Delamerian National Drilling Initiative: stratigraphy of Murray Basin cover sediments

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Introduction

The Delamerian Orogen is a key greenfield target for the Geological Survey of South Australia under the MinEx CRC National Drilling Initiative (NDI). The project includes a geoscientific drilling program and allied research to understand the geology and mineral potential of both the Delamerian basement and overlying Murray Basin cover. This article focuses on understanding the characteristics of the cover sediments to assist mineral exploration and for planning drillholes for the NDI. Its purpose is to:

1. summarise the history of the stratigraphic nomenclature of the cover sediments in the Delamerian NDI, namely the northwest Murray Basin
2. present descriptions of selected drillholes and composite sections at the sites of maximum thicknesses of the known cover strata in the northwest Murray Basin area and establish their stratigraphic correlation
3. summarise the sedimentological characteristics of the cover sediments including regional facies changes in the context of a regional cross-section
4. resolve the differing stratigraphic positions and units in the northwest Murray Basin.

There have been a number of previous investigations of the basin strata in the northwest Murray Basin and much of that work is summarised herein. Revised work presented includes descriptions of selected drillholes, regional cross-sections and thoughts on the regional facies changes.

Geological setting

The Delamerian NDI region covers stratigraphic and/or tectonic units of Proterozoic to early Paleozoic; middle Paleozoic to Mesozoic; and Cenozoic ages (Fig 1, Table 1). Due to the Quaternary cover and very sparse bedrock outcrop and drillholes, the geology of the area is poorly known, compared to the adjacent areas of the Adelaide Rift Complex to the east and the Curnamona Province to the north. The Proterozoic to early Paleozoic units include sedimentary rocks, volcanics, metasediments and intrusives of the Adelaide Rift Complex (including the Kanmantoo Trough), Stansbury Basin and interpreted equivalents to the east under the Murray Basin. The middle Paleozoic to Mesozoic is represented by rocks within the Darling, Nadda and Berri basins. The Cenozoic is represented by Paleogene and Neogene sedimentary rocks of the Murray Basin blanketed with a thin cover of Quaternary sediments and/or regolith.

The basal architecture is dominated by the Devonian Renmark Trough and Canegrass Lobe. The Renmark Trough is a northeasterly trending feature deepening to the north from ~2,700 to 3,500 m (Thornton 1974). Limited drilling data has shown that the cover sediments extend southwards from the Renmark Trough along a structurally controlled depression towards the Padthaway Ridge. The Paringa Embayment lies southeast of the Renmark Trough and comprises a series of erosional valleys scoured into the basement, each with a pronounced gradient towards the trough. The Canegrass Lobe is a large, gently westward shallowing depression northwest of the Renmark Trough, with depth to basement reaching ~1,200 m.

Underlying the study area are deformed Neoproterozoic (Adelaidean) to Cambrian sediments and volcanics, and Ordovician granitoids. Interpretation of the solid geology indicates the presence of these sedimentary and metasedimentary rocks and volcanics equivalent to those found in the eastern Mount Lofty Ranges, as well as granitoid and mafic–ultramafic intrusives associated with the Delamerian Orogeny (e.g. Preiss 2000; Wise 2020). The cover geographical features host the Devonian to Permian Darling and Nadda basins, Cretaceous Berri Basin and Cenozoic Murray Basin (Fabris 2003a).

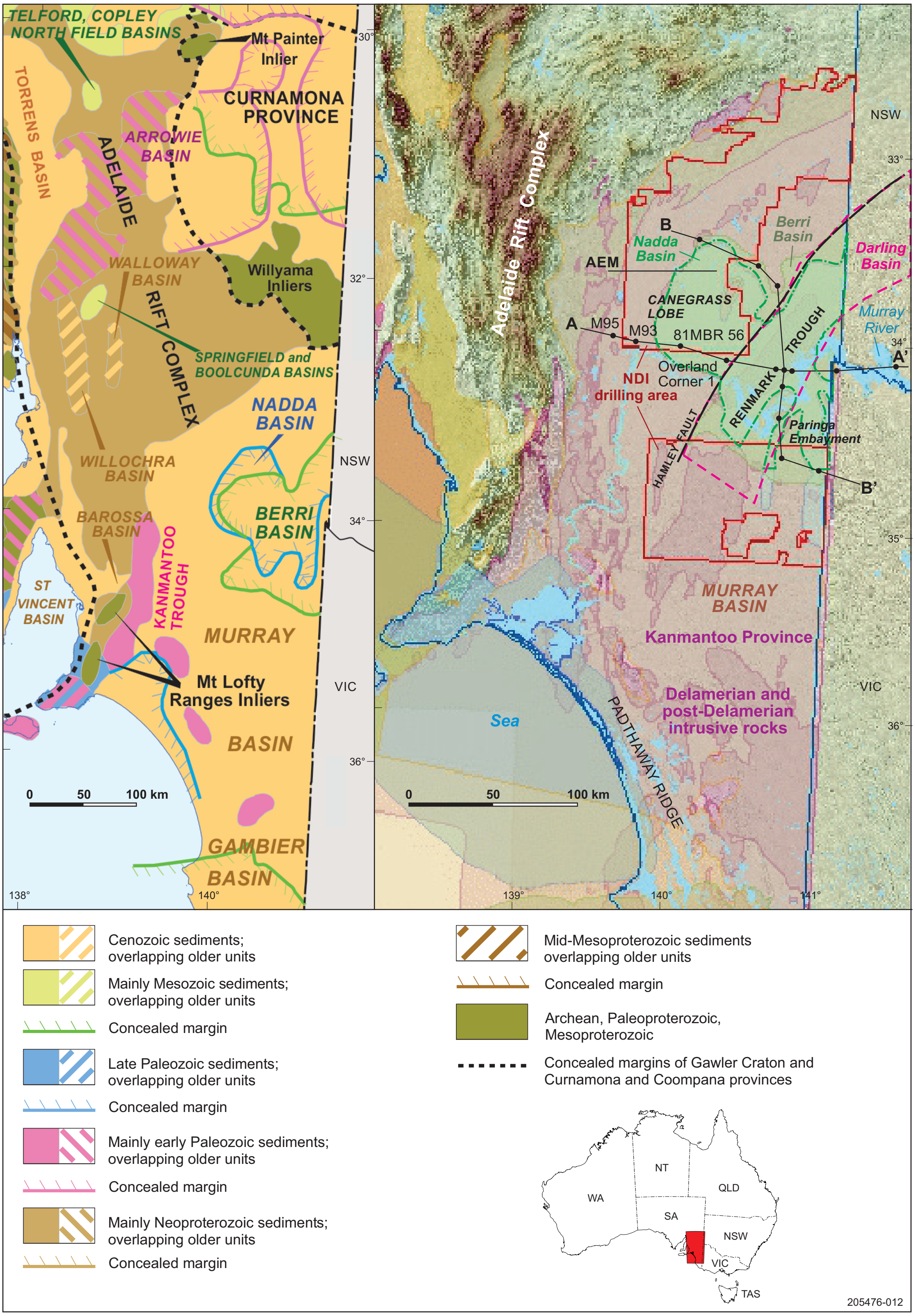

Figure 1 *Tectonic and geological domains of the Delamerian NDI area (modified from Cowley 2010).*

Table 1 *Stratigraphic nomenclature for the cover sediments in the NDI area*

Age	Unit	Domain
Holocene	Recent alluvium; regolith	
Late Pliocene to Pleistocene	Bridgewater Formation; upper Norwest Bend Formation; Bungunnia Limestone; Blanchetown Clay; Coomandook Formation; Chowilla Sand	
Late Miocene to Early Pliocene	Karoonda Surface; Loxton Sand; Norwest Bend Formation; Bookpurnong Formation	
Late Early Oligocene to Middle Miocene	Murray Group – Cadell Formation, Finniss Formation and equivalents, Geera Clay, Ettrick Formation, Winnambool Formation and Mannum Formation; Gambier Limestone (Cooltong 1); Olney Formation (upper Renmark Group)	Murray Basin
Late Paleocene to Early Oligocene	Ettrick Formation (lower Murray Group); Renmark Group – Buccleuch Formation, Olney Formation and Warina Sand	
Early Cretaceous	Monash Formation – Coombool, Merreti and Pyap members	Berri Basin
Permian	Urana Formation – shale, siltstone, sandstone, diamictite and conglomerate of the glacigene	Nadda Basin
Late Silurian to Early Carboniferous	Largely continental redbed facies but probably include marginal marine facies, current-bedded sandstone, grey-brown to green shale and slightly carbonaceous, micaceous siltstone	Darling Basin
Neoproterozoic to early Paleozoic	Adelaidean strata or Kanmantoo Group	Basement

Stratigraphy and distribution

Paleozoic

The western limits of the Late Silurian to Early Carboniferous (predominantly Devonian) Darling Basin extend southwestward from New South Wales to South Australia under the western Murray Basin as a trough into the study area. In the Renmark Trough area, there is a sequence of Devonian clastics (Thornton 1974) underlying the Permian Urana Formation and overlying Adelaidean strata or Cambrian Kanmantoo Group (Fig 2). Over 1,000 m of current-bedded sandstone, grey-brown to green shale and slightly carbonaceous, micaceous siltstone is tentatively dated as Devonian in Tararra 1 drillhole in the Tararra Trough in western New South Wales (Thornton 1974). Drillhole data from Cooltong 1 (SA Geodata drillhole 127802; Fig 3) in the Renmark Trough also confirms the presence of Devonian strata (Alley and Gravestock 1995). Although total thickness is unknown (Cooltong 1 only drilled 191 m into the South Australian portion of the Darling Basin), seismic information suggests that strata of this age may exceed 1,500 m in thickness in the north, decreasing to ~600 m in the south (Thornton 1974). Seismic interpretation also indicates that Devonian sediments may extend westwards across the Hamley Fault to the Canegrass Lobe area, implying that the sedimentation was probably continuous from the Tararra Trough (Alley and Gravestock 1995).

The nature of basement beneath the Darling Basin is largely unknown, but it coincides with boundaries between the Paleozoic Kanmantoo, Lachlan and southern Thomson fold belts. Seismic sequence analysis has identified an orogenic event or unconformity associated with the Tabberabbean Orogeny (~Emsian) and a prominent basin structuring or termination event associated with the Kanimblan to Alice Springs Orogeny (Middle Carboniferous; Thornton 1974). The sediments of the Darling Basin largely comprise continental redbed facies, but probably include marginal marine facies in the latest Silurian and the Early Devonian. In the study area the Darling Basin is mostly veneered by Cenozoic Murray Basin sediments.

Late Paleozoic sediments are preserved in basins controlled by northeast- and northwest-trending structures and include glaciomarine sediments in the Nadda Basin (Fig 1; Alley 1995). The sediments of the Early Permian Nadda Basin are confined entirely to the subsurface in the study area. They unconformably overlie sediments of the Late Devonian Darling Basin, Cambrian Kanmantoo Group or possibly Adelaidean strata (Thornton 1974; Alley 1995) and are preserved in structurally controlled depressions, namely the Renmark Trough, Canegrass Lobe and the Paringa Embayment (Derrington and Anderson 1970; Thornton 1974).

The Urana Formation is at least 395 m (Nadda 1, 126324, in the Paringa Embayment; Fig 4) although it is thought to be considerably thicker in the Renmark Trough where seismic evidence suggests that the late Paleozoic sediments attain 900 m (Thornton 1974). It is also recorded in Cooltong 1, Berri North 1(126822) and Overland Corner 1, (103464; Figs 3, 4). The formation comprises shale, siltstone, sandstone and diamictite with occasional conglomeratic and carbonaceous intervals. Dropstones are common in the finer clastics and probably reflect ice rafting in glaciomarine to glaciolacustrine conditions. The Urana Formation, extending into New South Wales and Victoria, appears to represent a proglacial to post-or non-glacial sedimentary sequence (Alley 1995).

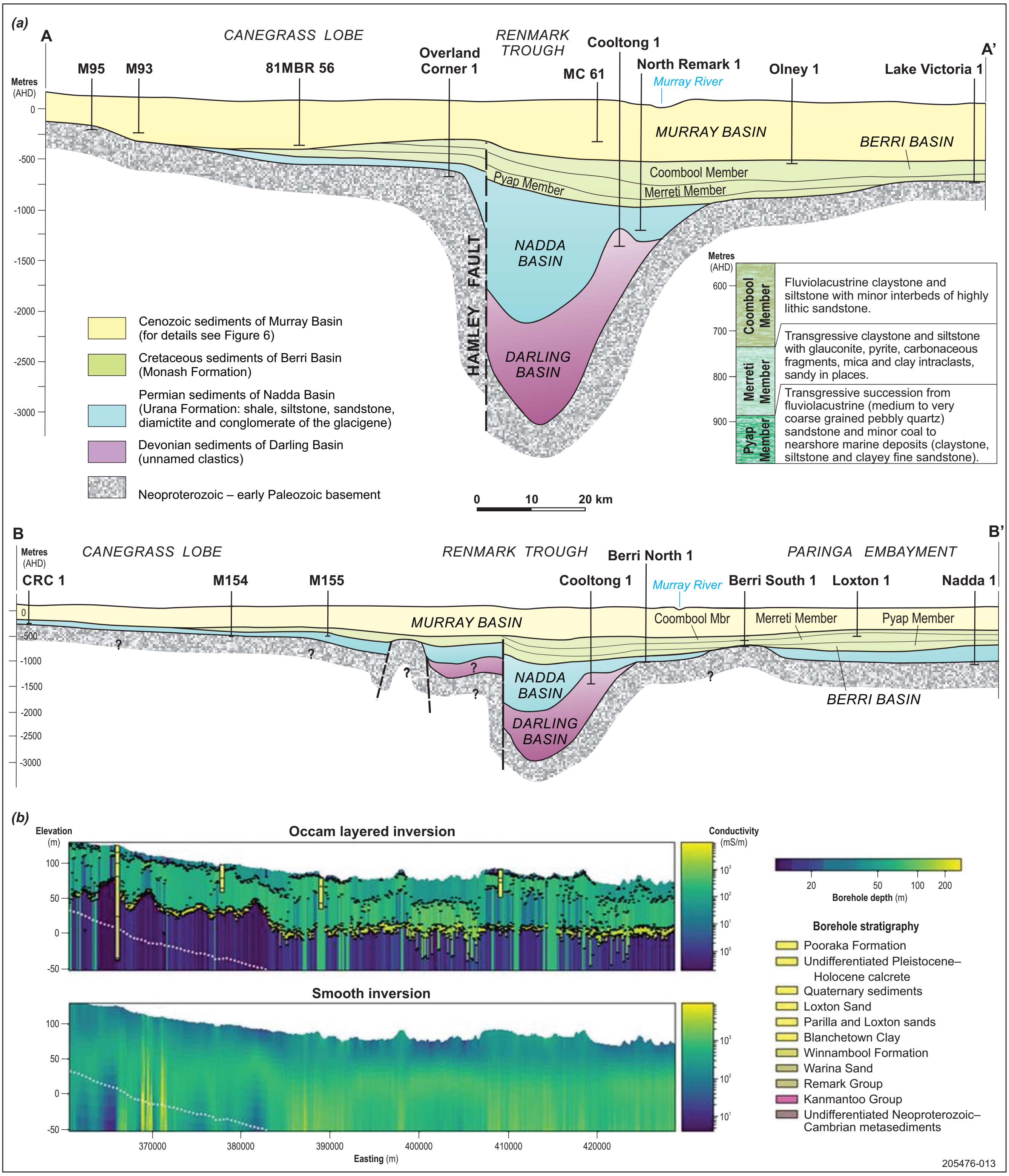

*Figure 2 **(a)** Cross-sections showing approximate limits and relationship of the sedimentary basins in the Delamerian NDI area (after Thornton 1974; Alley 1995; Rogers 1995). **(b)** Airborne electromagnetic section (King in prep). Sections are located on Figure 1.*

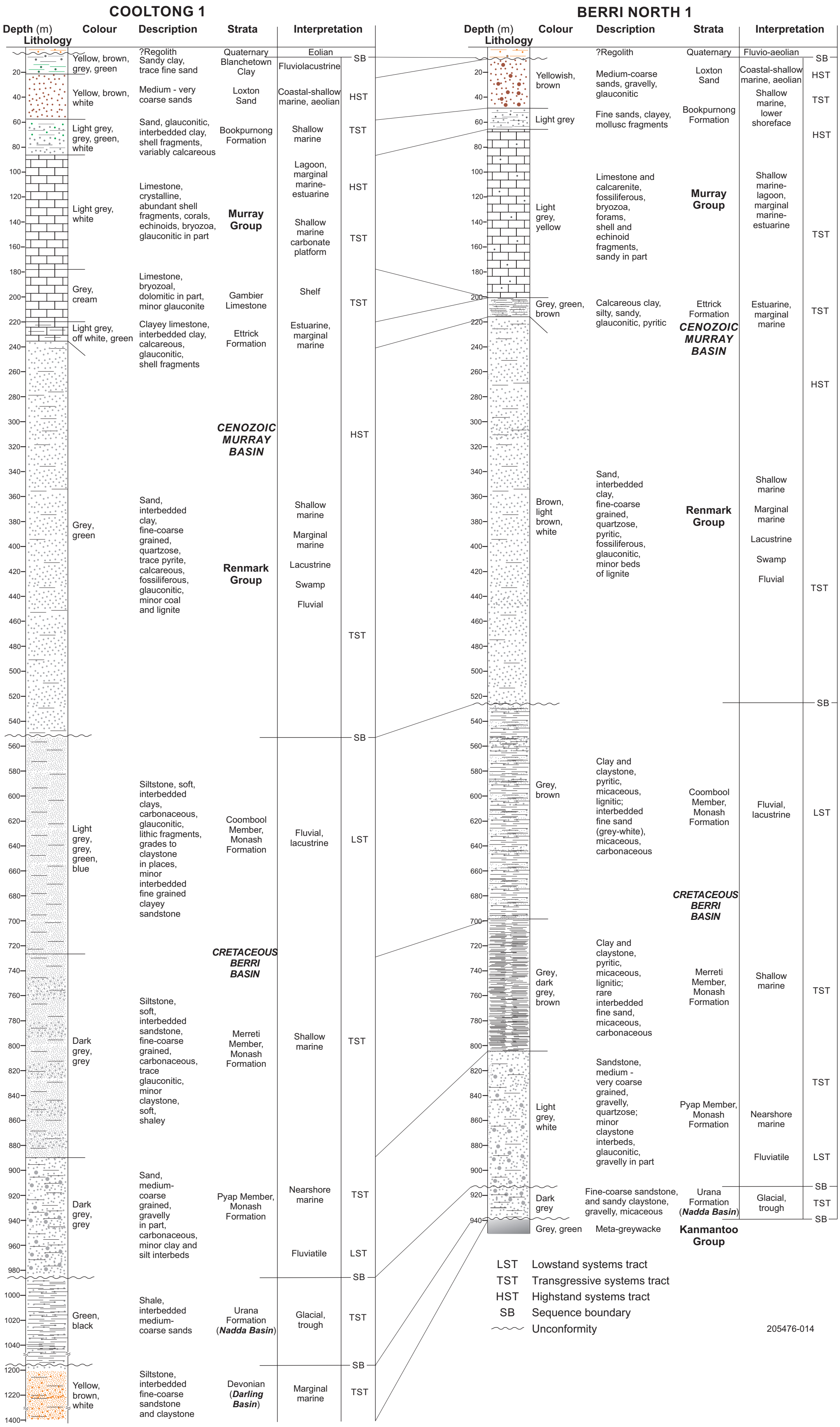

Figure 3 *Geological logs of Cooltong 1 and Berri North 1 drillholes. Relogged in 2020 for the Delamerian NDI.*

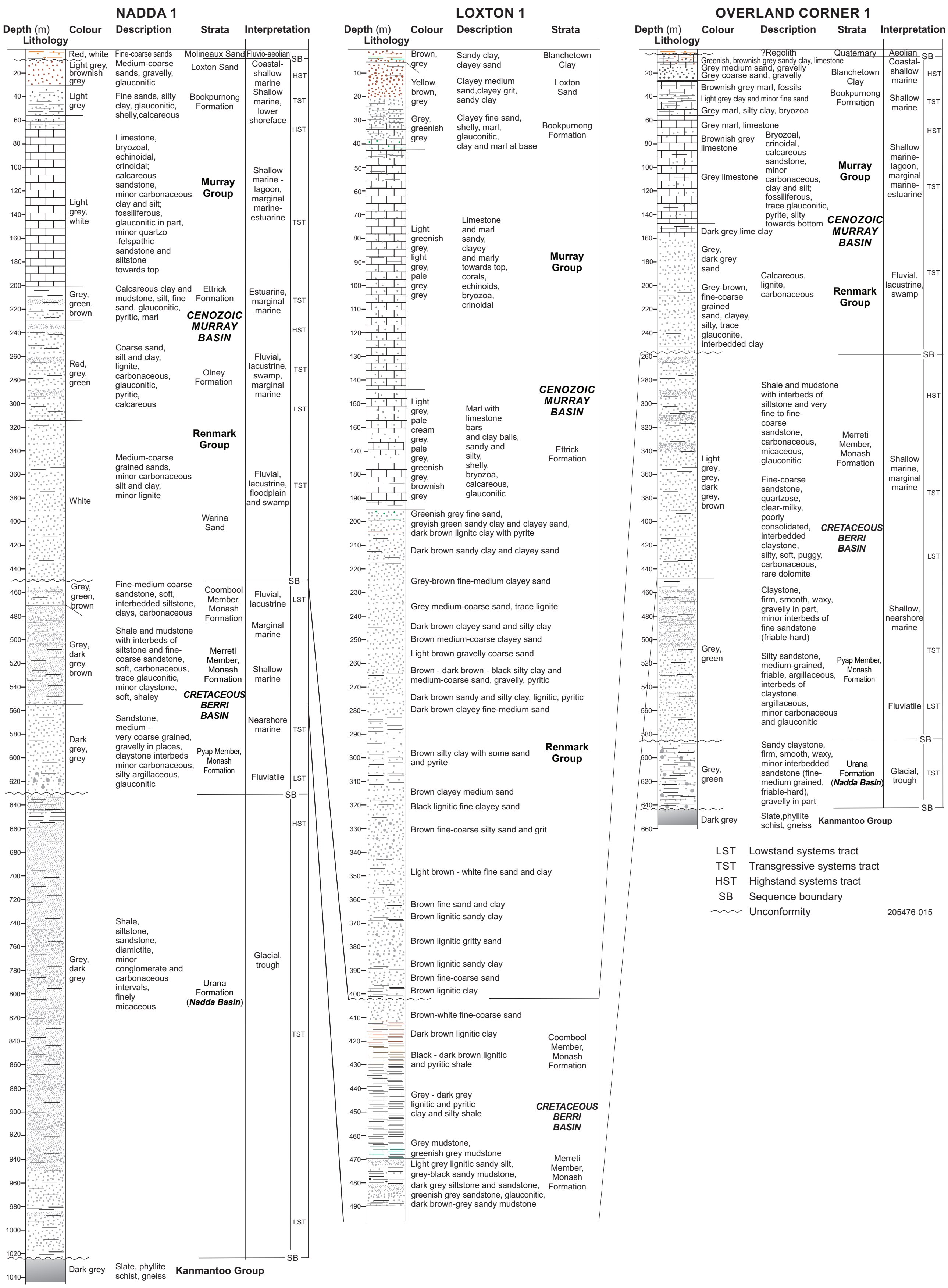

Figure 4 Geological logs of Nadda 1, Loxton 1 and Overland Corner 1 drillholes. Relogged in 2020 for the Delamerian NDI.

Mesozoic

Mesozoic sediments in the study area are mainly deposited in the Berri Basin, which underlies the Murray Basin. The Early Cretaceous Monash Formation is divided into the Pyap, Merreti and Coombool members (with a subsurface type section in North Renmark 1; Thornton 1972). Former descriptions of the Berri Basin consider it an extension of the Eromanga Basin, termed the Berri Embayment (Rogers 1995). Early Cretaceous sediments also occur in the Tararra and Wentworth troughs, and it is likely that a connection existed between these troughs and the Eromanga Basin through the Menindee and Blantyre troughs and the Wilcannia area, although later uplift and erosion has removed Mesozoic sediments from these areas (Rogers 1995). Seismic evidence suggests up to 600 m of Early Cretaceous fluviatiles occur in the Renmark Trough in the study area (Thornton 1974). The embayment appears to be controlled by similar tectonic elements to those of the underlying Nadda Basin, where the Early Cretaceous sediments of Monash Formation unconformably overlie late Paleozoic Urana Formation (O'Brien 1986), Neoproterozoic to early Paleozoic basement and possible Devonian sandstone, and is unconformably overlain by the Late Paleocene to Early Oligocene Renmark Group. Distribution of the Pyap Member appears to broadly follow these structures, but the two younger members of the Monash Formation are more widespread and overlap older sediments and intervening basement ridges onto adjacent basement highs.

The transgressive Aptian Pyap Member changes upwards from non-marine fluvial (medium to very coarse grained pebbly quartz sandstone and minor coal) to nearshore marine deposits (claystone, siltstone and clayey fine sandstone) at the top of the unit. It is overlain by the claystone and siltstone dominated Merreti Member which was deposited during a period of peak marine transgression into the Berri Basin via the Eromanga Basin (Rogers 1995). The Merreti Member contains varying amounts of glauconite, pyrite, carbonaceous fragments, mica and clay intraclasts and is sandy in places. Subsequent uplift or cessation of subsidence in Early Albian time led to deposition of non-marine (fluviolacustrine) Coombool Member that comprises claystone and siltstone with minor interbeds of highly lithic sandstone thought to have been derived from a volcanic source (Rogers 1995).

Cenozoic

Thin Cenozoic sediments are widespread, but thick sequences are confined to the central parts of the Murray Basin where epicontinental marine sedimentation commenced during the Eocene and dominated during the Miocene to Pliocene. The Murray Basin, one of Australia's most important sedimentary basins in exploring for heavy mineral resources, is a Cenozoic intracratonic basin of fluvial to shallow marine sediments. It comprises 3 main depositional packages:

- Paleocene to Eocene Renmark Group (fluvial sand overlain by paralic carbonaceous clay and lignite)
- Oligocene to Middle Miocene Ettrick Formation (marl; lower Murray Group) and Murray Group limestone (marine glauconitic grey-green marl and marine bryozoal limestone)
- Late Miocene to Early Pliocene Bookpurnong Formation (formerly Bookpurnong Beds; marine shelly dark grey clay and silt) and Pliocene sand (fluvial to marginal marine quartz sand).

The western Murray Basin extends over the study area, where the Cenozoic sedimentary rocks form an extensive, but relatively thin succession (generally <200–300 m) reaching a maximum thickness of 600 m over the Renmark Trough area (Fig 5). Cenozoic sedimentary sections are described in Figures 3 and 4 with more detail provided for Loxton 1 (126322). The succession has been described by a number of workers including Brown (1985), Rogers et al. (1995), Brown and Stephenson (1991), Miranda el al (2009) and McLaren et al (2011). The stratigraphy is summarised below and shown in Figures 6 and 7.

Late Paleocene to Early Oligocene

The oldest sediments in the Murray Basin are the Renmark Group, comprising the Warina Sand and Olney Formation, together exceeding 330 m in thickness near Renmark. The Renmark Group is dominated by marginal marine, fluvial to lacustrine sediments and is thought to underlie most of the Murray Basin (Brown and Stephenson 1991). The carbonaceous sand, clay and silt of the Warina Sand and Olney Formation resulted from deposition in floodplain and swamp environments. A minor marine incursion in the Late Eocene was marked by deposition of fossiliferous clay and marl of the Buccleuch Formation (formerly Buccleuch Beds) in northern South Australia.

The poorly consolidated fluvial Warina Sand is restricted to the deeper parts of the basin and consists of pale grey to pale brown medium- to coarse-grained quartz sand with minor thin, lenticular interbeds of locally carbonaceous silt and clay. The sandy facies is interpreted as a fluvial, braided-channel deposit and the finer grained interbeds as lacustrine and floodplain deposits (Roger et al. 1995). The Olney Formation overlies the Warina Sand and is relatively more widespread, extending into marginal areas of the basin where it rests on pre-Cenozoic bedrock or basement (Brown and Stephenson 1991). Commonly, sandy silt and silty clay form alternating multi-coloured laminae. Thinly bedded grey to green carbonaceous sand, silt, clay and lignite (including the Moorlands Lignite Member and lignite in the Sedan and Anna coal deposits) were deposited in fluvial, lacustrine and swamp environments (Rogers et al. 1995). The upper part of the Olney Formation is often marginal marine in the western Murray Basin (Rogers et al. 1995). It is suggested that the Olney Formation was mainly deposited in the vicinity of a coastal swamp

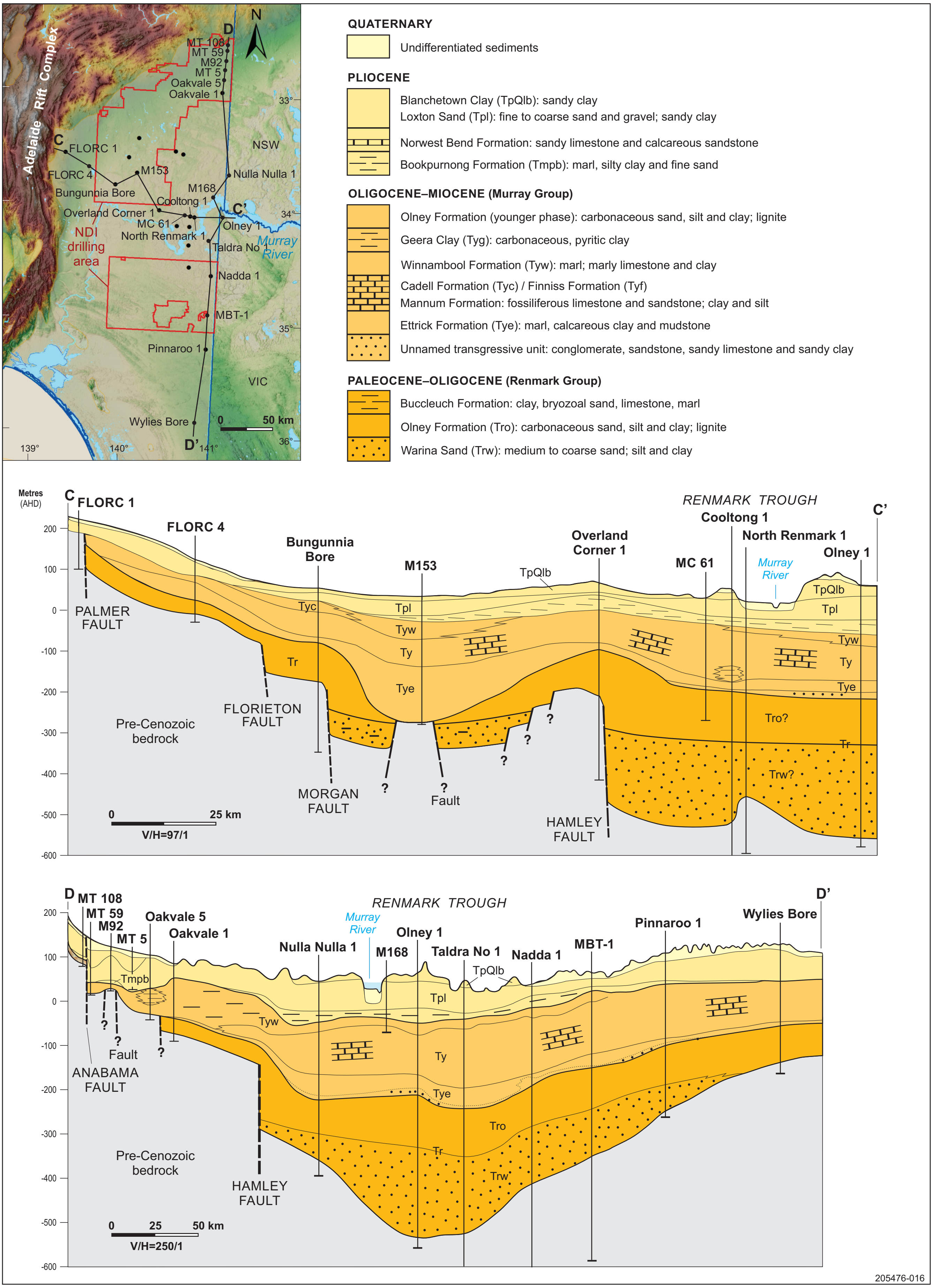

Figure 5 *West–east (C–C′) and north–south (D–D′) cross-sections through the western Murray Basin in South Australia (after Rogers et al. 1995).*

environment as the formation contains abundant swamp community taxa *(Phyllocladidites mawsonii, Podocarpidites ellipticus, Lygistepollenites florinii)* coupled with a minor marine presence (dinoflagellate cysts; Fabris 2003b). It was placed in the upper *Nothofagidites asperus* to *Proteacidites tuberculatus* zones, indicating an Oligocene to Lower Miocene age (Stoian 2002).

The Buccleuch Formation consists of bryozoal and glauconitic limestones, bryozoal clayey sand and black pyritic clay, and a thin layer of black ferruginous clay (Rogers et al. 1995). The marine sediments of the Buccleuch Formation grade laterally into the marginal marine upper Olney Formation. The Ettrick Formation comprises mainly grey to green glauconitic and fossiliferous marl, calcareous clay and mudstone, and silt and fine quartz sand, as well as skeletal debris (Brown and Stephenson 1991). It represents a Late Oligocene transgressive phase of shallow-marine shelf environment, found extending northwards from the margin of the Padthaway Ridge (Rogers et al. 1995).

Late Early Oligocene to Middle Miocene

The dominantly carbonate Oligocene to Middle Miocene sequence of the Murray Group was deposited on a shallow-marine platform (Figs 2, 6; Ludbrook 1969). The Murray Group consists of mostly shallow marine fossiliferous limestone and sandstone with minor clay and silt (Rogers et al. 1995). Marine incursions resulted in sandy fluvial environments being replaced by muddy lagoonal and marginal marine environments where Geera Clay accumulated. In deeper water, marl of the Ettrick and Winnambool formations and limestone of the Mannum Formation (formerly Mannum Limestone) were deposited. A Late Miocene eustatic sea-level fall terminated this depositional cycle and led to local erosion and weathering.

In Cooltong 1, Gambier Limestone was recorded underlying Mannum Formation and interpreted as open marine shelf.

The Mannum Formation formed during Early to Middle Miocene. It consists of calcareous sandstone and sandy limestone, and bryozoal limestone and marl (Rogers et al. 1995). These cream to yellow-brown skeletal

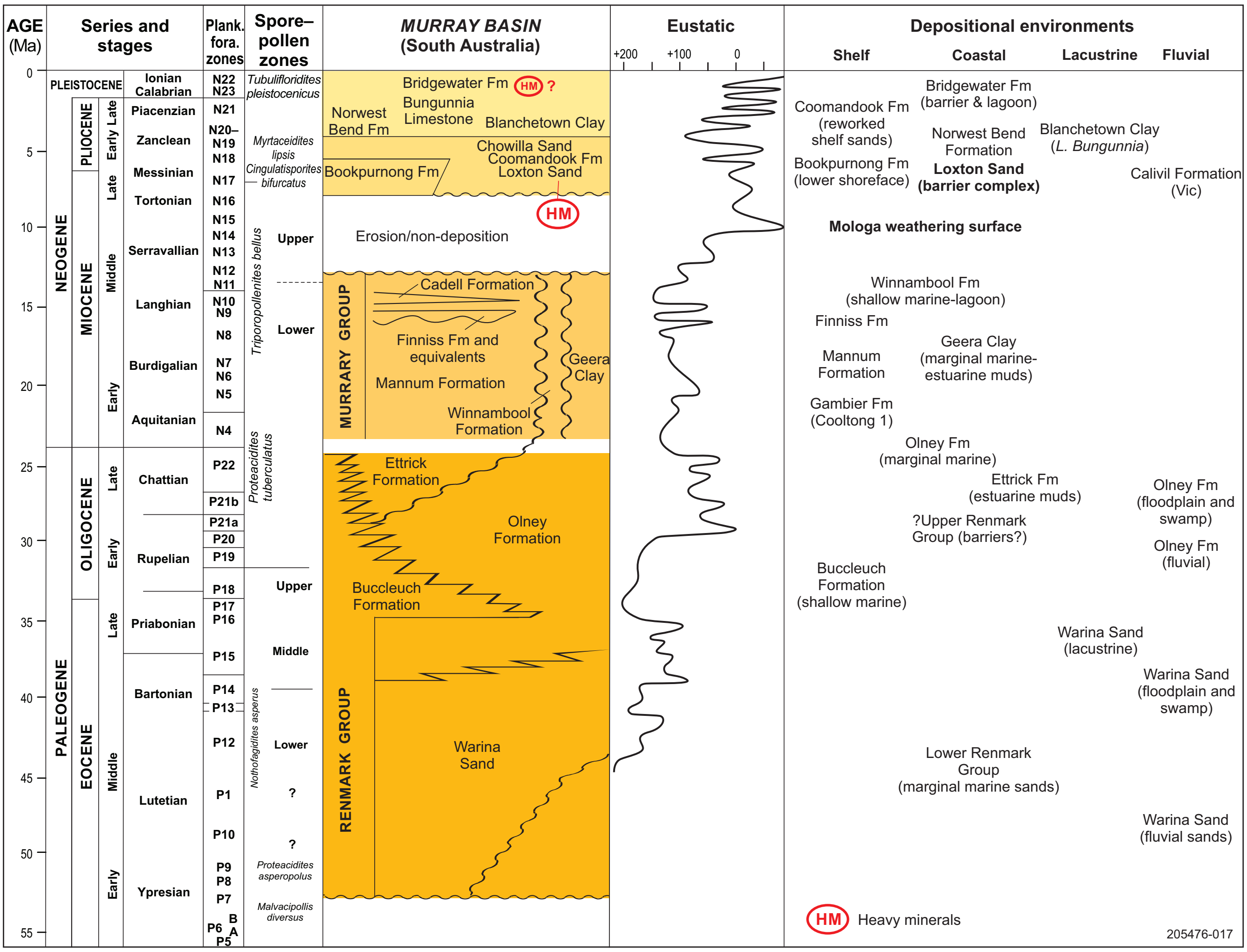

Figure 6 *Cenozoic stratigraphy of the Murray Basin in southeastern Australia (modified from Rogers et al. 1995; Brown and Stephenson 1991; Hou et al. 2012). Eustatic changes are based on Haq et al. (1987).*

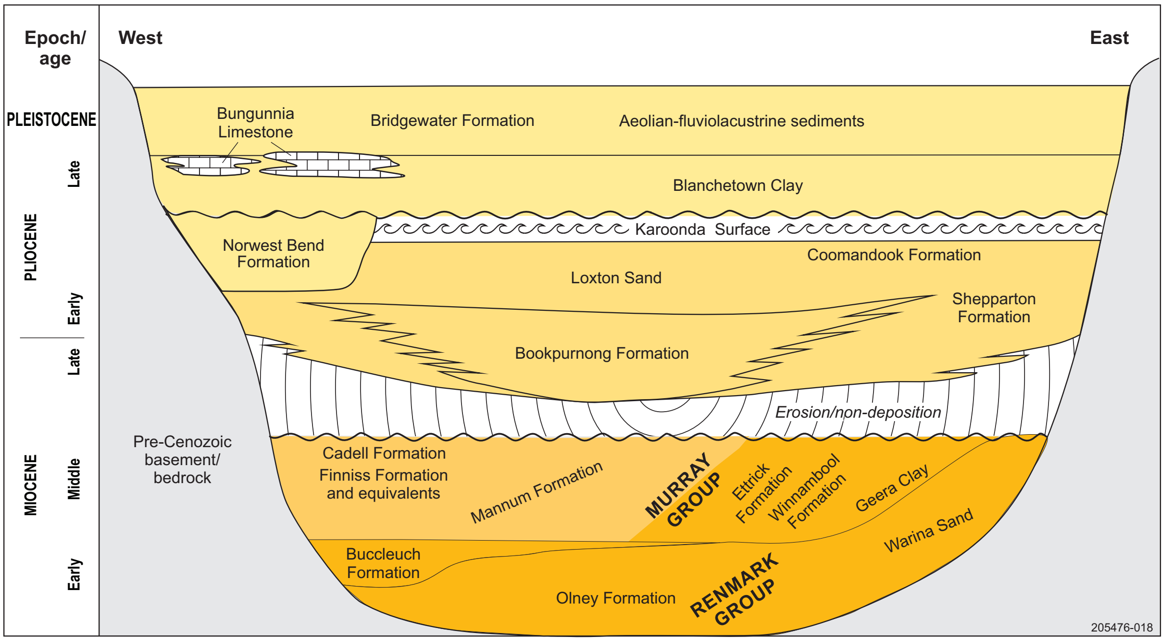

Figure 7 Simplified stratigraphic section of the Murray Basin showing the major Neogene stratigraphic units across the Murray Basin (modified from Brown and Stephenson 1991; Miranda et al. 2009).

calcarenites and calcareous sandstones with variable clay and mega-fossils were deposited in shallow-marine to littoral conditions (Brown and Stephenson 1991). The sands are medium to coarse grained, subangular to well rounded and commonly cemented in a calcareous matrix.

The Finniss Formation (formerly Finniss Clay) and equivalents are patchily distributed along the southwestern margin of the Murray Basin (Rogers et al. 1995). Several lithologically distinct lenses of clays occur within the Murray Group and are intercalated with Mannum Formation in places. In some areas, the lower part of the Mannum Formation passes up sharply into the late Early Miocene Finniss Formation, a thin regressive marine clay lens which in turn is overlain conformably and gradationally by the middle part of the Mannum Formation.

The shallow marine carbonates of the Murray Group grade northwards to the progressively more marginal Winnambool Formation and Geera Clay. Winnambool Formation consists of grey to light green fossiliferous marl, glauconitic marly limestone and marly clay, characterising shallow-water restricted marine and lagoonal facies (Brown and Stephenson 1991). It is interpreted that most of the Winnambool Formation was deposited adjacent to an estuarine environment due to the abundance of marine dinoflagellate cysts and also freshwater algae Botryococcus (Fabris 2003b). This grade towards a marginal marine environment at the top of the unit is supported by a greater influence of marine taxa and the reduction of freshwater algae. The assemblage suggests the Canthiumidites bellus Zone, giving an age range of upper Lower to Middle Miocene (Stoian 2002).

Geera Clay, characterised as marginal marine and tidal sediments in the northwest Murray Basin, is mainly composed of black to grey-green, carbonaceous, pyritic clay and silt with minor sand and glauconite and sparse marine fossils that was deposited in a shallow to marginal marine environment (Brown and Stephenson 1991). Fabris (2003b) interpreted the Geera Clay as fluvial with a minor marine and swamp influence at the base, grading into fluviolacustrine followed by a swamp environment influence at the top. It was placed in the Proteacidites bellus Zone, indicating an age of Upper Oligocene to upper Lower Miocene (Stoian 2002).

A non-marine sequence set of carbonaceous and pyritic sand, silt and clay with lignite overlies the Geera Clay and Winnambool Formation in the northern margin of the Murray Basin. It may be correlative with the Late Oligocene to Middle Miocene component of the Olney Formation, although alternatively it could be a carbonaceous facies of the Late Miocene to Early Pliocene Loxton Sand (Rogers et al. 1995).

Late Miocene to Early Pliocene

The third major sedimentary association of the Murray Basin was deposited during the Late Miocene to Pliocene. Middle to Late Miocene sea-level fall, mild tectonic activity and erosion resulted in an unconformity developed at the top of the Murray Group and its equivalents (e.g. Mologa weathering surface in the eastern part of the Murray Basin; Macphail et al. 1993). The latest Miocene marine transgression led to drowning of fluvial tracts and development of shallow marine depositional environments, which is represented by clay with occasional sandy, silty, carbonaceous and calcareous beds of the Bookpurnong Formation. As sea-level rose slowly and became steady, a move towards highstand deposition resulted in the formation of prograding beach strandplains and barrier islands (Loxton Sand).

Upfaulted remnants of Miocene marine limestone indicate post-Miocene uplift of the eastern Mount Lofty Ranges in the order of 60 to >100 m, with some of this movement occurring during the Pleistocene (Bourman and Lindsay 1989). Tectonic damming related to uplift of the Pinnaroo Block at c. 2.4 Ma, and estimated rainfall of at least 500 mm/yr, is believed to have led to the formation of a large freshwater lake known as Lake Bungunnia (Brown and Stephenson 1991; McLaren et al. 2009).

The Bookpurnong Formation lies unconformably and/or disconformably on the Upper Oligocene to Mid Miocene sediments of the Murray Basin (Ludbrook 1957). Outcrops of the Bookpurnong are limited to a small region around Loxton (type section) in South Australia. Drilling has revealed subsurface thicknesses ranging from a few metres to as much as 50 m near the tri-state border (Brown and Stephenson 1991). Its overall distribution is in a broad arc within the (deeper) central sections of the Murray Basin (Brown and Stephenson 1986). Early paleontological, foraminiferal and palynological evidence indicated deposition between the middle Late Miocene (e.g. Brown and Stephenson 1986) and the Early Pliocene (e.g. Brown and Stephenson 1991). Palynologically, this unit is now placed in the *Monotocidites galeatus* Zone (*Myrtacedites lipis* subzone; Stoian 2002), indicating an age of Early Pliocene to early Late Pliocene. Miranda et al. (2009) employed strontium isotope analyses from shelly fossils of the Bookpurnong Formation, providing a range of ages from 1.7 to 7.2 Ma.

The Bookpurnong Formation consists of brown or greenish grey marl, silty clay and minor fine sand, with relatively high carbonate contents. It overlies Middle Miocene limestones, all variably shelly, glauconitic and micaceous (Carter 1985). These lithologies become less calcareous and less fossiliferous up-section, where they grade into more micaceous and coarse-grained sands and gravels of the shallow-marine Loxton Sand. The Bookpurnong Formation is considered to have formed on the lower-shoreface (offshore) during the initial transgressive phase, as well as during the regressive phase that deposited the coastal and strandline (onshore) facies of the 'Loxton-Parilla Sands' (Miranda et al. 2009).

Loxton Sand

The Loxton Sand is a composite sand sheet (formerly Loxton Sands; Ludbrook 1957; Lindsay 1977; Geoscience Australia 2021).While the Loxton Sand is conformably underlain by the Bookpurnong Formation, around the western margin of the Murray Basin the basal part of the Loxton Sand may be equivalent to the Bookpurnong Formation (Brown 1985). Loxton Sand comprises glauconitic, micaceous and shelly fine sand, overlain by planar and cross-bedded fine to coarse-grained sand and fine gravel, and planar bedded, calcareous, micaceous, medium- to coarse-grained sandstone with abundant shell debris. It incorporates shallow marine, beach dune, estuarine and fluvial sediments.

It is interpreted as an upward-coarsening regressive sequence of shallow marine and marginal marine sediments passing up into beach and coastal barrier deposits (Rogers et al. 1995). The upper part of the Loxton Sand forms an extensive regressive strandplain composed of gently arcuate beach ridges. The latter extends from their southernmost limit, the Marmon Jabuk Range, northwards to the vicinity of `Canopus', but have been eroded and reworked into Late Pliocene to Early Pleistocene fluvial and lacustrine deposits in the vicinity of the Murray River. The beach sand contains heavy minerals, including ilmenite, zircon, rutile and tourmaline.

Loxton Sand was previously mapped as the 'Loxton-Parilla Sands' and 'Parilla Sands' in Victoria; the name 'Parilla Sands' was used for dune and fluvial deposits, whereas the 'Loxton Sands' was used for marine strata (see below). As it is often not possible to map the marine and dune sediments separately (VandenBerg 2009), these names are best regarded as junior synonyms of the Loxton Sand (see Robson and Webb 2011). We use Loxton Sand in our stratigraphic revision rather than Parilla Sand or 'Loxton-Parilla Sands'.

Parilla Sand

Parilla Sand is composed of unfossiliferous, non-marine, fine- to medium-grained clayey quartz sand with thin beds of sandy clay (Firman 1966, 1973), and is underlain by the Loxton Sand. The formation was derived mainly from Loxton Sand by aeolian and fluvial reworking and may include large transgressive dune complexes (Belperio and Bluck 1990), as well as lacustrine and fluvial deposits laid down in depressions between stranded coastal ridges (Rogers et al. 1995).

Undifferentiated 'Loxton-Parilla Sands'

As stratigraphic terms, Loxton and Parilla have been used for separate Pliocene sand units in some areas of the Murray Basin (e.g. Mason et al. 1998) but the distinction between them is not everywhere apparent. To overcome various nomenclatural complications, the undifferentiated 'Loxton-Parilla Sands' was defined as a 'single composite sand sheet' (Brown and Stephenson 1991) that was deposited in a complex array of strandplain environments varying from shallow to marginal marine, estuarine and fluvial, occurring across western Victoria, southwestern New South Wales and southeastern Australia (Fig 7). The 'Loxton-Parilla Sands' was invoked to address difficulties encountered in stratigraphic correlation across state boundaries, particularly between the 'Loxton Sands' of Ludbrook (1957), the 'Parilla Sand' of Firman (1966), and the 'Diapur Sandstone' of Lawrence and Goldberry (1973). The composite 'Loxton-Parilla Sands' name has been widely used to describe the Pliocene strandline sands of the Murray Basin (e.g. Kotsonis 1995; Rogers et al. 1995; Roy et al. 2000; Wallace et al. 2005; Miranda el al. 2009).

The sediments of the 'Loxton-Parilla Sands', displaying generally impoverished fossil assemblages, are characterised by fine to coarse, well-sorted quartz sand and sandstone, yellow-brown in colour, with minor silt, clay and pebble conglomerates, locally containing micaceous quartz sands and/or gravel facies (Brown and Stephenson 1991) and large concentrations of heavy minerals (mainly rutile, zircon and ilmenite; Roy et al. 2000). Well-laminated horizons often exhibit cross-bedding, particularly within the quartz-gravel units (Miranda el al. 2009). The thickness of the unit typically ranges from 20 to 60 m (Roy et al. 2000) and may be up to 150 m thick in places (Lawrence and Abele 1988). In the western and southwestern Murray Basin, the 'Loxton-Parilla Sands' contain calcareous, often fossiliferous, facies that overlie the Miocene Murray Group limestones (Miranda el al. 2009). In the west, the more estuarine lithologies of the 'Loxton-Parilla Sands' appear similar to those of lower Norwest Bend Formation, and thus both the lower Norwest Bend Formation and the 'Loxton-Parilla Sands' are overlain by the oyster coquinas of the upper Norwest Bend Formation, separated from them by an irregular disconformity surface (Pufahl et al. 2004). The sands are thought to have been derived from discharge of sediment from fluvial systems that drained the interior of the basin, and from reworking of sand from the bed of the Pliocene gulf by long-period swell waves (Roy et al. 2000).

Karoonda Surface of the Loxton Sand

The upper parts of the Loxton Sand are capped by an indurated ferricrete horizon throughout much of the Murray Basin, characterised by a distinctive, highly lithified, variably ferruginous and/or siliceous layer (e.g. in the eastern and southern region of Overland Corner 1; Firman 1973). This layer separates the Miocene to Pliocene Loxton Sand from the overlying Late Pliocene to Pleistocene lacustrine sediments of the Blanchetown Clay and associated sediments of the Lake Bungunnia system. The ferruginous unit is known as the Karoonda Surface (~2 m thick at Overland Corner 1) and represents an important stratigraphic marker thought to have formed due to subaerial exposure of the Miocene to Pliocene strandline system (Firman 1973). The Karoonda Surface indicates a regional unconformity within and/or above the Late Pliocene sediments of the Murray Basin that gives rise to distinctive topographic and magnetic signatures of the strandplain sediments (Wallace et al. 2005).

The Norwest Bend Formation (Ludbrook 1957) unconformably overlies the Miocene Murray Group limestones and conformably to disconformably overlies the lower part of the Loxton Sand. It comprises fossiliferous sandy limestone, calcareous sandstone and oyster beds that were deposited in a narrow estuarine zone extending northwards from Tailem Bend along the western margin of the Murray Basin between Overland Corner and Nildottie, where the Loxton Sand ridges are absent (Ludbrook 1957; Brown and Stephenson 1991). It also caps many of the cliffs along the Murray River gorge (Ludbrook 1957; Brown and Stephenson 1991). These estuarine sediments are considered to be the result of tectonism which occurred in this western margin during the Late Miocene to Early Pliocene (Miranda et al. 2008). In the western Murray Basin, there exists an important stratigraphic, paleoenvironmental and historical relationship between the Norwest Bend Formation and the more extensive Loxton Sand. Miranda et al (2008) suggested the terms upper Norwest Bend Formation for the oyster-dominated coquina in the western Murray Basin, and lower Norwest Bend Formation for sandy, oyster-rich sediments where it is considered laterally equivalent to the 'Loxton-Parilla Sands' of Brown and Stephenson (1991). A sand and/or gravel-dominated facies in the lower Norwest Bend Formation was deposited between 4.2 and 5.3 Ma, while a distinctive oyster-dominated estuarine facies occurs in the upper Norwest Bend Formation (Miranda et al. 2008).

Late Pliocene to Pleistocene

The major Late Pliocene to Pleistocene unit, the Blanchetown Clay (Firman 1965), represents the most common lacustrine phase within Lake Bungunnia. In the central and eastern Murray Basin, the Blanchetown Clay or Coomandook Formation unconformably overlie the ferricretes of the Karoonda Surface (Firman 1973). In the western Murray Basin, the Blanchetown Clay unconformably overlies the oyster coquinas of the upper Norwest Bend Formation. Here the Blanchetown Clay usually infills depressions within an irregular karst surface which separates it from the underlying Pliocene sediments (Miranda et al. 2008). The Blanchetown Clay is mainly composed of poorly laminated, or occasionally very finely laminated, clays and sandy clays, and also incorporates a minor quartz-sand dominated facies (McLaren et al. 2009). In the western Murray Basin The Blanchetown Clay the colour typically varies from olive-grey to green-grey, while elsewhere it exhibits colours ranging from red-brown to grey-brown. In some areas the basal sediments of Lake Bungunnia occur as fluvial-dominated lithologies of the Chowilla Sand, consisting of dark-yellow to pale-yellow fine quartz-sand (Firman 1966). In areas to the east of Overland Corner 1 (Fig 4), for instance, the Chowilla Sand overlies the Karoonda Surface and lies stratigraphically beneath the Blanchetown Clay, indicating the presence of Pliocene fluvial systems (possibly incorporating minor channels, as suggested by Firman 1973) that drained into Lake Bungunnia (Miranda 2007).

Another major unit associated with the Late Pliocene to Pleistocene is the Bungunnia Limestone. This occurs as a thin (1–3 m thick) carbonate unit (interlaminated calcite, dolomite and magnesite) and clay that caps the Blanchetown Clay, especially in the western portions of the Murray Basin (Firman 1965). The carbonate bands usually show grey and white colours, whilst the more clay-rich parts of the unit are often pale green and appear similar to the Blanchetown Clay. An abundance of pisolitic and ooid grainstones, as well as ostracod-rich sands, is associated with the more silt–sand dominated facies of the Bungunnia Limestone. These ooid-rich layers (1–15 cm thick), often underlying the carbonate-rich laminations, are commonly found in the upper parts of the Blanchetown Clay and may sometimes define a transitional zone between it and the Bungunnia Limestone (Miranda 2007).

Early to Late Pleistocene Bridgewater Formation (Boutakoff 1963) outcrops as an extensive sequence of subparallel linear ridges in the southwestern Murray Basin and is contiguous with sediments on the Gambier coastal plain in South Australia. The Bridgewater Formation is typically 15–20 m thick, with a maximum thickness of 45 m and is composed of strandlines which rise from sea level at the modern coastline to ~64 m near the Kanawinka Escarpment (Jenkin et al. 1988). The Kanawinka Escarpment was first described as a low-lying fault scarp by Fenner (1930), and later as a series of connected faults by Boutakoff (1952) and Kenley (1971). It was also suggested to be a paleoshoreline feature (e.g. Rogers 1980; Wallace et al. 2005) or a combination of a fault and a coincident paleoshoreline (Sprigg 1962). The escarpment, originated between 5 Ma (the age of the youngest Loxton Sand strandline preserved above the escarpment) and 1.2 Ma (McLaren et al. 2011). It extends more than 600 km from the Mount Lofty Ranges in South Australia (also previously known as the Marmon-Jabuk Scarp in the South Australian portion of the escarpment; Rogers 1980) to near Portland in western Victoria (Miranda et al. 2009; McLaren et al. 2011).

The sediments of the Bridgewater Formation consist of a well-sorted, fine- to medium-grained bioclastic carbonate sand, commonly laminated and well cemented (Jenkin et al. 1988), as well as subtidal, intertidal and aeolian dune facies (Kenley 1988). The unit varies from a fine to very fine grained quartz sand in the south and east, to a sequence consisting almost entirely of carbonate fragments (probably wave-derived shelf sediments) closer to the Kanawinka Escarpment. The Bridgewater Formation is characterised by a sparse faunal assemblage comprising benthic and rare planktonic foraminifera, echinoderms, bivalves, bryozoans and articulated tidal bivalves. Variations in depositional environment are reflected in the degree of cross-bedding, from gentle (near-shore) to steep (aeolian). As the Bridgewater Formation is interpreted to comprise sediment reworked from inner shelf deposits, the marine microfossils may reflect the depositional environment of the shelfal sediments, rather than depositional conditions of the Bridgewater Formation (McLaren et al. 2011).

Cenozoic stratigraphic relationships and evolution

During the Cenozoic, Paleogene to Neogene sediments of the Murray Basin were deposited in most of this area. The arcuate shape of the western margin is largely controlled by Delamerian structures in the Nackara Arc. The southern margin is identified along the Padthaway Ridge where there was partial connection with the Gambier Basin (Miranda 2007). The sediments of the Murray Basin host one of the largest and best preserved strandplain sequences found anywhere in the world (Brown and Stephenson 1991; Miranda et al. 2009), and are also significant for their economic heavy mineral resources (Roy et al. 2000) and groundwater reservoirs essential for agriculture across the semi-arid interior of Australia (e.g. Brown and Stephenson 1986; Miranda el al. 2009). Associated with the formation of the heavy mineral deposits are 4 prominent paleogeographic features (Fig 8): paleoshorelines and strandplain of the Late Miocene to Early Pliocene Loxton Sand; paleoshorelines of the Mount Gambier coastal plain; Plio-Pleistocene paleo-megalake, Lake Bungunnia; and prominent and laterally extensive Kanawinka Escarpment.

Following the break-up between Antarctica and the southern margin of Australia in the late Mesozoic to early Cenozoic (Deighton et al. 1976; Cande and Mutter 1982), terrestrial sedimentation began during the Early Eocene and Oligocene as fluvial and swamp deposits resulting in the gradual spread throughout the basin of floodplain alluvium and swamp deposits (lower Renmark Group), while the western side was flooded with seawater and received the Warina Sand (Brown and Stephenson 1991). A sea-level fall towards the Late Eocene led to the deposition of silt and clay of the Olney Formation. One minor sea incursion in the Late Eocene resulted in the Buccleuch Formation in South Australia, as indicated by the presence of shelly clays and evaporitic limestone interbeds in the mouth of the basin at this time. Major marine incursion commenced in the Late Oligocene (c. 29 Ma) as a shallow sea that spread inland behind the Padthaway Ridge, a linear cluster of early Paleozoic granite intrusions (Lukasik et al. 2000). Marine calcareous clay and marl of the Ettrick Formation interfingered with marginal marine dark bioturbated muds of Geera Clay; while onshore deposits included fluvial sands of Olney Formation, upper Renmark Group.

During Late Oligocene to Middle Miocene times, the Murray Basin experienced a major marine incursion (McGowran et al. 1997) resulting in deposition of Murray Group sediments under open-marine conditions in the western basin. Thick deposits of bryozoan-rich calcisiltite and calcarenite formed (Lukasik et al. 2000), with marl and limestone in the deeper locations and the Geera Clay in the shallow waters (Rogers et al. 1995). The long period of gradual expansion and final contraction of these marine environments is recorded in the distribution of the Ettrick and Winnambool formations, the Geera Clay (and its equivalent) and the Murray Group limestones (Brown and Stephenson 1991). Fluvial conditions, represented by middle and upper Renmark Group sediments, persisted in landward parts of the basin. A sea-level fall during mid-Miocene (McGowran et al. 2004) resulted in the deposition of Geera Clay and Olney Formation farther westward over the limestone. The upper formations of the Murray Group carbonates contain a fossil assemblage equivalent to low-latitude Miocene planktonic foraminiferal zone N6, possibly extending into zone N7, and equivalent to c. 13.5 Ma (Gallagher and Gourley 2007). The break in marine sedimentation lasted around 6 million years. Over this period Middle Miocene sediments were exposed to weathering and erosion, particularly in the western portion of the basin.

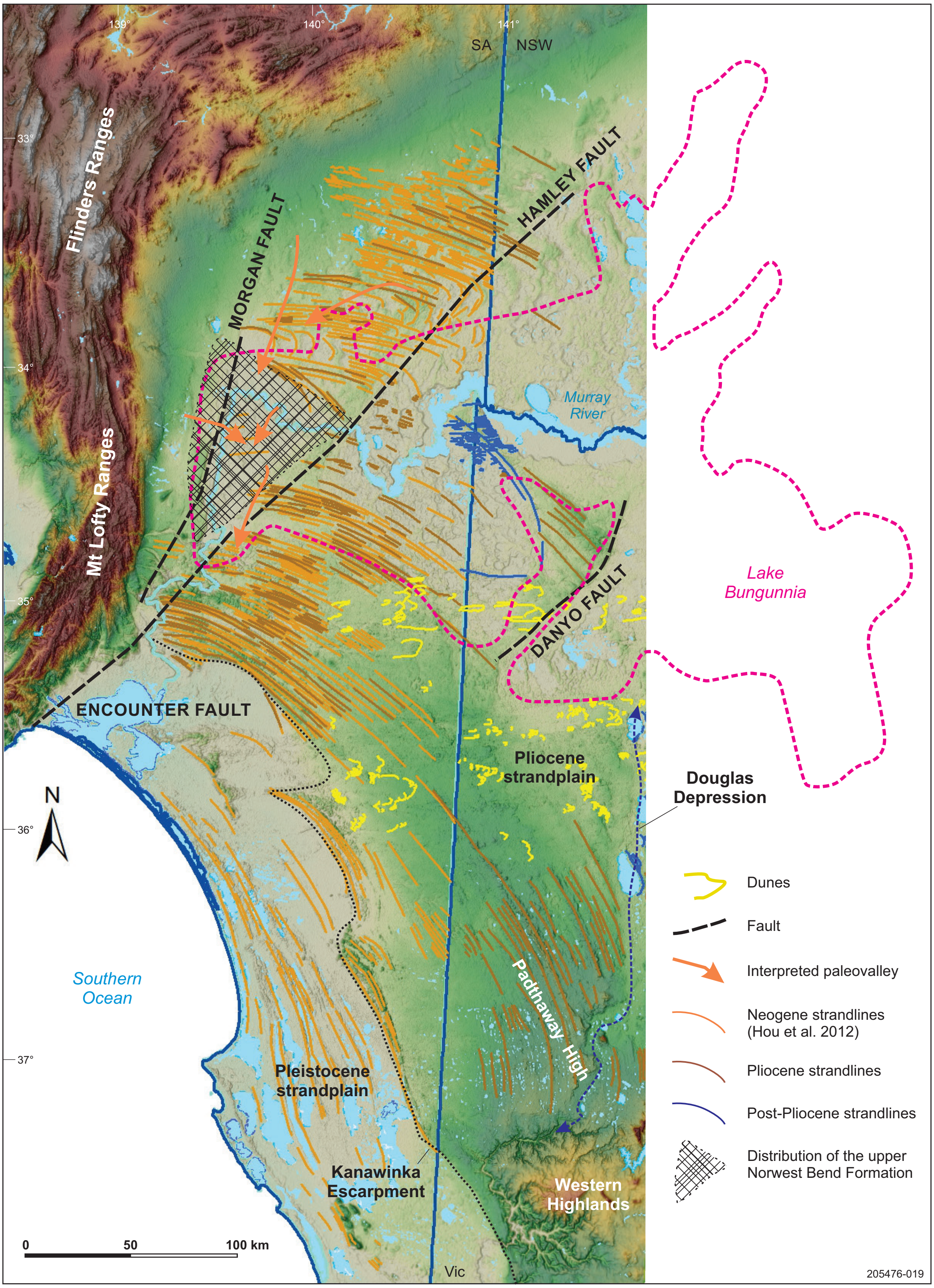

Figure 8 *Inferred features of the western Murray Basin showing dunes and extent of Lake Bungunnia (Miranda 2007; McLaren et al. 2011), Neogene strandlines (Hou et al. 2012), Pliocene and post-Pliocene strandlines (Köhler 2020), major structural features controlling the distribution of the upper Norwest Bend Formation, and paleodrainage channels with suggested drainage directions (Miranda 2007; Miranda et al. 2008). Also located are the Pleistocene strandplain, Kanawinka Escarpment (marking the southern edge of the uplifted zone), the Padthaway High and the Mount Gambier coastal plain (Miranda 2007; McLaren et al. 2011).*

By Late Miocene to Early Pliocene time, interactions along the Australian–Pacific plate boundary had established an approximate east–west to southeast–northwest oriented compressional stress field across southeastern Australia (Sandiford et al. 2009). The stress regime initiated faulting within the basin sediments and reactivated faults along the basin margin. Water depth and sand supply were sufficient for persistent long wavelength wave action to develop extensive shorelines of quartz-rich sandy beaches and dunes. A long period of erosion and non-deposition occurred across the Murray Basin during the Mid-Late Miocene associated with globally low eustatic sea levels (Mologa weathering surface; Brown 1985). Paleodrainage channels were developed above Miocene limestones, particularly in the western Murray Basin, which subsequently influenced the deposition of marginal marine and estuarine sediments during the Early Pliocene.

The final depositional cycle in the Murray Basin was initiated by a rapid marine transgression at the end of the Miocene. The major marine inundation commenced in the Late Miocene with deposits of Bookpurnong Formation, which were mostly thin, offshore marine deposits (average thickness 15 m) distributed across the central-western Murray Basin (Brown and Stephenson 1991). They are absent over the Pinnaroo Block, a probable topographic high, but extended east for a maximum of ~400 km (Brown and Stephenson 1991). The Late Miocene to Pliocene sedimentation of the Murray Basin is dominated by shallow-marine, offshore and coastal facies following a marine transgression during the Late Miocene. A few sea-level changes occurred during Late Miocene to Pliocene (Fig 6). The Murravian Gulf formed during the first sea-level rise resulting in the deposition of clay and marl of the Bookpurnong Formation in the west, while the Calivil Formation (the fluvial counterpart of the Loxton Sand) non-marine sands developed landward in the east (Fig 7). Relative sea-level changes and/or occasional transgressive phases resulted in the formation of elevated stacked barrier islands. Between these barriers, variegated silty clay was deposited in fluviolacustrine environments.

During Pliocene regression, the Loxton Sand formed on the beaches and coastal plain. Highstand deposition throughout the Pliocene led to the progradation of the Loxton Sand – a composite assemblage of shoreface, beach, dune and back-barrier – lagoonal facies that cover more than half of the basin and host economic deposits of heavy minerals sourced from the highlands around the Murray Basin (e.g. Keeling et al. 2015; Köhler 2020). Locally, heavy minerals have been concentrated in the strandplains, including rutile, zircon and ilmenite. The southwest-facing orientation and subparallel alignment of the Loxton Sand barriers suggest that they were formed by long-period swell waves from the Southern Ocean. The resulting paleoshorelines of the Loxton Sand were thus aligned obliquely to the dominant westerly and southwesterly winds blowing across the Murray Basin, resulting in sand transported onshore from the bed of the gulf by swell and moved alongshore, mainly to the east and southeast, by local wind waves (Roy et al. 2000).

Landward of the Pliocene barriers (to the eastern basin), relatively coarse and poorly sorted fluvial sands and muddy overbank deposits of the Calivil Formation were deposited over the upper Renmark Group and in paleovalleys. The paleovalleys onlap the basin margin and grade upward into the Pliocene and Quaternary alluvial Shepparton and Coonambidgal formations (Stephenson and Brown 1989). Due to regional, compressive intraplate tectonism, post-Pliocene uplift along the Padthaway High was responsible for altering the orientation of strandlines and drainage systems, as well as contributing to increased erosion across the strandplain (Miranda et al 2009). The 250+ m uplift in the Grampians in Victoria dammed the Murray River during the Pleistocene (c. 2.5 Ma) which contributed to the formation of Lake Bungunnia (~40,000 km^2; Fig 8). This uplift both restricted and starved the coastline of sandy sediments, changing the depositional environment from one of progradation to active erosion. A series of scarps were produced along the southwestern Murray Basin, ultimately contributing to the formation of the Kanawinka Escarpment, a large erosional cliff feature that is not exclusively the result of fault-related tectonism. After a hiatus of about 2 million years, corresponding to the regressive–transgressive cycle at the end of the Pliocene and Early Pleistocene, barrier progradation began again in the southwestern Murray Basin, forming the Mount Gambier Coastal Plain (i.e. carbonate-rich Bridgewater Formation; Huntley et al. 1993).

The formation of Lake Bungunnia influenced the Pliocene coastal dynamics, depriving the coastline of a sediment source and changing the coastal system from a prograding strandline system to an erosional one (McLaren et al. 2011). The Blanchetown Clay was deposited within this shallow lake, and later shallowing led to deposition of variably dolomitic limestone (Bungunnia Limestone). The formation of Late Pliocene to Pleistocene Lake Bungunnia was likely responsible for the extensive erosion of Pliocene sediments in the western Murray Basin. In places this has resulted in the removal of the oyster coquina, leaving the lower, more open-marine facies of the Norwest Bend Formation, directly overlain (generally unconformably) by these younger lacustrine sediments of the Blanchetown Clay (Miranda 2007). Higher rainfall (>500 mm/yr) kept the lake filled at first, but insufficient rainfall during later times led to the development of saline lakes depositing dolomite.

Conclusion

This study develops a better understanding of the stratigraphic characteristics and geological–depositional environment of sedimentary basins in the study area. The sedimentary basins, together with the underlying basement, are some of the most underexplored Neoproterozoic–Paleozoic–Cenozoic provinces in the Delamerian region. The potential for discovery of new heavy mineral sand deposits, and further extensions of existing ones, are high. This work, together with new information being derived from the MinEx CRC NDI, will provide a greater understanding of the timing and development of the sedimentary basins in the area which in turn will assist with mineral exploration.

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FURTHER INFORMATION

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