arid and, as it crosses the Murray Basin, the Lachlan loses most of its discharge through evaporation and infiltration. Unlike most river terminations, the Lachlan ends in the Great Cumbung Swamp without dividing into distributaries; neither are there large fresh-water lakes nor playas. Only during floods, occuring in 15–20% of years, does Lachlan water flow past the swamp into the Murrumbidgee River to the south. The swamp water remains fresh because salt is lost with water that infiltrates into underlying aquifers. This water loss causes the river to terminate because it reduces stream competence and prevents the Lachlan from forming a lake which could then overflow and breach the low topographic barriers that defeat it.

The Great Cumbung Swamp is divided into three depositional environments:

- The Lachlan channel is sinuous and up to 40 m wide. It shows morphology equivalent to cut-bank and point-bar morphology when it first enters the swamp but becomes straight as it reaches the central, lowest part of swamp. Its most distal reach is sinuous with a slight upstream bed gradient.
- Phragmites Marsh: Most of the Great Cumbung Swamp is marsh colonised by *Phragmites australis*. Very slight topography controls flood frequency and degree of desiccation, and hence *Phragmites* growth. The marsh displays a dendritic texture resembling small-scale drainage networks possibly formed by floodwater etching out micro-relief developed on the deep-cracking flood plain clays. Within the *Phragmites* marsh are bodies of open water less than 0.75 m deep connected to the main channel through breaches in the levees. The lakes grade into the surrounding marsh with a gradual increase in the density of *Phragmites* clumps.
- Overflow areas: The Great Cumbung Swamp proper is surrounded by alluvial plain colonised by scrub and eucalypts. It is underlain by black to grey deep-cracking clays. Traversing this plain are anastomosing channels that carry water from the swamp to the Murrumbidgee during floods. These channels are slightly sinuous and up to 20 m wide, 1 m deep, and have symmetrical cross-sections.

Great Cumbung Swamp sediments are largely black clays with those deposited in the *Phragmites* marsh being extensively bioturbated by roots. The development of pedogenic textures and preservation of organic matter depends on the frequency of desiccation. The Lachlan channel accumulates massive black clay with only a few thin sandy beds in the upstream reach. These sandy beds probably drape the channel bottom during the falling stage.

The Lachlan River in the Great Cumbung Swamp has a very low gradient and provides an example of fluvial deposition at the lowest end of the energy spectrum. Ancient analogues for this style of river termination will probably be found in fine-grained sediments interpreted as flood plain or lake deposits. Other deposits interpreted as deltaic, but for which no connection with lake or marine deposits can be demonstrated, may also be the deposits of swamps. Some sediments in the Triassic to Jurassic basins of the eastern U.S.A. may be good analogies.

Introduction

In many dry parts of the world, rivers lose their capacity to transport sediment and maintain their channels and so terminate on land (Ori, 1989). Low-gradient terminal fans can develop in arid regions where water loss and slope reduction causes sediment deposition. The river channels lose their identity, with water dissipating in distributive channel systems (McCarthy et al., 1991) either as sheet floods (Bull, 1972) or spreading out in playas (Hardie et al., 1978).

The Lachlan River of eastern Australia differs from such terminations in that it maintains a single channel as it dissipates in the Great Cumbung Swamp. It represents a low-gradient, suspended load end-member in the range of inland river terminations. This paper reviews published hydrological information and gives a reconnaissance description of the Great Cumbung Swamp comparing its geomorphology and sediments with those of other river terminations documented in the literature. It also summarises the characteristics that might identify such deposits in the rock record, comparing these with a possible Mesozoic analogue in the eastern USA.

Methods

Environments within the Swamp were delineated from satellite imagery (LANDSAT TM) and aerial photographs. Field inspections were undertaken using an aluminium dinghy. Deeper channel environments were studied and sampled using SCUBA. Precise surveying was undertaken by the Australian Survey Office. Salinities were measured in the field using an American Optics hand-held refractometer. Short cores were obtained in order to characterise the deposits of various environments, using the method of Tratt & Burne (1980).

Regional setting

The Riverine Plain of southeastern Australia comprises the fluvial plains of the Murray, Murrumbidgee, Goulburn and Lachlan Rivers and their tributary and distributary streams in southern New South Wales and northern Victoria. It is about 77 000 km^2 in area, and lies between the hilly water-shedding regions of the east and south, and the low, undulating, wind-worked semi-arid lands on the west and northwest (Fig. 1; Butler et al., 1973). When viewed on satellite images, the rivers of the Riverine Plain can be seen to have constructed broadly fan-like alluvial plains (Fig. 1a). The very low gradients of the streams and their alluvial plains make application of the term alluvial fan inappropriate. In general, the Riverine Plain has gradients of about 1 in 2000, but along the Lachlan and Loddon Rivers are as low as 1 in 7000.

The Lachlan River has constructed an alluvial plain by nodal avulsion from the point it leaves its bedrock valley. Surrounding the Lachlan alluvial plain to the west are fields of inactive Pleistocene dunes and relict groundwater discharge lakes with their accompanying clay dunes (lunettes; Brown & Stephenson, 1989). The Great Cumbung Swamp lies at the termination of the Lachlan River

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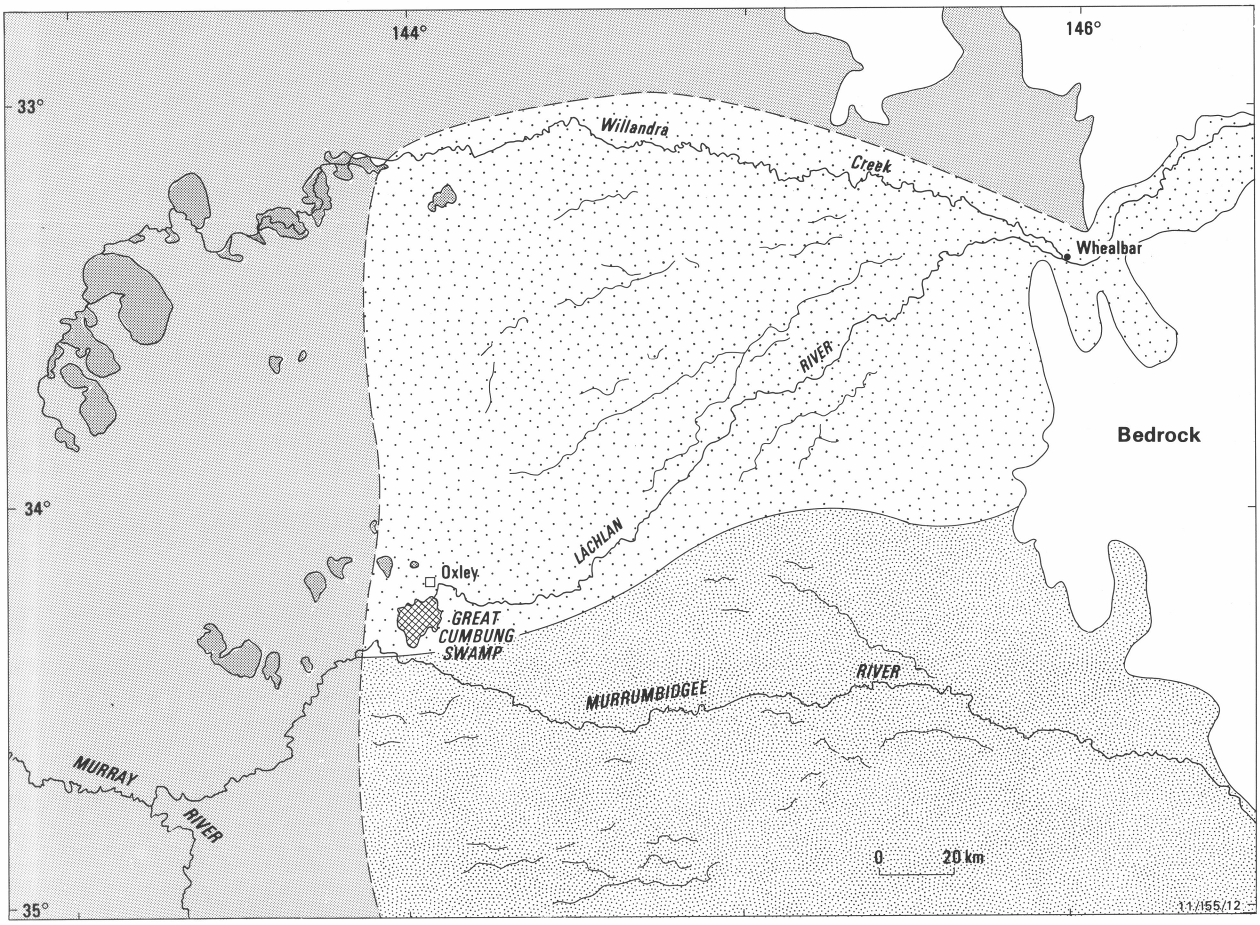
on the Riverine Plain (Fig. 1a; Oxley, 1820). Lachlan water flows into the Murrumbidgee River only during floods.

The geological history of the Riverine plain has been described by Brown & Stephenson (1989). The long continued action of the streams is signified both by the depth of alluvium accumulated on the Riverine Plain and by the presence, close to the present courses, of Upper Miocene and Pliocene buried channels (palaeochannels; Butler et al., 1973). A drill hole adjacent to the Cumbung Swamp (39°19′09″S, 143°58′39″E; Kellett, 1992a) shows that swamp and lake sediments extend down to the base of the Calivil Formation (early Pliocene) at 78 m below the surface. This is quite deep for the Murray Basin in which the total Cainozoic section is less than 600 m thick, supporting the conclusion that the underlying basinal structure, the Balranald Trough, is subsiding (Kellett, 1989). The age of the present course of the Lachlan River is several thousand years (Adamson et al., 1987). The



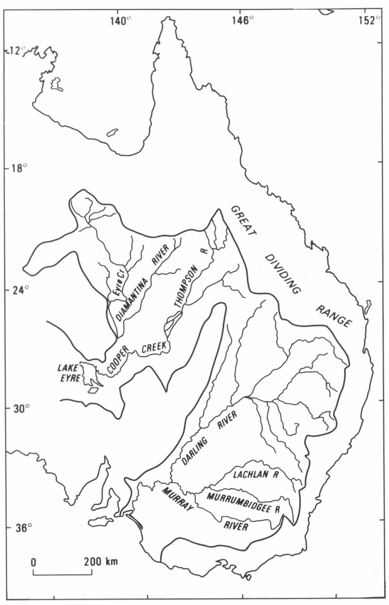


Figure 1a,b. Generalised map of the low-gradient fan-like alluvial plain of the Lachlan River in the Murray Basin.
The Lachlan alluvial plain is bounded in the east by bedrock outcrop, in the south by alluvium of the Murrumbidgee River and to the west and north by Quaternary aeolian sand sheets and dune fields (generalised from Brown & Stephenson (1989). The Riverine Plain is a term applied to the alluvial plain constructed by the Lachlan, Murrumbidgee and Murray Rivers and their tributaries. The insert shows west-flowing river systems in eastern Australia. Low-gradient streams are common in both the Cooper's Creek system and the Murray–Darling system (Schumm, 1968; Taylor & Woodyer, 1978; Rust, 1981; Alam, 1983).

swamp depression has not filled in that time, suggesting that sedimentation rates have been low.

Climate and hydrology

The Lachlan River rises in the Great Dividing Range of eastern Australia (Fig. 1b) and has a catchment of about 80 000 km^2. The catchment climate is sub-humid with rainfall between 600 and 800 mm/yr throughout (Parkinson, 1986). It flows into an area of semi-arid climate; average annual rainfall at Oxley, just upstream from the Great Cumbung Swamp is 282 mm with Mean evaporation 1580 mm/yr (Pressey et al., 1984). The annual variation in stream flow is considerable, with climatic fluctuations on a scale of years caused by the Southern Oscillation being more significant than simple seasonal variations (Adamson et al., 1987). Consequently, the river's mean annual discharge is more meaningful than a volume per second figure. The river's mean annual discharge reaches a maximum of 990 x 10^9 L/yr where it flows into the Murray Basin (Pressey et al., 1984). On leaving the semi-humid ranges, the river enters the semi-arid climate of the Murray basin and starts to lose water by evaporation, infiltration, and irrigation-diversion. By the time it reaches Oxley, the Lachlan River has a mean annual flow of 166 x 10^9 L/yr. This reduction takes place over approximately 220 km of valley according to Pressey et al. (1984), and they estimate peak flood flow velocities for the Lachlan River at Oxley reach 0.3 m/sec.

Though most maps show the Lachlan River flowing in a single channel into the Murrumbidgee River southwest of the Great Cumbung Swamp, Lachlan water only reaches the Murrumbidgee during floods which occur in 15 to 20% of years. The rest of the time, the Lachlan dissipates in the swamp. Low flow dominates in 50% of years, so that for periods of 2 to 4 consecutive years flow at Oxley may average less than 100 x 10^9 L/yr, and periods of no inflow into the Great Cumbung Swamp of 6 months or more occur in 10% of years. Despite this, the swamp always remains fresh with salinity generally less than 1 ppth. The highest reading obtained during our survey, which followed a long period of low flow and low rainfall, was 2 ppth in a shallow lake on the swamp margins (North Lake; Fig. 2b). Even lakes dry during of our visit (e.g. Lignum Lake; Fig. 2b) showed no sign of evaporites within 1 m of the surface.

The pattern of older river courses, which are clearly recognisable on air photos of the alluvial plain (Fig. 2a), suggests that it has shifted by the river avulsing and reoccupying old courses rather than by systematic migration of the meanderbelt (Butler, 1950; Wells & Dorr, 1987). About 15 x 10^3 years B.P., the stream switched from Willandra Creek at the northern margin of the fan to progressively more southern courses, finally reaching its present position along the southern margin in the last few thousand years (Adamson et al., 1987). All courses of the Lachlan are very low gradient (the present one has a valley slope of 0.0002) and all are highly sinuous (usually greater than 2), so that channel slopes are lower still.

When not in flood, the Lachlan River looses most of its water in the swamp. Pressy et al. (1984) estimate that the average input from the river and local rainfall exceeds evaporation and transpiration by about 3 x 10^9 L/yr. Maintenance of low salinities, even after long periods of low inflow, suggests significant losses to aquifers beneath. Groundwater mounds in the Shepparton and Calivil Formation aquifers beneath and adjacent to the swamp (Kellett, 1989, 1992a,b) show that the Great Cumbung Swamp is a significant source for the regional unconfined aquifers of the Balranald Trough.

The Lachlan River is suspended-load dominated. The first European to visit the area, John Oxley remarked on July 5th, 1817 "I must observe as a remarkable feature in this singular country, that for the last 50 miles we have not seen a stone or pebble of any kind, save two, and they were taken out of the maws of emus" (Oxley, 1820). Our sampling of the river bed found a similar lack of particles coarser than medium sand; the coarsest particles being rare carbonate nodules up to 4 mm across. Long-term rates of sediment transport into the swamp could not be estimated during our visit because inflow was essentially zero at the time and because present suspended sediment concentrations are strongly influences by filter-feeding European carp that invaded the Lachlan River in 1974 (K. Harris, pers. comm., 1988). These fish re-suspend significant quantities of silt and clay from the river bed.

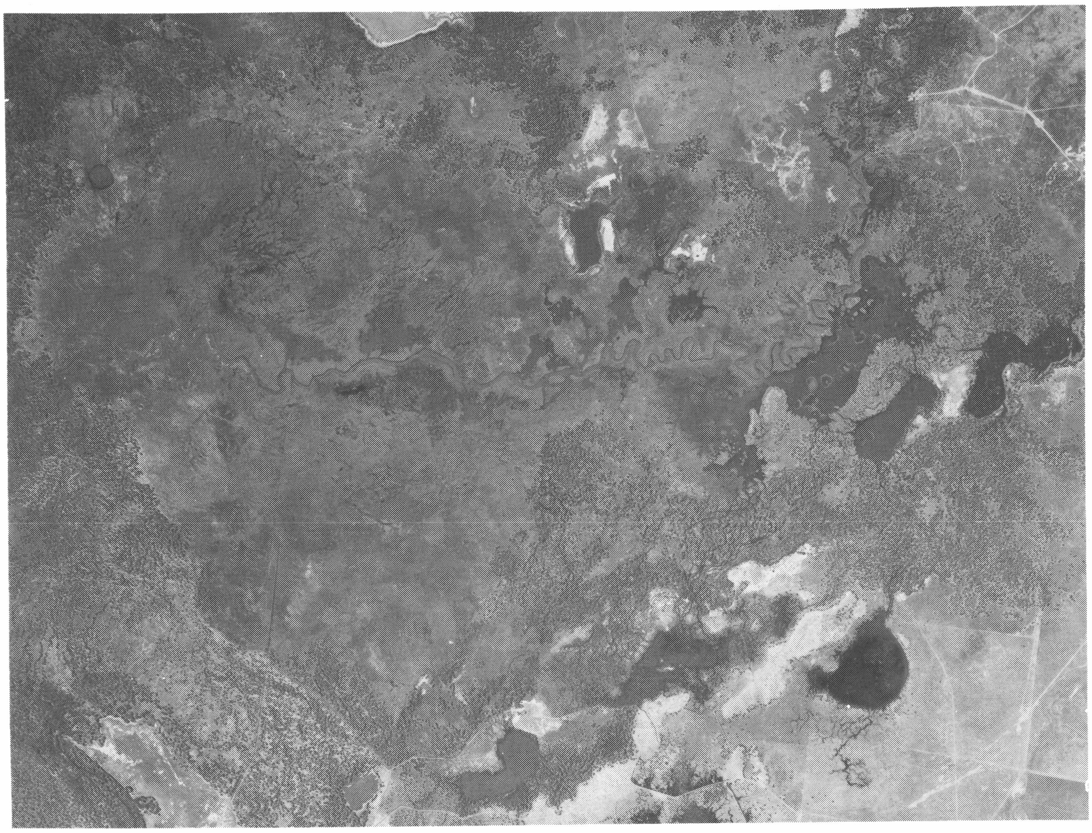
Depositional environments

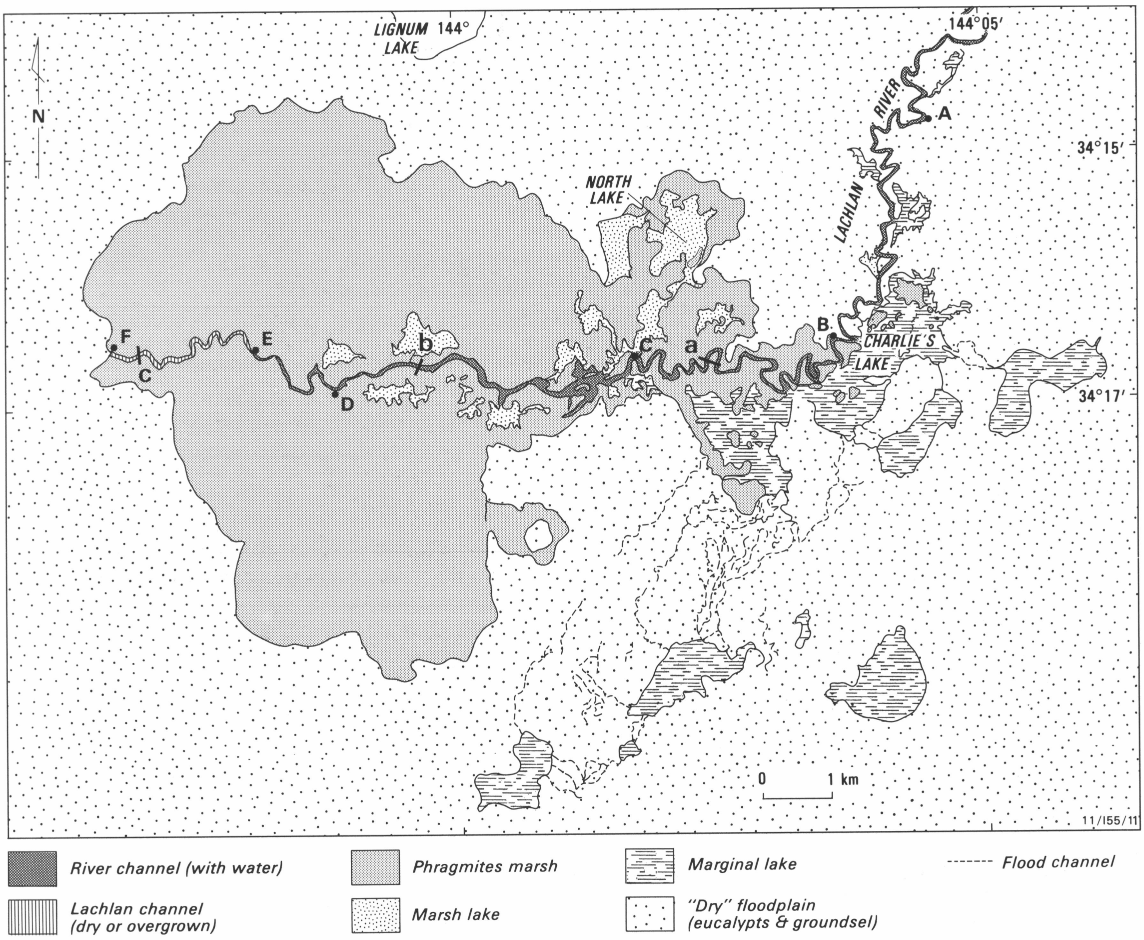
Three depositional environments are distinguished: the Lachlan channel; the *Phragmites* marshes; and marginal lakes and alluvial plains (Fig. 2b).

The Lachlan channel

Upstream of the swamp, the channel is sinuous (P = 2.15), 20 m wide and 1.5 to 2 m deep, with low levees about 0.3 m above the flood plain. At Oxley, the channel has steep cut banks on the outside and upstream side of bends, and more gently sloping downstream sides with cumbungi (*Typha orientalis*) colonising the shallow water up to 2 m out from the bank. Farther downstream, the cutbank disappears and *Typha* grows on both sides of the channel. As the channel approaches the swamp, first backswamps containing standing water and colonised by *Typha* develop (Fig. 2) within the dry flood plain. Still farther downstream, the flood plain becomes wetter and is colonised by *Phragmites australis*. A 1 m core from the channel bed upstream of the swamp (Fig. 6a) shows an upper layer of dark-grey, fluid clay about 0.12 m thick with scattered fragments of fibrous plant matter. This clay grades downwards becoming very dark-grey to black, stiff and massive, with a few ferruginous nodules up to 10 mm in diameter. Spherical gas bubbles 5 mm in diameter develop, which then flatten with depth. Two beds of sandy clay 60 and 75 mm thick, consisting of 20 to 30% fine to medium sand, with a few small calcite-cemented nodules several millimetres across, are the coarsest sediments in the entire depositional system.

The upstream reach of the swamp channel is still sinuous (P = 2.25) and widens to 30 to 40 m. It shows morphology equivalent to cut-bank and point-bar morphology in that the upstream banks of the meanders are steeper, and slightly deeper than the downstream banks. Initially, the channel is fringed by 1 to 3 m wide belts of *Typha,* but farther into the swamp this is replaced by *Phragmites* growing in a stand up to 2 m high with a straight edge on the upstream bank (Fig. 4). However, on the downstream bank it grows in clumps presenting a ragged edge to the channel (Fig. 4,7). Floating clumps of *Phragmites* are common on the downstream sides of bends, but rare on upstream sides. Where this asymmetry is developed, the channel cross-section is also asymmetric (Fig. 3a).




LIGNUM LAKE
144°
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N
A
34°15′
LACHLAN RIVER
NORTH LAKE
B
CHARLIE'S LAKE
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C
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b
D
c
a
34°17′
0
1 km
11/I55/11
River channel (with water)
Lachlan channel (dry or overgrown)
Phragmites marsh
Marsh lake
Marginal lake
"Dry" floodplain (eucalypts & groundsel)
------ Flood channel

The channel is about 0.7 m deep on the downstream side adjacent to the phragmites and, near the opposite, upstream-facing bank, it is up to 1.5 m deep.

The sinuous reach of the swamp channel is flanked by low levees with crests 0.1 to 0.2 m high behind the tall *Phragmites* on the channel margin. The *Phragmites* that colonises the levees and flood plains is shorter and less luxuriant than that of the channel margin. Breaches in a few places feed water into marginal lakes (Fig. 2). These breaches are only a few tens of centimetres deep and up to 10 m wide, and overgrown with *Typha*.

A core taken from a dry levee crest with extensive desiccation cracks has the topmost 0.3 m consisting of chocolate-brown clay with a granular texture, abundant fine rootlets and large Phragmites roots and stem fragments (Fig. 8a). With depth, stem fragments disappear, although large vertical *Phragmites* roots are still plentiful, as are their accompanying horizontal hair rootlets. From 0.2 m below the surface, the clay has pellets with shiny surfaces. The upper pellets are 1 mm in diameter, but with depth attain diameters of 4 mm.

The channel passes downstream into a low-sinuosity reach (P = 1.15) and widens to 50 to 60 m. Here it has a symmetrical cross-section (Fig. 3b), reaching a maximum depth of 1.2 m in the centre. Its margins are lined with a discontinuous belt of *Typha* standing in 0.6 to 0.8 m of water. Levees are less distinct than along the sinuous swamp channel. At the time of examination, the *Phragmites* beds beside channel were covered with shallow water, though the separation of marsh lakes from the channel by these *Phragmites* beds (Fig. 2) indicates that they are growing on subdued levees. The channel merges with marsh lakes through broad breaches in the levees, which are less choked with *Typha* than are breaches farther upstream.

The low-sinuosity channel reach is floored by grey fluid clay 0.17 m thick with very fine organic fragments (Fig. 6b) becoming darker and firmer with depth, with the lower 0.3 m containing gas bubbles and larger plant fragments. With depth, this grades into a stiff, dark browny-grey clay, 0.14 m thick, with a granular "sandy" texture due to distinct pellets 1 to 3 mm in diameter. These peds become larger with depth, reaching a diameter of 10 mm near the bottom of the bed which eventually grades into stiff, massive dark-grey clay.

The low-sinuosity swamp channel progressively narrows towards the distal end of the swamp, increasing in sinuosity (P = 1.36) and decreasing in width; finally reducing to an ephemeral channel about 10 m wide and 1 m deep (Figs. 2, 3c). In places, *Typha* grows across the channel. Sediments of this channel show a similar gradation from chocolate-grey, fluid clay to stiff clay with depth (Fig. 6c) to those of upstream channel reaches. Distal swamp channel sediments contain abundant plant fragments that are mostly fine and fibrous, but with some large horizontal stems present in the upper 0.35 m; vertical roots are scattered through the lower 0.83 m of the core, as are yellow patches up to 20 mm across with charcoal fragments.

A topographic survey of the Great Cumbung Swamp included levelling of both the water surface and the channel-bed elevation at the mid-point of the Lachlan channel at numerous locations. Although the elevation of the channel mid-point does not give the thalweg elevation in the sinuous parts of the channel, this data does indicate the trend of bed elevations (Fig. 5). The bed has slight upstream gradients in the distal sinuous and straight reaches, supporting the view that channel shaping processes in these reaches are driven purely by the water-surface slope induced by flood waves. Taylor & Woodyer (1978) reached the same conclusion for the low-gradient Barwon River.

The morphology and sediments of the three reaches of the Lachlan channel within the Great Cumbung Swamp suggest some possible causes of the observed channel patterns. Meandering channels require sufficient flow velocities to produce secondary flow in bends and flow velocities sufficient to erode the concave banks (Richards, 1982). In the sinuous upstream channel reach, the concave banks are steeper and lined by a narrow continuous stand of *Phragmites,* and the downstream-facing side of the channel slopes gently up to shallow marsh colonised by clumps of *Phragmites*. This suggests that sediment and floating clumps of *Phragmites* are eroded from the upstream-facing side of bends and deposited on the downstream-facing side (Fig. 4). A comparison of channel patterns on air photos and satellite images showed no apparent channel migration, suggesting that erosion rates and hence channel migration rates are low. Air photos do not reveal scroll bars or other clear evidence for bend migration, but they do show that upstream-facing banks have narrower levees than downstream-facing banks that may indicate progressive erosion of the upstream-facing bank.

Because of very low gradients and associated velocities, the low-sinuosity reach appears not to erode its banks, but rather to experience flows just sufficient to remove within-channel sediments, thereby preventing colonisation by *Typha* and *Phragmites* and so maintaining a recognisable channel. In contrast, the downstream sinuous reach is characterised by resumption in meandering. The channel here contains stagnant water, except during floods when the water slope induced by a flood wave is sufficient to force water past the low-sinuosity reach and up the slight upstream slope of the channel bed (Fig. 5). Under such conditions, secondary flow and minor bank erosion must be sufficient to cause gentle meandering. Between floods, this reach is shallow enough to be encroached upon by *Typha* and *Phragmites*.

The *Phragmites* marshes

The most extensive environment of the Great Cumbung Swamp is marsh colonised by *Phragmites australis* (Figs. 2, 7). The limits of the marsh are defined by flood frequency, hence by elevation and minor topography, with the *Phragmites* marsh edge usually at an elevation of about 71 m AHD (Australian Height Datum). Maximum water depths are in the order of 0.3 m. Very slight topographic variations control the distribution of the marsh vegetation, with the height and vigour of the

Figure 2a,b. Aerial photograph and map of environments of the Great Cumbung Swamp.
Photograph is a black and white rendition of a colour infra-red negative.
Stream flow is from right to left (east to west). Dendritic surface texture is best developed in the northeast corner of the *Phragmites* marsh. Locations a, b and c are channel cross sections shown Figure 3. Channel reaches are: **A–B**. Lachlan channel upstream of swamp. **B–C**. Sinuous swamp reach. **C–D**. low-sinuosity swamp reach. **D–E**. Distal sinuous reach.

Phragmites apparently controlled by water availability and degree of desiccation.

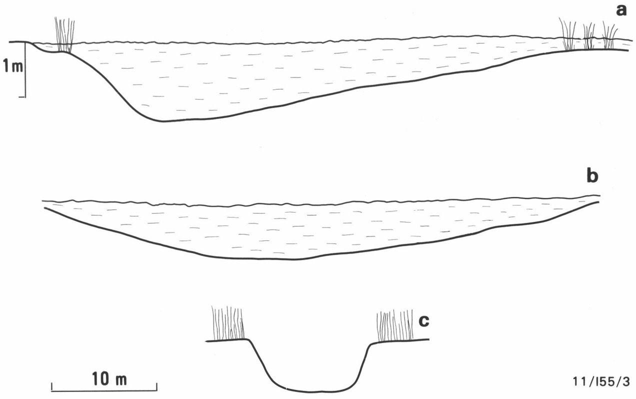

Figure 3. Sketch channel cross-section, Great Cumbung Swamp.
Locations of cross-sections shown on Figure 2. **a**. Sinuous swamp reach. This reach show asymmetry similar to channels with point bars. **b**. low-sinuosity swamp reach. **c**. Distal sinuous reach.

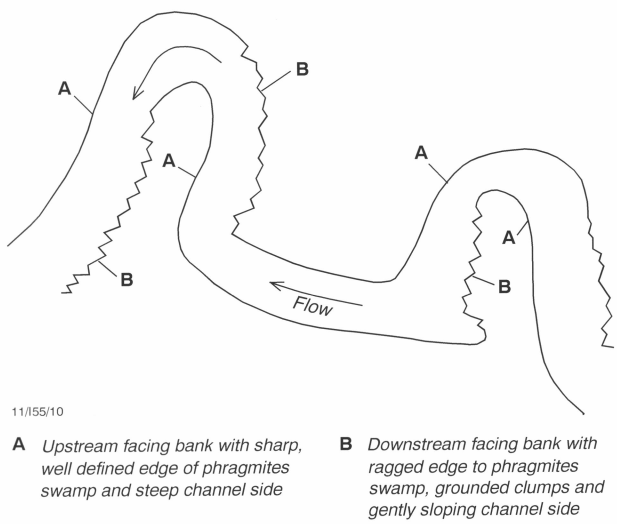

Figure 4. Bank types on the Lachlan River channel in the Great Cumbung Swamp.
A. Upstream-facing bend with sharp, well-defined edge of Phragmites marsh and steep channel side. **B**. Downstream-facing bank with ragged edge to Phragmites marsh, grounded detached Phragmites clumps and gently sloping channel floor.

From the air, the *Phragmites* marsh displays a dendritic texture resembling small-scale drainage networks (Fig. 2a). These network textures are also present in less-vegetated flood plain areas surrounding the marsh, though less clearly visible. The network pattern is not apparent to an observer on the ground. They may be small drainage networks formed by receding floodwater etching out micro-relief formed on by the deep-cracking flood plain clays (Vertisols; U.S. Soil Survey Staff, 1975) and appear to be characteristic of such clays on semi-arid and arid flood plains in Australia (Rust, 1981). Multi-spectral analysis of LANDSAT data indicates that parts of the marsh with these networks are drier than those without, so that they are slightly more elevated. Because they are more elevated, desiccation cracks are probably better developed.

A core taken within the inundated *Phragmites* marsh has a top 70–150 mm of a poorly compacted spongy mass of clay and rotting vegetation penetrated by abundant fibrous rootlets (Fig. 8b), with total organic carbon content 10% dry weight. This overlies black clay with abundant stem fragments and fibrous rootlets, which in turn overlies a layer with abundant large horizontal rhizomes and rootlets. The lower 0.5 m of the sequence is massive black clay, with vertical roots 2 to 3 mm in diameter and horizontal fibrous rootlets.

Within the *Phragmites* marsh are bodies of open water. These marsh lakes are close to the straight reach of the Lachlan channel and are connected to the channel through breaches in the levees. The lakes grade into the surrounding marsh with a gradual increase in the density of *Phragmites* clumps. Some lakes have clusters of *Phragmites* clumps well out from their margins also. The lakes examined were less than 0.75 m deep and had low salinity water.

Marsh lakes are typically floored by a thin layer of soft dark-brown to black clay with fine plant fragments, passing down into black clay with 1 to 5 mm diameter pellets (Fig. 9 a,b). The deeper parts of both marsh lake cores contain calcite-cemented nodules 1 to 5 mm in diameter, sometimes concentrated in bands. Fibrous rootlets are also present, though not abundant.

Marginal lakes and alluvial plains

On the edges of the Great Cumbung Swamp proper are a series of lakes which differ from the marsh lakes in that they are not surrounded by extensive *Phragmites* marsh but by drier flood plain colonised by groundsel and eucalypts. Some of these lakes are at least partly formed on older alluvium. For example, Charlie's Lake is ponded by older, sandy alluvium on the southeastern

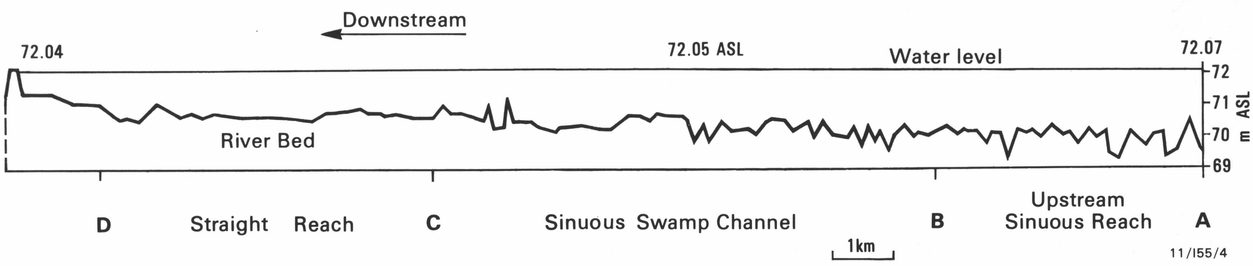

Figure 5. Channel mid-point elevations along the Lachlan in the Great Cumbung Swamp indicating the general upstream slope of the channel.

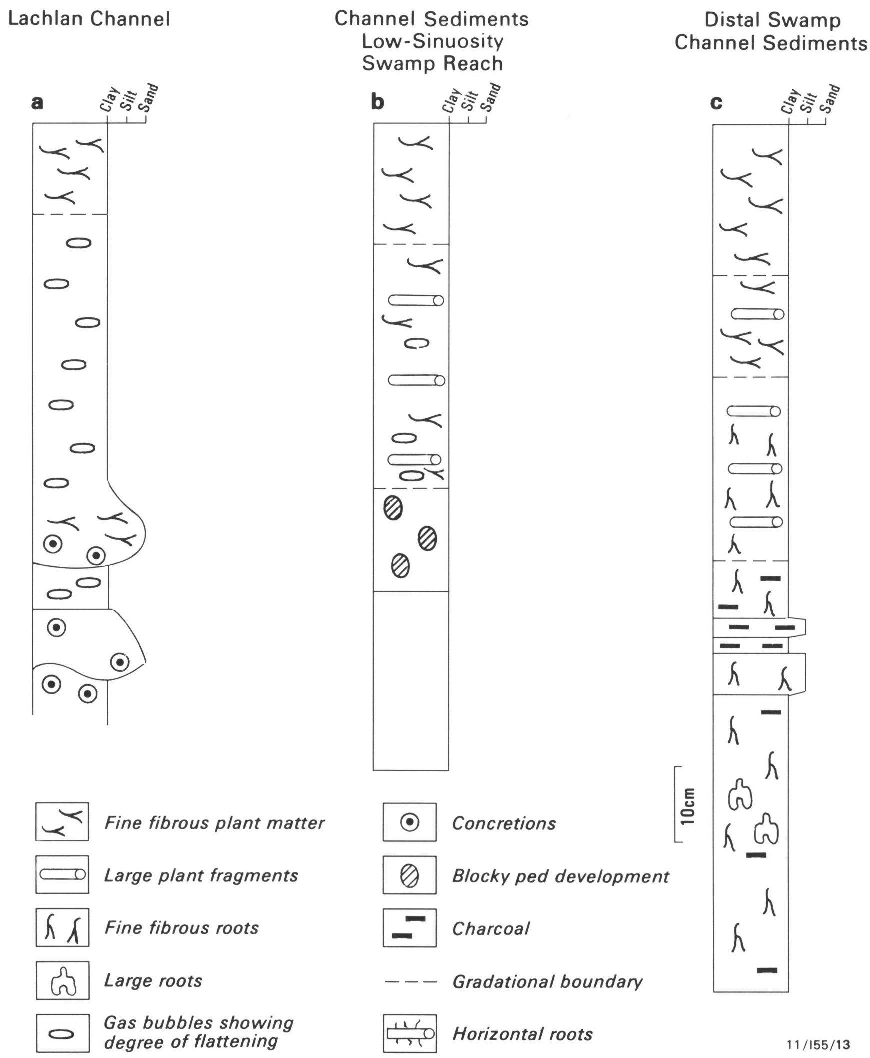

Figure 6. Core logs of channel sediments, Great Cumbung Swamp.
a. Core from Lachlan channel near Locality A, Figure 2. **b**. Core from Lachlan channel near Profile b, Figure 2. **c**. Core from channel just up stream from Locality E, Figure 2.

side and by the levee of the Lachlan on the northwestern side. These marginal lakes are fed by levee breaches and overflow channels, some of which have been enhanced by human interference. The more permanent lakes are fringed by *Typha* and some *Phragmites* stands. Some have large clumps of *Typha*. The more remote lakes such as Lignum Lake are more prone to desiccation, have no aquatic vegetation, but show no evidence of evaporite accumulation.

Figure 7. *Phragmites* marsh viewed from the Lachlan channel. Channel edge is downstream-facing with clumps of *Phragmites*.

The Great Cumbung Swamp proper is surrounded by alluvial plain colonised by bushy groundsel (*Senecio cunninghamii*) and river red gums (*Eucalyptus camaldulensis*). It is underlain by black to grey deep-cracking clays. Traversing this plain are two types of channel: the fine dendritic networks already mentioned in the description of the *Phragmites* marsh and anastomosing channels (Fig. 2) that carry water from the Great Cumbung Swamp to the Murrumbidgee during floods. These channels are slightly sinuous, up to 20 m wide and 1 m deep with symmetrical cross-sections. The Lachlan channel itself degenerates into such a channel, but is more sinuous. These anastomosing channels connect some of the distal, marginal lakes with the Great Cumbung Swamp. Excavation of tree roots along them indicates they are erosional features, probably cut during rising flood stage before the establishment of sheet flow across the entire area.

Discussion

Sedimentation in the Great Cumbung Swamp is largely by vertical accretion of clay and silt from suspension. The few sandy beds found in the Lachlan channel are probably draped over the river bed during falling stage of large floods (cf. Taylor & Woodyer, 1978). The extent, if any, of lateral accretion associated with the channel sinuosity is unknown.

Sediments of the Great Cumbung Swamp consist almost entirely of black to grey clays composed mostly of clay to silt-sized quartz and smectite with minor kaolinite and illite present. When dry, these vertisols (U.S. Soil Survey Staff, 1975) clays develop networks of deep cracks, some up to 0.2 m wide. In spite of their apparent uniformity, there are subtle variations in texture, organic content, and colour between the different depositional settings.

The clay beds of the *Phragmites* marsh and of the vegetated levees are both bioturbated by roots and have a relatively high content of plant remains. Clays which shrink and crack on desiccation accumulate in areas that dry out frequently. Evidence of pedogenesis, including blocky and granular structures, result from cyclic volume changes due to repeated wetting and drying (Brewer, 1964; Butler, 1976; Nanson et al., 1986). These structures are best developed in sites such as levees and distal parts of the marsh experiencing regular drying and wetting. The presence of such structures at depth in the cores from the low-sinuosity channel reach and marsh lakes may reflect burial of the previous flood plain by channel clays or, alternatively, may reflect a previous hydrological regime in which the deepest parts of the swamp were prone to desiccation.

The facies architecture of the Great Cumbung Swamp, shown schematically in Figure 10, comprises massive, organic-rich, clay lenses deposited in the swamp channels and the deepest marsh lakes and widespread beds of root-bioturbated clay deposited in infrequently desiccated marsh. This association grades outwards into clays showing increasing evidence of desiccation and pedogenesis, such as relict blocky textures and colour mottling and less organic matter. The Lachlan channel accumulates massive black clay with only a few thin sandy beds in the upstream reach that probably drape the channel bottom during the flood falling stage. Therefore, in an analogous system with slightly more sand input, channel bed-parallel sand drapes (Taylor & Woodyer, 1978) may be characteristic of channel fills. Drier flood-plain facies will gradually replace the wetter marsh and lake facies as the depression fills (Fig. 10).

Ancient analogues of this facies model will probably be found in fine-grained sediments interpreted as flood-plain or lake deposits. Other sediments interpreted as deltaic, but for which no connection with lake or marine deposits can be demonstrated, may also have originated in inland river terminations similar to the Great Cumbung Swamp. The deposits of marshes could contain remains of freshwater crustaceans, molluscs, and fish. Tracks of vertebrates could be preserved in levee or marsh sediments when nearly dry.

Smoot & Olsen (1988) described the Newark Supergroup in the Triassic to Jurassic basins of the eastern U.S.A. that include widespread mudstone with features suggestive of similar depositional environments to the Great Cumbung Swamp. In particular, they describe root-disturbed massive mudstone with abundant fine root casts, deep mud cracks, burrows, and pedogenic carbonate nodules strongly reminiscent of the *Phragmites* marsh clays in the Great Cumbung Swamp. The Newark Supergroup includes channel fills of fine sandstone that feature abundant root casts, burrows and sedimentary structures suggesting deposition by vertical accretion during occasional periods of high flow (Smoot & Olsen, 1988, their fig. 10–19). Thus, although the depositional system carried sand, these Newark Supergroup channels probably had similar regimes to the distal Lachlan River. Massive mudstones in the Newark Supergroup feature burrows and lacustrine fossils associated with deep mud cracks. This combination of structures might be expected from either marsh lake sediments or broad channels that dried out occasionally, similar to the low-sinuosity swamp channel in the Great Cumbung Swamp.

The massive mudstones of the Newark Supergroup are thought to represent the drier part of sediment cycles interpreted as reflecting alternations of wet and semi-arid to arid periods (Smoot & Olsen, 1988). The Newark Supergroup accumulated in rift basins, a very different tectonic setting to the modern Murray Basin that is a very slowly subsiding intracratonic basin (Brown & Stephenson, 1989).

Comparison of several river terminations provide insights into their origin (Table 1). River terminations develop in response to factors that reduce the sediment-carrying capacity of the stream. Channel geometry changes also take place in response to these changes (Leopold & Bull, 1979). The Lachlan River, on entering the swamp, develops perennially flooded backswamps and lakes, and its channel changes from highly sinuous to straight, all in response to water loss and reduced gradient. In comparing the Great Cumbung Swamp with other river terminations (Table 1), the two factors common to all are gradient reduction and water loss by infiltration and/or evapotran-

Table 1. Characteristics of three river terminations. Markanda Fan from Parkash et al. (1983), Okavango Delta from McCarthy et al. (1991) and Dincer et al. (1987).

	Markanda	*Okavango*	*Great Cumbung Swamp*
Tectonic setting	Foreland basin	Extensional graben	Intracratonic sag
Climate	Semi-arid	Semi-arid	Semi-arid
Channel pattern	Distributive, low-sinuosity	Distributive, low-sinuosity	Single channel, high to low-sinuosity
Major deposit	Channel fills	Channel fills, peat bog	Marsh deposits
Dominant grain size	Sand	Sand	Clay + silt
Water loss	not discussed	Evapotranspiration, infiltration, overflow to salinas	Evapotranspiration, infiltration

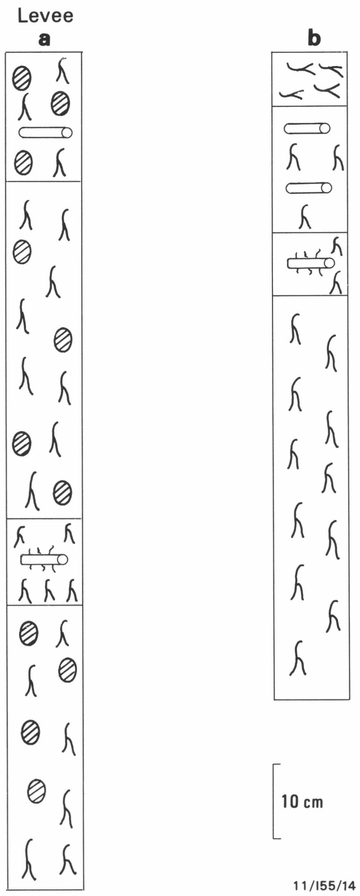

Figure 8. Core Logs of a. levee and b. *Phragmites* marsh sediments near locality E, Figure 3.

spiration. The Markanda Fan (Parkash et al., 1983; Mukherji, 1975, 1976) flows into a subsiding foreland basin, whereas the Okavango River flows into an actively subsiding graben that also produces a flat floor that reduces channel gradients (McCarthy et al., 1991). All of these streams are exotic, flowing through semi-arid to arid regions. The Lachlan River likewise is an exotic stream that loses water by evapotranspiration (Pressy et al., 1984), but its low salinities in the Great Cumbung Swamp suggest that infiltration into underlying aquifers is relatively important.

The Okavango Delta and the Newark Super Groups have developed in depressions formed by normal faulting. The Great Cumbung Swamp occupies a shallow depression delineated by the alluvial ridge of the Murrumbidgee to the south (Schumm, 1968) and by silt dunes (lunettes) on the eastern side of a line of Pleistocene ephemeral lakes to the northwest and west (Fig. 1a). These form low barriers sufficient to defeat the Lachlan except during large floods. Kellett (1989) also found that the area of the swamp was one of relatively greater Cainozoic subsidence, so that tectonism could also have been a factor in forming the Great Cumbung Swamp. Water losses in the swamp prevent the Lachlan from forming a lake behind these topographic barriers, or cutting a spillway through them.

There are many examples of tectonic subsidence reducing river slopes and so inducing sedimentation or causing lake formation (Alexander & Leeder, 1987). Subsidence

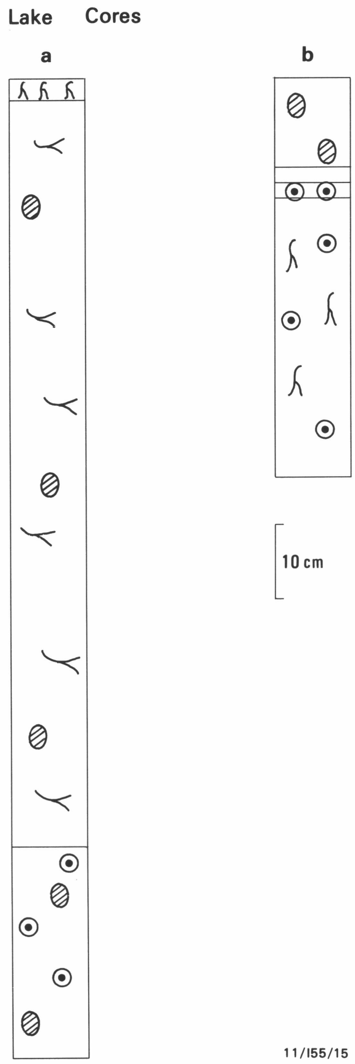

Figure 9. Core Logs of lake sediments from a. Marsh lake north of Profile b, Figure 3, and b. Charlie's Lake.

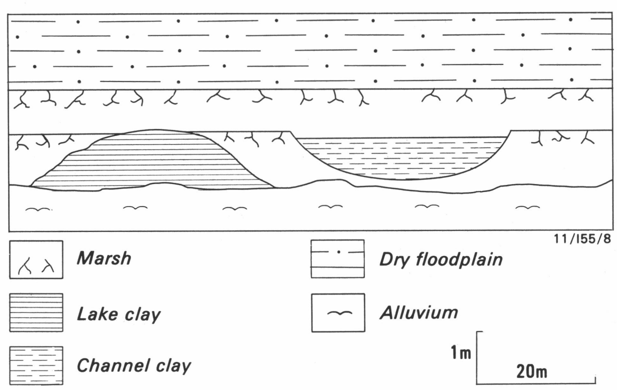

Figure 10. Depositional model derived from the Great Cumbung Swamp.

Massive, organic-rich, clay lenses deposited in the swamp channels and the deepest marsh lakes are interbedded with widespread beds of root-bioturbated clay deposited in infrequently desiccated marsh. As the marsh depression is filled by sediment, these facies would be replaced by cracking clays deposited in dryer floodplain conditions.

causes accommodation to increase faster than the stream can aggrade, so that the river profile becomes flatter. If subsidence greatly exceeds sediment supply, a lake will form, otherwise the stream adopts a lower-energy fluvial style, typically changing either from braided to meandering or meandering to anastomosing (Smith & Putman, 1980). In the case of a river with a fluvial terminus, such as the Okavango, the situation is analogous to a lake except that water dissipates by evapotranspiration, infiltration, and by some minor overflow.

In the case of the Lachlan River and the Great Cumbung Swamp, the influence of subsidence may be less direct. Kellett (1989) demonstrated relatively rapid subsidence rates. Such subsidence may contribute to forming a gentle topographic basin that defeats the Lachlan River, but also may cause the development of raised geomorphic barriers around the edge of the basin. During the Pleistocene, groundwater discharge lakes have developed in many parts of the Murray Basin in response to increased recharge of its aquifers (Bowler, 1978; Brown & Stephenson, 1989). These lakes develop where the aquifers are constricted because of facies changes or because of thinning against basement ridges (Brown & Stephenson, 1989). They typically develop clay and silt dunes, called lunettes, on their eastern sides when they dry out and their floors are deflated by prevailing westerly winds (Bowler, 1978). A line of such lakes and lunettes occurs along the western edge of the Great Cumbung Swamp, suggesting that the lunettes form a barrier to the river along this side of the swamp. The position of this barrier is probably controlled by an aquifer constriction on the western side of an area of enhanced subsidence beneath the swamp (Kellett, 1989). Thus, subsidence contributes to the formation of the Great Cumbung Swamp indirectly by controlling the underlying aquifers that control the surface geomorphology.

Conclusion

The Great Cumbung Swamp is the inland termination of the low-gradient Lachlan River in the Murray Basin of southeastern Australia. The river deposits clays in sinuous to relatively straight channel reaches, with the straight reach possessing rising bed gradients downstream. This downstream end of the Lachlan River represents fluvial sedimentation at the very lowest end of the spectrum (Fig. 11), and probably only maintains a channel by its ability to remove fluid clay from the bed of the straight reach during floods. Its distal reaches meander because they experience formative flows only when flood waves provide enough water surface slope to set up conditions whereby meandering can occur. Water spreads out through ephemeral flood channels into a marsh colonised by reeds (*Phragmites australis*) and cumbungi (*Typha orientalis*). Despite high evaporation, the lakes in the marsh and around the edge of the swamp remain fresh because water is lost to underlying aquifers.

Characteristics of a stream system necessary for development of an inland termination like the Great Cumbung Swamp are: low stream gradient, a slight topographic depression, low sediment load, and significant loss of water to underlying aquifers. However, these alone seem insufficient conditions for the development of a terminal swamp. The continuing subsidence of the Balranald Trough is probably significant in maintaining the localised development of marshes at the termination of the Lachlan River.

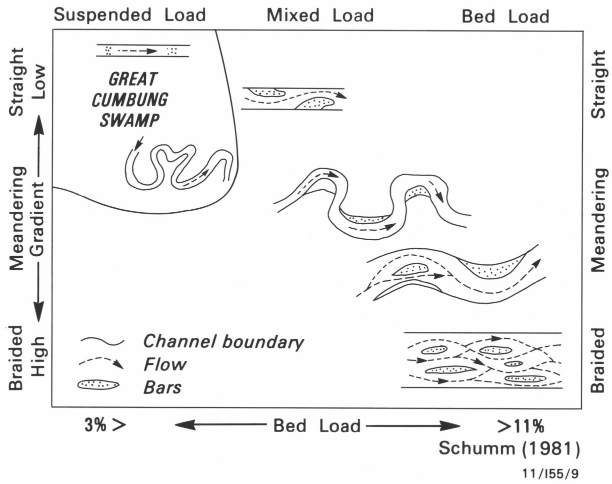

Figure 11. Diagram depicting the position of the Lachlan channel in the Great Cumbung Swamp in the spectrum of fluvial styles after Schumm (1981).
The Lachlan exhibits both sinuous and straight suspended-load channels.

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