Mineral systems of the Murray Basin, New South Wales

Abstract

The Murray Basin in southeastern Australia is an intracratonic sedimentary basin of Cainozoic age that extends across 300,000 square kilometres of New South Wales, Victoria and South Australia. The upper sequences, principally the Loxton–Parilla Sands, Calivil Formation and Shepparton Formation, contain economic accumulations of heavy mineral sands; bentonite; kaolin; and gypsum. Mineral sands are the most significant commodities in the Murray Basin because of their large resources of high-quality coarse-grained rutile, zircon and ilmenite. Quartz sand amenable to construction applications occurs in many places, primarily as aeolian dune deposits, alluvial sequences associated with modern drainage courses, and ancient stream channels along the eastern margin of the basin.

Mineral deposits of the Murray Basin formed in a large geological province in which critical interactions of depositional, eustatic, climatic and tectonic processes influenced their development. High-quality kaolin deposits along the eastern margin of the basin are believed to have been derived from weathering of nearby basement rocks. The kaolin accumulated in lacustrine or floodplain settings. Thick deposits of heavy mineral sands that accumulated in early Pliocene sequences in the northern Murray Basin are believed to represent coastal barrier stacking that occurred during multiple sea level fluctuations of at least 40 m. Bentonite deposits scattered across much of the southern and central Murray Basin were probably derived from volcanic ash emitted from inferred late Pliocene eruptive centres, now concealed by younger sedimentary units.

Cainozoic sequences of the Murray Basin are disrupted in many places as extensive faulted and uplifted basement ridges that mainly trend northeast to southwest. Tectonic activity played a major role in the development of heavy mineral sands concentrations by the formation of uplifted fault blocks upon which beach placers preferentially formed. Structural depressions formed in response to subtle downwarping provided favourable sites for volcanic ash accumulations subsequently altered to bentonite.

During the last 0.5 Ma, large quantities of marine salts from the Southern Ocean have been deposited over much of southern Australia. Those salts leached into shallow aquifers resulting in their typically saline groundwater from which salt is extracted commercially at several locations. Favourable structural or stratigraphic pathways in many places allowed groundwater to migrate to the surface to form hypersaline lakes that dried out leaving numerous deposits of gypsum.

KEYWORDS: kaolin; bentonite; gypsum; salt; heavy minerals; rutile; zircon; ilmenite; Loxton–Parilla Sands; Shepparton Formation; Calivil Formation; Pliocene; Miocene; Iona Ridge; Neckarboo Ridge; Gingko; Murray Basin; Tertiary; Cainozoic; Cenozoic; Woorinen Formation; lunette

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Introduction

The Murray Basin is an extensive intracratonic sedimentary basin of Cainozoic age that extends across New South Wales, Victoria and South Australia (Figure 1). The stratigraphic sequences, which are dominated by variably consolidated sand, silt, clay and lime-rich sediments, formed in a diverse array of marine to marginal marine, deltaic, fluvial and aeolian depositional environments (Figure 2). The Murray Basin has the geological distinction of having an extraordinary, almost-complete, record of ancient shorelines formed over the past six million years that extend in a southwesterly direction from about 500 km inland to the present coast.

There are widespread deposits of heavy mineral sands (rutile, zircon and ilmenite), bentonite, kaolin and gypsum, large quantities of saline groundwater and extensive resources of quartz sand (amenable to various construction applications) in the Murray Basin. These mineral resources principally occur in the Loxton–Parilla Sands, Calivil Formation, Shepparton Formation, Coonambidgal Formation and Woorinen Formation. They formed in a large geological province in which depositional, climatic and structural influences were critically involved in deposit formation. These include relative changes in sea level, differing sediment provenances, episodic climatic variations, complex groundwater systems, subtle tectonic movements over prolonged periods and intermittent volcanic activity.

This paper provides a regional analysis of mineral systems involved in the formation of the mineral resources of the Murray Basin — with concentration upon the New South Wales portion. The distribution of the mineral resources in the Murray Basin is poorly understood, primarily because of limited exploration and the complex depositional, climatic and structural mechanisms involved in their development. In this investigation, the term mineral system includes all geological factors that control the generation and preservation of mineral deposits (Lewis & Downes 2008). Descriptions of the location of the mineral deposits are complimented by comments on their resource significance; their main geological attributes; and a review of mineral exploration techniques that might be useful in delineation of similar deposits. The coal seam methane, coal and petroleum and water resources associated with Cainozoic sequences of the Murray Basin have not been investigated.

Geological setting

The Cainozoic Murray Basin in southeastern Australia is an intracratonic basin extending over 300 000 km² in New South Wales, Victoria and South Australia (Figures 1 & 2) that contains a complex sequence of
Figure 1. Location map of the Murray Basin. The Murray Basin covers an area of about 300 000 km². The region is serviced by main roads, rail, unsealed tracks and numerous towns including the main population centres of Broken Hill, Mildura and Wentworth. The Shuttle Radar Topography Mission digital elevation data contained in this map are from the National Geospatial Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA). The data were made available by the U.S. Geological Survey.
marine, coastal and continental sedimentary sequences (Brown & Stephenson 1991; Ray 1996; Cameron 1996, 1997)). The stratigraphic units of the Murray Basin (Figure 3) form important regional aquifers, confining aquitards and barriers for commonly saline groundwater (Evans & Kellet 1989). The Cainozoic sequence in the entrance of the former ‘Murrayian Gulf’ to the southwest extends beyond the present shoreline. Very low rates of sedimentation and restricted sediment supply resulted in development of a relatively thin sequence, commonly less than 200 m thick, of flat-lying, poorly lithified, partly consolidated sand, silt, clay and lime-rich sediments (Whitehouse et al. 1999).

In the central and western Murray Basin, the Tertiary sequences are largely concealed by younger aeolian, fluvial and lacustrine sediments (Brown & Stephenson 1991). There, entrenched river channels and associated floodplain and lake complexes of the lower Murray River, Darling River and Darling Anabranch form well-defined meander belts in a predominantly aeolian landscape. The Riverine Plain, an extensive relatively flat surface of coalesced alluvial floodplains in the eastern side of the Murray Basin, is associated with the west flowing Murray, Murrumbidgee and Lachlan rivers. Although the Riverine Plain has received sediments over millions of years, primarily derived from adjacent basement rocks along its eastern margin, major palaeochannels that transect much of its surface largely developed during the last full glacial cycle between about 105 ka and 10 ka (Page & Nanson 1996).

Intermittent faulting since the Miocene along reactivated basement faults has produced areas of differential uplift and subsidence creating extensive northeast-trending concealed basement ridges (Evans & Kellet 1989). The Neckarboo and Iona ridges, which dominate the central New South Wales part of the Murray Basin, consist of numerous upthrown fault blocks. In contrast, downthrown fault blocks appear to be marked by normally dry lakes with associated lunettes (Brown & Stephenson 1991). Besides many predominantly northwest-trending topographic rises, the western and central parts of the basin have sporadic isolated curvilinear fault lines. Shallow circular depressions up to several kilometres wide in some places are possibly related to blockfaulting or downwarping. Rather than developing extensive alluvial plains through continual channel migration, river courses commonly show abrupt stepping. It is thus likely that palaeodrainage in places was structurally controlled.

Three main Tertiary depositional cycles in the Murray Basin were distinguished by Brown and Stephenson (1991):
Figure 3. Stratigraphy of the Murray Basin (from Ray 1996).
1. Sedimentation started about 60 Ma with deposition of the fluvial Warina Sand of the Renmark Group, which was overlain by the predominantly fluvial and lacustrine Olney Formation.

2. Beginning in the late Oligocene (circa 30 Ma) and culminating with the ‘Miocene Optimum’ in the middle Miocene (circa 15 Ma), the basin experienced a major marine incursion in which fluvial sedimentation was replaced by shallow shelf deposition followed by deeper water limestone sequences. The Ettrick and Winambool formations, the Geera Clay (and Geera Clay equivalents) and Murray Group limestone sequences were deposited during development and final contraction of these marine environments. In the late Miocene, sedimentation in the Murray Basin was interrupted by a global fall in sea level resulting in a regression that was accompanied by the seaward spread of the upper Renmark Group across the Geera Clay. This was followed by a period of non-deposition and subaerial weathering known as the Mologa Surface.

3. The final depositional cycle in the Murray Basin was initiated by a rapid marine transgression at the end of the Miocene. Deposition throughout the Pliocene led to the progradation of the Loxton–Parilla Sands — a composite assemblage of (regressive) shoreface, beach, dune and back barrier–lagoonal facies that cover more than half the basin.

During the Pliocene, the climate was warmer and wetter and barrier sands at various times were subject to lateritic weathering during depositional breaks to produce ferricrete (iron-rich) horizons, palaeosols and erosional surfaces. The Loxton–Parilla Sands contain widely dispersed economic concentrations of heavy minerals, notably ilmenite, rutile and zircon (Whitehouse et al. 1999; Roy et al. 2000). Bentonite deposits, derived from alteration of volcanic ash that mainly accumulated during the latter stages of the formation of the Loxton–Parilla Sands, occur at various locations. In the southern part of the basin, the Loxton–Parilla Sands overlie shelf muds, the Bokpurnong beds, which might have formed during the marine transgression or as low-energy, offshore environments dominated by channel, levee and floodplain deposits. The Calivil Formation, mostly poorly consolidated, consists of pale grey, poorly sorted medium- to coarse-grained quartz sand/sandstone and locally thick lenses of kaolin that assume commercial significance along the eastern margin of the Riverine Plain.

Although barrier progradation continued seaward in the Quaternary, uplift reversed regional gradients elsewhere in the Murray Basin — with the result that drainage of inland rivers was impounded to form Lake Bunguninja (circa 2.5–0.7 Ma) (Brown & Stephenson 1991). The resulting fine-grained lacustrine deposits, which correspond to the Blanchetown Clay, disconformably cover low areas and swales between the numerous barriers of the Loxton–Parilla Sands. The disconformity is commonly marked by a weathering profile that is locally siliceous or lateritic and is known as the Karoonda Surface. Increasing aridity, which occurred during the Quaternary, caused Lake Bunguninja to shrink and break into saline playas and groundwater discharge areas, precursors of present dry lakes in the basin. This was accompanied by aeolian reworking of surface deposits into active dunes, source-bordering dunes and lunettes (principally the Woorinen Formation and Molineaux–Lowan Sands) and fluvial activity in areas bordering the main rivers.

Late Quaternary sediments of stranded lake floors, gypsum flats, salinas, gypsum and clay pellet dunes and lunettes have developed across the Murray Basin in association with ancient and active groundwater discharge zones. Silcrete occurs on and in sandstones of Pliocene age in some places, the rock type generally being clay-cemented quartz arenite. Lunettes, generated by the deflation of gypsum (kopi), clay and salt by predominantly westerly winds, occur within and on the eastern sides of salt lake complexes. Older salt lake complexes have been infilled with aeolian sand dunes derived from the west of the lakes.

Along the margins of the Riverine Plain, mixed aeolian and colluvial deposits or outwash fans consist of polygenetic soils and sediments, including gravity-transported bedrock fragments of inferred middle to late Pleistocene age (Brown & Stephenson 1991). These materials are comparable to the Pooraka Formation in the western Murray Basin that was derived from the eastern flanks of the Mount Lofty Ranges and Flinders Ranges. The Shepparton Formation is present mostly as slightly elevated backbasins within the Riverine Plain. This coarser-grained (than floodplain units closer to the main channels) formation represents initiation of sedimentation on the modern Riverine Plain. The Shepparton Formation, deposited in a predominantly
fluvial setting with sporadic (aeolian) parna deposits and overflow lake sediments, forms extensive flat alluvial floodplains traversed by traces of meandering palaeochannels (Cameron 1996; Page & Nanson 1996). In much of the Riverine Plain, this sequence is associated with the Coonambidgal Formation, primarily poorly consolidated, mottled, variegated clay and silty lenses of polymictic sand and gravel (Brown & Stephenson 1991).

Mineral systems

The upper sequences of the Murray Basin, principally the Loxton–Parilla Sands, Calivil Formation and Shepparton Formation, contain economic accumulations of heavy mineral sands, bentonite, kaolin and gypsum (Figure 4). Complex depositional, eustatic, climatic and tectonic processes were involved in the formation of the mineral resources — as discussed below. The heavy mineral sands deposits are the most significant commodities owing to their large resources of high-quality rutile, zircon and ilmenite. Silica (quartz) sand amenable to mainly construction applications occurs in many places, primarily as aeolian deposits in the Woorinen Formation and as alluvial sequences in the Coonambidgal Formation and ancient stream courses along the eastern margin of the basin. The Loxton–Parilla Sands is also a valuable source of silica sand in various places, particularly in South Australia.

The Riverine Plain, occupying much of the eastern margin of the Murray Basin, includes Tertiary units overlain by fluvial and lacustrine and minor aeolian sequences that contain scattered deposits of kaolin derived from the weathering of nearby basement rocks; extensive sand and gravel deposits; and minor gypsum occurrences. In the central and western Murray Basin, the predominantly marine sequences of the widespread Pliocene Loxton–Parilla Sands contain numerous deposits of mineral sands and scattered deposits of bentonite thought to be derived from alteration of volcanic ash emitted by nearby eruptive centres. At many places, particularly near Balranald, saline groundwater in the Loxton–Parilla Sands migrated to the surface along various pathways to form numerous salt lakes in which gypsum deposits developed when the climate became increasingly arid. Saline groundwater is exploited for its salt content, principally sodium chloride and magnesium chloride, at several locations through solar evaporation pond technology.

Dating of zircons in the Pliocene Loxton–Parilla Sands (Sircombe 1999) indicated that the heavy mineral assemblages were derived from varied geologic sources (ranging in age from about 100 Ma to more than 1000 Ma); distant sedimentary repositories; and complex sediment transport pathways. A study of chrome spinels in heavy mineral assemblages of the Loxton–Parilla Sands (Powneby 2005) found that multiple source areas of ilmenite were involved although that work did not extend to the identification of specific provenances. Bentonite deposits are believed to have been derived from volcanic ash emitted from inferred nearby eruptive centres now covered by younger sediments (Gardam et al. 2008). Widespread deposits of gypsum that formed in the late Quaternary represent the drying of hypersaline lakes (Bowler 1976).

Depositional regime influencing mineral deposit formation

The mineral deposits of the Murray Basin primarily formed in a diverse array of alluvial, lacustrine, estuarine, deltaic, backbarrier, shoreface and shallow marine settings (Brown & Stephenson 1991). Aeolian dunes are also potential sources of sand for construction applications. The Riverine Plain, which contains fluvial and lacustrine sediments of the Calivil Formation and Shepparton Formation, hosts commercial occurrences of kaolin — derived by erosion of basement rocks along the eastern margin. The predominantly marine Loxton–Parilla Sands contains major resources of heavy mineral sands and regionally significant deposits of bentonite, gypsum and saline groundwater.

In the early Pliocene, relict Miocene sands, reworked from the ocean floor and transported shoreward, were probably the main source of sand for the prograding Pliocene barriers of the Loxton–Parilla Sands (Whitehouse et al. 1999; Roy et al. 2000). Periodic sea level fluctuations, probably linked to Milankovitch systems, shifted the zone of wave reworking backwards and forwards to produce multiple transgressive highstand barrier sand bodies (Whitehouse et al. 1999).
These remnant, generally featureless former shorelines extend alongshore in an overall northwest to southeast direction as smooth arcs spread over a total distance of 400–500 km. The development of at least 150 barriers of the Pliocene Loxton–Parilla Sands — now some 450 km inland of the present shoreline — involved cyclic sea level rises over the past 6 Ma (Brown & Stephenson 1991). Thick accumulations of heavy mineral sands in the early Pliocene northern part of the Murray Basin are inferred to represent barrier stacking that occurred in response to multiple sea level fluctuations (Roy & Whitehouse 2003). In the middle and late Pliocene, deposition of marine muds (Bookpurnong beds) on the floor of the Murrayian Gulf seawards of the prograding barriers saw a change from seabed erosion to seabed deposition (Whitehouse et al. 1999). Changes in the depositional regime might have been due to increasing deposition of continental sediments and/or deepening of the basin. This would have resulted in a marked reduction in the quantity of reworked heavy mineral-bearing sand available for prograding barriers. As a result, much of the central and southern parts of the basin became less favourable for the formation of beach placers.

Climatic regime influencing mineral deposit formation

The influence of climatic variation across the Murray Basin became important in the Miocene when deep weathering of basement rocks to kaolin clays along the eastern margin of the Riverine Plain were eroded and deposited in bordering fluvial and lacustrine sediments of the Calivil Formation (Pearce 1975; Brown & Stephenson 1991). Accumulation of scattered occurrences of kaolin was accompanied by influxes of sand and gravel, resulting in formation of extensive occurrences of materials suitable for construction applications. The climatic regime experienced during the evolution of the Murray Basin, particularly during the early and middle Pliocene and during the late Quaternary, played a major role in mineral deposit formation. Numerous oscillations of the Western Antarctic ice sheet related to a 40 000 year periodicity linked to the Earth’s orbital obliquity occurred during the Pliocene (Gallagher et al. 2003; Ravelo et al. 2004; Pollard & DeConto 2009). During the early development of the Loxton–Parilla Sands, the Antarctic ice sheet was probably around two-thirds of its present size, and was periodically shrinking and growing until it stabilised in the late Pliocene, at approximately 2.5 Ma. Repeated fluctuations in sea level associated with these cycles, for instance, are believed to have been responsible for the formation of thick beach placer deposits of mineral sands, as much as 40 m, in parts of the northern Murray Basin (Roy & Whitehouse 2003). Ensuing widespread stillstand conditions that broadly coincided with the stabilisation of the western Antarctic ice sheet were marked by development of beach placer deposits of much lesser thicknesses, typically 3–5 m.

In the late Quaternary, the role of climate in the formation of mineral deposits in the Murray Basin, principally gypsum, again became significant. During that period, increasing aridity resulted in the widespread development of gypsum-bearing ancient lakes and bordering lunettes (Bowler 1976). This trend culminated in formation of extensive aeolian deposits through loss of vegetation from stable sand sheets and aeolian dune building. Development of ancient hypersaline lakes in turn is related to accumulation at the surface of saline water that migrated to the surface from shallow Pliocene aquifers, referred to as the Pliocene Sands aquifer system (Brown & Stephenson 1991). The saline water evolved in response to huge quantities of marine aerosols (salts) that were brought inland over vast distances by intense winds from the Southern Ocean (Jones et al. 1994; Warren 1999; Whitehouse 2003). The marine salts infiltrated shallow Pliocene aquifers after deposition on the land surface to form groundwater of mixed continental–marine character. Weathering of the Loxton–Parilla Sands, including alteration of ilmenite to pseudorutile, anatase and leucoxene (Paine 2005), is associated with development of a ferruginous duricrust as much as 15 m thick — in places known as the Karoonda Surface (Brown & Stephenson 1991). Alteration of ilmenite during post-depositional weathering has involved the loss of Fe and Mg, mechanical breakdown, and the incorporation of impurities into grain surfaces (Whitehouse 2006). Iron lost from ilmenite subject to intermittent oxidation–reduction conditions is believed to have resulted in formation of ferruginous mottles in the weathering zone (Paine 2005). The commercial value of the altered ilmenite might, to some extent, have benefited from the late-stage period of intense weathering because potential increases in the proportion of titanium dioxide could improve ilmenite amenability to synthetic rutile production.

Structural regime influencing mineral deposit formation

The Cainozoic sequences of the Murray Basin are disrupted in many places, notably over concealed basement ridges consisting of numerous typically northeast to southwest-trending fault-bound blocks that form areas of distinct positive relief (Evans & Kellet 1989; Whitehouse et al. 1999). These appear to have developed in response to growth faulting that...
involved vertical displacements of Pliocene sediments by circa 60 m. Away from the largely flat Riverine Plain, much of the topography is quite irregular — indicating that recent growth faulting is widespread. Growth faulting is thought to have played a significant role in development of beach placers through formation of uplifted fault blocks that acted as ‘virtual’ headlands during the formation of coastal barriers (Whitehouse et al. 1999). Winnowing by storm waves that were directed onto oversteepened shore faces associated with the fault blocks concentrated heavy minerals to form extensive beach placer deposits.

Distinct plateaus or ridges along the eastern margin of the Riverine Plain, some of which are known to contain thick deposits of kaolin, could represent uplifted fault blocks that were substantially protected from erosion by adjacent drainage. Another interpretation is that the kaolin deposits (see below) form part of a remnant plateau formed by erosion of the surrounding Riverine Plain. In some places, particularly along the western margins of the Riverine Plain, gypsum-bearing salt lakes have formed where basement ridges intersect Pliocene aquifers allowing saline groundwater to reach the surface (Brown & Stephenson 1991).

Moderate downwarping along the eastern margin of the Neckarboo Ridge allowed relatively thick deposits of airborne or waterborne volcanic ash, subsequently altered to bentonite, to accumulate on the Loxton–Parilla Sands (Gardam et al. 2008). There, volcanic ash initially settled within an inferred graben and subsequently in a nearby coastal lagoon.

**Mineral commodities**

**Bentonite**

Bentonite deposits (Figure 5) are widespread in the Murray Basin, particularly in its central and southern regions, where these deposits are largely developed on or within the Pliocene Loxton–Parilla Sands, and (to a lesser extent) in younger sediments (Brown & Stephenson 1991). A summary of the geology of bentonite deposits in the Murray Basin is given in Appendix 1. Bentonite production in the 2006/07 financial year from deposits in the New South Wales part of the Murray Basin was almost 16 000 tonnes (Figure 4) (about 52% of the state’s total production of bentonite). The Loxton–Parilla Sands is a favourable horizon for bentonite formation because of its potentially numerous back barrier lagoons, lakes and drainage depressions that could have formed depocentres for volcanic ash accumulation. Local downwarping helped to control the thickness and extent of the bentonite deposits. The Loxton–Parilla Sands also covered much of the basin when eruptive activity was most pronounced — enabling volcanic ash to be deposited over large areas of relatively intact barrier systems.

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**Figure 5.** Bentonite deposits of the Murray Basin.
The most important deposits, near Arumpo (Figure 5, Photograph 1), are inferred alteration products of volcanic ash that largely accumulated along the Neckarboo Ridge on or within the Loxton–Parilla Sands. According to Gardam et al. (2008), the Arumpo deposits consist of several bentonite layers usually 5 m thick, overlain by 5–20 m of clay and sand, that are developed over an area some 10 km long by 5 km wide. They believe that distinctive geochemical variations in the unique Na–Mg bentonite deposits at Arumpo are related to depositional settings in which volcanic ash accumulated. The Arumpo bentonite deposits apparently represent an earlier phase of eruptive activity of intermediate and mafic composition — involving ash deposition into a graben setting dominated by saline estuarine depositional conditions — and a second episode of eruptive activity involving deposition in a nearby coastal lagoonal system. The nature of the boundary between these adjacent depositional sites is unclear. Several episodes of ash accumulation, during which these deposits and much of the surrounding area were variably infilled, followed. The high-purity of the bentonite indicates that, apart from several apparent episodes of aeolian sand deposition that left generally thin layers of sand between the various bentonite horizons, there was comparatively little aeolian or fluvial contribution to sedimentation during periods of intense ashfall.

The Arumpo deposits are in relatively close proximity to scattered groups of high-intensity magnetic features interpreted by Gardam et al. (2008) as concealed volcanic pipes. They speculated that these features might have been responsible for eruption of ash material involved in bentonite formation rather than sources in the more distant Victorian Highlands (Whitehouse et al. 1999).

Bentonite has also been identified at Trida, northeast of Hay (Holmes 1983). In contrast to Arumpo, bentonite deposit at Trida is of very poor quality and contains large proportions of quartz. The Trida deposits appear to be associated with a small claypan on the Riverine Plain, which is dominated at this locality by irregular drainage courses, sporadic low relief hills, claypans and numerous gypsite deposits. Gardam et al. (2008) believed that deposits at Trida might also be genetically related to the Arumpo deposits as they are relatively close to inferred concealed volcanic pipes defined to the southwest.

**Photograph 1.** Arumpo bentonite mine, Arumpo. This mine has large resources of high quality Na–Mg bentonite derived from volcanic ash that accumulated along the flank of the Neckarboo Ridge, a northeast-trending concealed basement ridge. Photograph courtesy of Matt Gardam, Arumpo Bentonite Pty Ltd.
Gypsum

Gypsum deposits (Figure 6, Photograph 2) are widely distributed across the central and western parts of the Murray Basin as crystalline, sand- and silt-size deposits of late Pleistocene to Holocene age in continental salt lakes, or playas, within active and preserved groundwater discharge zones (Brown & Stephenson 1991). A summary of the geology of gypsum deposits in the Murray Basin is given in Appendix 2. The Murray Basin is the main source of agricultural gypsum in New South Wales. Gypsum production in this region for the 2006/07 financial year (Figure 4) was about 94 000 tonnes (almost 75% of the state’s production of gypsum).

Gypsum formation primarily occurred in the late Quaternary, about 25 000 ka to 15 000 ka ago, when salt lakes shrank drastically during periods of intense aridity to form evaporative brine pools (Bowler 1976; Brown & Stephenson 1991). Crescent-shaped dunes (lunettes) of gypsum and/or clay that form rims along their eastern margins developed in response to predominantly westerly wind-induced deflation of the salt lakes. Gypsum deposits within preserved and active saline (brine) lake floors are generally crystalline and typically about one metre thick, indicating that the land surface during their formation was relatively stable over large areas. Gypsite (very fine-grained or powdery gypsum) associated with lunettes can be locally extensive, of varying purity and several metres or greater in thickness. Most of the gypsum has been derived from saline groundwater in the underlying Pliocene sands aquifer system which, in the central Murray Basin, has salinities exceeding 100 000 mg/L (Jones et al. 1994; Warren 1999; Whitehouse 2003).

Photograph 2. Gypsum Palace gypsum mine, Ivanhoe. These are old workings in the Gypsum Place gypsum mine area near Ivanhoe (with wombat burrow on right hand side, width ~1 m). Although there has been no large-scale extraction of crystalline gypsum for many years, small quantities of gypsite are intermittently mined. Photographer: Tony Mason.

Figure 6. Gypsum deposits of the Murray Basin. Gypsum-bearing salt lakes are associated with locally variable groundwater discharge areas, in mostly wind deflation zones, and interdune (swale) areas of the Pliocene Loxton–Parilla Sands. They are also associated with an extensive groundwater discharge zone where aquifers in the Miocene Renmark Group, and younger sediments, intersect the Iona Ridge (concealed basement fault-block complex).
During the last half-million years large quantities of marine salts from the Southern Ocean were deposited over much of southern Australia, and leached into shallow aquifers, resulting in saline groundwater.

At numerous places, saline groundwater migrated to the surface along favourable structural or stratigraphic pathways to create hypersaline lakes that dried out to form numerous deposits of gypsum (Evans & Kellet 1989). In parts of the Murray Basin, groundwater involved in gypsum formation probably also came from other aquifers, notably within the Renmark Group. Gypsum deposits in the northern Murray Basin are likely to be related to local discharges of saline groundwater from Miocene sediments.

Many gypsum deposits are associated with an extensive north–south zone along the western and northern margins of the Riverine Plain. There, groundwater discharge occurs along a zone where aquifers of the Renmark Group and younger sediments intersect the Iona Ridge creating a favourable structural pathway for groundwater to reach the surface.

Kaolin
The eastern margin of the Murray Basin has locally significant occurrences of high-quality kaolin derived from weathered basement rocks that accumulated in lacustrine or floodplain settings associated with coalesced stream channels of the Riverine Plain (Figure 7). A summary of the geology of the kaolin deposits in the Murray Basin is given in Appendix 3. The most important deposits, near Oaklands (Photograph 3), contain high-grade kaolin suitable for various industrial applications that include brick manufacture, industrial fillers and whiteware ceramics. Production in this part of New South Wales during the 2006/07 financial year (Figure 4) was about 26 000 tonnes (about 50% of the state’s production of kaolin). Elsewhere, in modern fluvial systems of the Murray River and Murrumbidgee River, irregular

Photograph 3. Oaklands kaolin mine, Oaklands. These kaolin deposits form part of a well-defined north–south trending plateau some 60–80 m above the Riverine Plain. This plateau could either be tectonically uplifted or represent an erosional remnant. Photographer: Bob Brown.
deposits of sand and clay are associated with floodplain sequences of the Coonambidgal Formation (Brown & Stephenson 1991). These clays have apparently been used in the manufacture of bricks although their current importance is unknown (probably minor).

Kaolin occurrences in fluvial and lacustrine sequences along the eastern margin of the Riverine Plain are believed to be late Miocene weathering products of basement rocks in adjacent highlands (Brown & Stephenson 1991). These deposits form irregular, commonly lens-shaped deposits of kaolinitic clay, silty clay and sandy clay that occur mainly above, but also within and probably below, sand and gravel deposits of the Calivil Formation. The Oaklands kaolin deposits broadly consist of a lower, mostly kaolin-rich zone with sporadic layers of sand and an upper zone dominated by interbedded kaolin and sand (Pearce 1975). In turn these horizons are separated by sandy clay units. Although the specific depositional conditions have yet to be examined in detail, these features suggest that predominantly lacustrine conditions (e.g. Posamentier & Allen 1999) prevailed during formation of the lowermost kaolin layer. The increasing quantities of sand and gravel in overlying sequences indicate that fluvial conditions eventually became more dominant. The Oaklands kaolin deposits (Photograph 3) form part of a distinctive north–south plateau that occur some 60–80 m above the Riverine Plain and extends over an area of at least 50 km². The origin of this plateau, which could have significant potential for more resources of kaolin, is unclear. This area might be an erosional remnant of the Riverine Plain or alternatively formed in response to localised uplift.

Heavy mineral sands

Numerous deposits of heavy mineral sands that contain premium-quality rutile, zircon and ilmenite are found in the central and western parts of the Murray Basin (Figure 8). They occur as relatively coarse-grained placers (100–350 microns) that formed in the beach-surf zone of prograded barriers of the Pliocene Loxton–Parilla Sands, and fine-grained deposits (40–100 microns) (‘WIM-style’ deposits) that accumulated in lower shore and inner shelf environments (Williams 1990; Whitehouse et al. 1999). Heavy mineral sands deposits of unknown resource potential have also been identified during exploration drilling in the underlying Renmark Group. A summary of the geology of heavy mineral sands deposits in the Murray Basin is given in Appendix 4. Heavy mineral sands production in New South Wales for the 2006/07 financial year (Figure 4) was about 874 000 tonnes (100% of the state’s production of heavy mineral sands).

Heavy mineral deposits are primarily developed in the landward part of the Loxton–Parilla Sands
in a broad zone (Figure 8) that directly overlies the upper Renmark Group (Whitehouse et al. 1999). This zone of enhanced mineralisation contrasts with central and southwestern parts of the basin where the Loxton–Parilla Sands barriers are underlain by shelf muds (Bookpurnong beds). The Bookpurnong beds contain disseminated occurrences of very fine-grained heavy minerals though this sequence is believed to have a lower heavy mineral resource potential. Beach placers are typically 3 m thick, narrow (<100 m wide), high-grade (10–25% HM composite basis) single beach deposits (e.g. Farrell et al. 2001). Within sequences of the northern Murray Basin, some heavy mineral sands deposits are up to 40 m thick, high-grade (10–25% HM composite basis) (e.g. Farrell et al. 2001). In contrast to the narrow deposits, which probably formed during periods of prolonged relatively stable sea levels, the thick, wide deposits are inferred to have formed in response to barrier stacking.

Along the southern margin of the Murray Basin in Victoria, a group of coarse grained high-grade beach placers (Douglas deposits) accumulated against basement rock headlands formed by localised early Pliocene faulting (Farrell et al. 2001; Paine et al. 2004). The Douglas deposits are typically very narrow (80–100 m wide), moderately thick (up to 10 m) beach and dune facies of single beach deposits containing high-grade zones of heavy minerals. Farrell et al. (2001) believed that, east of the Douglas deposits, major faulting and uplift brought WIM-style deposits (and their associated beach placers) towards the surface. Erosional stripping of the beach placers is inferred to have recycled and reconcentrated the heavy minerals into younger beach placers nearby. This implies that the Douglas beach placers are younger than other placer deposits in the Murray Basin.

In the central Murray Basin, many beach placers deposits, such as the Ouyen group of deposits (northern Victoria) and numerous deposits near Balranald, have sharply defined aeromagnetic responses. The intensity of the aeromagnetic response of the Ouyen deposits played a major role in their discovery. The proportion of ilmenite in the heavy minerals assemblage might be of critical importance in determining the magnetic tenor of these deposits. Thickness of overburden does not appear to be crucial as some magnetically responsive deposits are relatively deeply buried, at depths of 30–40 m or more. The Ginkgo deposit (Figure 8, Photograph 4) in the northwestern Murray Basin has an ilmenite-rich heavy minerals assemblage 30–50 m deep and up to 500 m wide, but has no significant aeromagnetic response.

Overall, aeromagnetic detection of beach placers appears to be more effective where the overburden is mostly alluvial sediment, which dominates the eastern extension of the Loxton–Parilla Sands. The interval between magnetic basement rocks and overlying beach placers is inferred to be greater in the eastern part of the Murray Basin.

Beach placers dominantly formed as localized accumulations of heavy minerals through enhanced (or concentrated) erosion by storm waves on up-faulted blocks associated with growth faults intersecting the coastline. Two separate possible mechanisms for the creation of localised concentrations of heavy minerals in the Murray Basin have been proposed (Whitehouse et al. 1999):

1. ‘Transgressive barrier fractionation’ processes (Roy 1999) operating during the early Pliocene in the Murravian Gulf. Primary controls on the formation of beach placers appear to be: suitable, heavy mineral-bearing parent sand derived from the bed of the Murravian Gulf for incorporation into wave-formed barriers; and episodic fluctuations in sea level that drove successive barriers landward.

2. Littoral bypassing fractionation’ processes operating in an environment where growth faulting in parts of the basin created relatively steep, ‘virtual’ headlands in the otherwise featureless, sandy coastline.

Single deposits of high-grade heavy minerals were thought by Farrell et al. (2001) to have formed during single storm events comparable to modern cyclones, which imply that relatively short-lived, intense reworking occurred. Severe shoreline erosion associated with numerous intense storms and hurricanes in Holocene barrier systems, Maine, United States of America, has produced narrow buried storm scarps containing sands with more than 50% heavy minerals (Buynevich et al. 2004).

Photograph 4. Ginkgo heavy mineral sands mine, Poocarrie. The considerable thickness of the heavy minerals-bearing sand at Ginkgo — in the order of 40 m — is attributed to barrier stacking that occurred in response to multiple sea level rises in the early Pliocene (circa 3–5 Ma). Photographer: John Whitehouse.
Development of heavy minerals concentrates depends both on the quantity of sand that can be mobilised during single storms (or cycles of storms), which is probably comparatively limited, and on the quantity of heavy minerals present (Roy 1999). Fractionation mechanisms that produce heavy mineral concentrations on the beach face involve winnowing leaving heavy mineral lags that build up over hundreds or thousands of years. During the Pliocene, southeastern Australia had climatic regimes comparable to those experienced at present (Kotsonis 1999; Gallagher et al. 2003). Storms of cyclonic intensity similar to those envisaged by Farrell et al. (2001) were probably uncommon in southeastern Australia and not likely to have played a significant role in the accumulation of heavy mineral sands deposits.

Whitehouse et al. (1999) believed that beach placers over much of the Murray Basin formed during extended periods of generally elevated sea level interspersed with relatively small-scale sea level fluctuations, possibly related to 20–40 ka Milankovitch cycles. These deposits are mostly 2–3 m thick, occur at depths ranging from near-surface to over 50 m, are generally narrow (about 100–200 m wide) and are developed over distances in the order of several kilometres to as much as 40 km. In contrast, the northern, early Pliocene part of the Murray Basin has several deposits of considerable thickness (e.g. Ginkgo and Snapper). The Ginkgo deposit has, for example, heavy minerals layers with a thickness of 40 m and widths exceeding 500 m (Roy & Whitehouse 2003). Such occurrences are inferred to represent composite or stacked deposits that developed episodically in response to multiple sea level fluctuations.

Intensive mineral sands exploration in the northern Murray Basin has discovered high grade (20–30% HM composite basis) single beach placers 3–5 m thick, commonly deeply buried, that extend continuously or intermittently over distances of 20–30 km. The most important of these, the West Balranald deposit, contains about 12 Mt of rutile, zircon and ilmenite, making it the largest known beach placer in the Murray Basin (Whitehouse 2006). This deposit appears, based on remnant barrier trends defined using Digital Elevation Model (DEM) imagery, to have formed in the same group of barriers occupied by the Ginkgo deposit further northwest. Development of several quite dissimilar groups of beach placers at the same time in different parts of the Loxton–Parilla Sands might be due to different local rates of sedimentation (Posamentier & Allen 1999).

The origin of the West Balranald deposit (and similar nearby mineral sands deposits) remains unclear. There are, however, several mechanisms that could account for their development (Whitehouse et al. 1999). These deposits could be transgressive barrier deposits that formed along locally steepened, tectonically controlled substrates in barrier processes by which offshore dispersal of ‘light’ sand occurred and a heavy mineral-enriched ‘condensed’ section developed on the shoreface. The formation of such a large deposit could also occur if a pre-existing barrier containing some heavy minerals is redeposited by a transgressive barrier with heavy minerals derived from the sea floor. This process could result in significant quantities of heavy minerals being added to an existing barrier and enable an extremely high-grade mineral sands deposit to form.

In several parts of the Murray Basin, notably southern Victoria, fine-grained heavy minerals (WIM-style) deposits are extensively developed and they have the potential to host very large resources of heavy minerals (Williams 1990). These deposits typically have broad lobe-shaped geometries and are irregularly distributed seaward-dipping lenses of heavy minerals-rich sand (HM grades up to 40%) separated by barren or poorly mineralised sand layers of variable thickness. Individual lenses of heavy minerals-rich sand range in thickness from a few centimetres to 2 m over distances of up to several hundred metres, and occur in deposits with cumulative thicknesses up to 15 m.

The origin of very fine-grained deposits of heavy minerals in the Murray Basin is poorly understood. Specific mechanisms by which segregation of quartz sand layers and heavy minerals lenses occur in this environment have yet to be fully explained. The presence of hummocky cross-stratification in the WIM-150 deposit (Williams 1990) indicates that their development was controlled by episodic storm-wave processes below fair-weather wavebase (Hampson & Storms 2003). Dumas and Arnott (2006) considered that hummocky cross-stratification forms above (but near) storm wavebase where depositional rates during storms are high enough to preserve hummocks.

Saline groundwater

Highly saline groundwater occurs across much of the Murray Basin, particularly within shallow aquifers (Evans & Kellet 1989; Brown & Stephenson 1991). In New South Wales (Figure 9), the most important groundwater system is the Pliocene sands aquifer system, a composite aquifer of the near-surface Loxton–Parilla Sands (western and central) and buried Calivil Formation (east) (Brown & Stephenson 1991). A summary of the geology of saline groundwater occurrences in the Murray Basin is given in Appendix 5.

Groundwater salinity, which exceeds 100 000 mg/L Total Dissolved Solids (TDS) in the upper 100 m of the central Murray Basin, is dominated by Na+ and Cl− ions, along with varying amounts of Mg2+, SO42− and Ca2+ ions (Jones et al. 1994; Warren 1999; Whitehouse 2003).
Photograph 5. SunSalt salt extraction operation, Lake Gol Gol, Mildura. Solar evaporation ponds are used to extract salt from saline groundwater pumped to the surface from shallow aquifers in the Loxton–Parilla Sands into the Mourquong salt disposal basin on the western side of Lake Gol Gol. Photographer: John Whitehouse.

Photograph 6. Lake Gol Gol, Mildura. This extensive salt lake contains numerous dunes of gypsite (powdery gypsum) overlying crystalline gypsum. Apart from being an important source of agricultural grade gypsum, salt is obtained from saline groundwater pumped into the Mourquong Swamps from nearby boreholes. Landsat 7 image © Commonwealth of Australia (Geoscience Australia) 2002. This material is released under the Creative Commons Attribution 2.5 Australia Licence. http://creativecommons.org/licenses/by/2.5/au/

Figure 9. Saline groundwater deposits in the Murray Basin.
Marine salt aerosols have been deposited across southern Australia in very large quantities and leached into basin-wide shallow aquifers on a long term basis, resulting in the saline character of Murray Basin groundwater. Processes involving past episodes of high groundwater surfaces and salt entrapment through evaporation have contributed to the saline nature of the shallow aquifers (Brown & Stephenson 1991).

Salt extraction, principally NaCl and MgCl₂, takes place in several parts of the Murray Basin to reduce the adverse effect of saline groundwater on agricultural production. Commercial salt extraction using solar evaporation technology is undertaken in the Mourquong salt disposal basin (Figure 9, photographs 5, 6) near Mildura (Whitehouse 2003). This involves salt extraction for markets that include food processing and industrial applications. Salt production in this region in the 2006/07 financial year (Figure 4) was 18 500 tonnes (100% of the state’s total production of evaporated salt). Additional processing after evaporation of saline mineral obtained from the groundwater could involve the manufacture of such materials as magnesium sulphate, chlorine, hydrochloric acid and various industrial materials (Aral & Sparrow 2002; Whitehouse 2003).

Silica sand

Silica sand deposits amenable to construction applications are found in aeolian dunes of the Woorinen Formation; fluvial and marine units of the Loxton–Parilla Sands; ancient fluvial sequences of the Riverine Plain; and in the Coonambidgal Formation along modern drainage courses (Figure 10) (Brown & Stephenson 1991). A summary of the geology of silica sand deposits in the Murray Basin is given in Appendix 6. Although sand resources occur widely, extraction is mainly concentrated in areas of more intense development. Production of sand in the 2006/07 financial year is uncertain.

The most important sources of construction are fluvial deposits associated with the Murray River and the courses of ancient stream channels on the Riverine Plain. Small deposits of high-purity alluvial sand amenable to such industrial applications as glass making have been found along the eastern margin of the Riverine Plain (Gobert & Corkery 1978). Those deposits, however, have yet to be exploited owing to their presence below a comparatively thick cover of intermixed sand and clay, the need for the silica sands to be processed to remove their clay fractions and their considerable distance from existing glass-manufacturing operations.

Figure 10. Silica sand deposits in the Murray Basin. Mainly sand associated with fluvial deposits of major channels, aeolian dunes, outcrops of Loxton–Parilla Sands, and isolated sand sheets.
Mineral resource development issues

The Murray Basin region is a large, sparsely populated region with areas of more intense development at Broken Hill and Mildura. Although the area’s economy is based on primary production, mineral resource exploitation is providing significant economic benefits for the area in terms of bulk transport developments involving road and rail, significant employment opportunities, mineral processing sites and the potential for mineral resource processing to produce diverse mineral products. Improved transport, water and energy infrastructure and local environmental issues (such as water supply) need to be progressively resolved as new mineral resource projects are proposed. The recent resurgence of the heavy mineral sands industry in New South Wales, Victoria and South Australia has seen the development of mineral processing sites, improved transport facilities and the utilisation of port facilities that will encourage future developments proposed for the region. The use of reverse osmosis facilities on remote mining sites, for example, is enabling these operations to process saline groundwater for their industrial (process) water requirements.

The mineral resources of the Murray Basin range in significance from such commodities as heavy mineral sands, which attract high premiums and are exported in large quantities, to silica sand and gypsum, which attract much lower premiums and need to be produced relatively close to their relevant markets. Although silica sand resources occur widely, their use is largely restricted to such construction applications as fill sand. Some of the lower value commodities, such as gypsum, have typically restricted applications yet reasonably large-scale, mainly agricultural use. In the eastern side of the Murray Basin, in parts of the Riverine Plain, there are isolated deposits of high-purity silica potentially suited to such higher-grade industrial applications as glass manufacture. These occurrences, however, are either deeply buried or would probably need extended processing to remove their high clay contents. Bentonite and heavy mineral sands, in contrast, have more extensive market application and tend to attract higher returns from their more specialised applications. Heavy mineral sands resources are expected to become increasingly more important as available resources of these commodities in Western Australia and Queensland are depleted.

Although gypsum is almost entirely utilised in agricultural applications, production of gypsum could substantially increase when drought conditions ease. Proposals to build a gypsum calcining plant near Balranald could see the production of more specialised gypsum products and market diversification. Salt, kaolin and bentonite have diverse applications and attract significant premiums when processed for use in specialised applications. Arumpo bentonite, which is of extremely high purity, is strategically close to large markets involving engineering, environmental and agricultural applications, manufacturing and food processing. Although markets for kaolin could be affected by the tendency of Australian manufacturing industries to relocate overseas, the Oaklands area has potential for additional resources. Commercial salt production in the Murray Basin has largely involved development of niche or specialised markets. This has enabled the salt industry to develop despite competition from large-volume, low-cost domestic and export based operations in Western Australia and South Australia.

Directions for future investigations and exploration

Additional studies of the mineral systems of the Murray Basin by the Geological Survey of New South Wales and exploration companies are warranted — with the primary aim of developing new geological insights into the evolution of the region’s mineral deposits. Such studies could compliment, and enhance, suggestions for ongoing exploration. Extensive mapping of the southwestern part of New South Wales has been presented by Ray (1996) and Cameron (1996, 1997):

1. Compilation of a GIS framework could integrate existing geological mapping, structural information and DEM, aeromagnetic, gravity and radiometric imagery relevant to the Pliocene–Quaternary history of the Murray Basin. This could include incorporation of open file mineral exploration reports and mineral occurrence data held in the Industry & Investment NSW (formerly NSW Department of Primary Industries) DIGS reporting system and MetIndeX mineral occurrence database relevant to the Murray Basin (this information is available online). This could also include the addition of water bore drilling data for additional subsurface information.

2. Subsurface data can be converted into basin-wide stratigraphic cross sections, and contoured bounding surfaces can be correlated with existing hydrogeological map sheet data published by Geoscience Australia. This would involve development of geological interpretations of the data in terms of lithofacies and/or depositional environments using sequence stratigraphy principles (cf. Posamentier & Allen 1999). Such a study would integrate geophysical imagery and radiometric data to identify barrier systems and growth faults in the Murray Basin.
3. Detailed studies of individual mineral deposits using mine, quarry and outcrop data in conjunction with drilling information and DEM, aeromagnetic and radiometric imagery would provide a review of aspects of their depositional, structural and weathering histories. A primary outcome should involve development of improved models to account for beach placer formation. Additional investigations of formation of mineral deposits could involve a systematic review of the depositional setting and structural development of kaolin deposits (eastern side of the Murray Basin), bentonite deposits (northern part of the Murray Basin), and an analysis of variations in gypsum quality (on a regional basis). This study should involve assessment of the capacity of such remotely sensed imagery as radiometric data and DEM to define specific mineral deposits.

4. Stratigraphic drilling of selected mineral deposits, particularly West Balranald-style heavy mineral sands deposits given their complete lack of subsurface exposure would provide intact samples for detailed analyses of their depositional, structural and weathering histories. This drilling could also be undertaken to develop improved geological criteria — such as the weathering characteristics of Murray Basin sediments — to assist in differentiating Loxton–Parilla Sands (marine) from Calivil Formation (alluvial), with emphasis on the northeastern Murray Basin. This would assist in defining places in which heavy mineral sands deposits might be developed.

Conclusions

The Murray Basin is a remarkable geological province characterised by an extremely well-preserved sequence of regressive Pliocene barrier sequences that extend over a distance of about 500 km inland from the present shoreline. This barrier sequence provides an extraordinary, almost unbroken, history of sea level changes going back some six million years. The mineral resources of the Murray Basin are also impressive in terms of their diversity and complex development. Mineral system models have been developed that assist understanding of, and exploration for, those mineral deposits. The upper sequences of the Murray Basin, principally the Loxton–Parilla Sands, Calivil Formation and Shepparton Formation, contain economic accumulations of heavy mineral sands, bentonite, kaolin and gypsum. The heavy mineral sands deposits are the most significant commodities owing to their large resources of high-quality coarse-grained rutile, zircon and ilmenite. Quartz sand amenable to construction applications occurs in many places, primarily as aeolian dune deposits, alluvial sequences associated with modern drainage courses, and ancient stream channels along the eastern margin of the Murray Basin. Mineral system models have been developed which assist understanding of, and exploration for, those mineral deposits.

The Murray Basin requires substantial exploration drilling to improve knowledge of its geology and mineral resources. Much of the early drilling was terminated at relatively shallow depths. Many important heavy minerals deposits were not initially detected because they occur at depths exceeding 30–40 m owing to post-depositional faulting and infilling by younger sediments (Whitehouse 2006). Aeromagnetic exploration has proved successful in locating significant beach placers (Whitehouse 2006). Major beach placers located using aeromagnetic trends include the Ouyen group of deposits in northern Victoria and numerous deeply buried high-grade deposits near Balranald. The variable nature of the magnetic response is probably related to the proportion of ilmenite in the heavy mineral assemblage and the magnetic susceptibility of and depth to basement rock. Digital Elevation Model (DEM) and LANDSAT satellite images, which provide sharply defined images of remnant Pliocene barriers, have markedly improved regional target generation. Radiometric images could prove to be of significant value in defining gypsum-bearing salt lakes and possibly bentonite deposits.

Mineral deposits of the Murray Basin formed in a large geological province in which critical interactions of depositional, eustatic, climatic and tectonic processes influenced their development. Sediment provenances of diverse geology and considerable age were also involved in evolution of the mineral deposits, particularly heavy mineral sands. Occurrences of high-quality kaolin of inferred Tertiary age along the eastern margin of the Riverine Plain are believed to have been derived from weathering of nearby basement rocks and then accumulation in lacustrine or floodplain settings.

Thick deposits of heavy mineral sands that formed in early Pliocene sequences in the northern Murray Basin are believed to represent coastal barrier stacking that involved sea level fluctuations of at least 40 m. This is in contrast to single beach placer deposits elsewhere in the Murray Basin, which appear to have mainly accumulated during prolonged periods of stable, highstand, sea level. However, a group of single, extremely high-grade beach placers in the northern Murray Basin might represent multiple erosion linked to variations in coastal sediment supply — in turn related to localised tectonic activity that led to development of heavy mineral sands-rich ‘condensed sections’ along the shoreline. Regional analysis of their location in relation to barrier trends on DEM imagery and other beach placers implies that some ‘condensed
section’ deposits and apparent composite barrier deposits formed simultaneously, albeit on different parts of the same shoreline.

Cainozoic sequences, particularly in the central region of the Murray Basin, are disrupted in many places, most prominently as largely concealed, typically northeast to southwest extensively faulted and uplifted basement ridges. Tectonic activity is believed to have played a major role in the formation of heavy mineral sands deposits through formation of uplifted fault blocks upon which beach placers preferentially formed.

Bentonite deposits scattered across the southern and central Murray Basin were probably derived from volcanic ash emitted from inferred eruptive centres, now concealed by younger sedimentary units, in the late Pliocene. At Arumpo, northeast of Mildura, distinctive sequences of Na–Mg bentonite developed in response to the alteration of volcanic ash deposited in brackish and saline waters.

During the last half-million years, large quantities of marine salts from the Southern Ocean have been deposited over much of southern Australia. These salts entered shallow Pliocene aquifers resulting in typically saline groundwater from which salt is extracted at several locations using solar evaporation technology. In numerous locations, favourable structural or stratigraphic pathways allowed this groundwater to migrate to the surface to form hypersaline lakes that subsequently dried out leaving numerous scattered deposits of gypsum.

ACKNOWLEDGEMENTS

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REFERENCES


## Appendix 1

### Bentonite mineral systems

<table>
<thead>
<tr>
<th><strong>Summary</strong></th>
<th>Bentonite is irregularly developed in the Murray Basin, principally in the Pliocene Loxton–Parilla Sands, and in younger sediments (to some extent). The most important deposits, near Arumpo, are thought to be the alteration products of volcanic ash derived from nearby concealed intermediate mafic eruptive sources. Although the Arumpo deposits have been investigated in some detail, the regional distribution and origin of bentonite remains inadequately known.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geographic extent</strong></td>
<td>Large deposits of Na–Mg bentonite have been identified at Arumpo, northeast of Wentworth. Variably developed bentonite has also been identified at Trida (Trida bentonite deposit); in the Ginkgo mineral sands mine near Pooncarie; and in the former Wemen heavy mineral sand mine (northern Victoria) and the Douglas heavy mineral sand mine (southern Victoria).</td>
</tr>
<tr>
<td><strong>Host formation</strong></td>
<td>The Loxton–Parilla Sands and, to some extent, Quaternary alluvial and aeolian sequences.</td>
</tr>
<tr>
<td><strong>Geological age</strong></td>
<td>Mainly late Pliocene. Inferred geological age based on bentonite layers conformably overlying (and within) the upper sequences of the Pliocene Loxton–Parilla Sands. Attempts at using potassium-argon techniques to determine the age of Arumpo bentonite have so far been unsuccessful.</td>
</tr>
<tr>
<td><strong>Resource importance</strong></td>
<td>The Arumpo Na–Mg bentonite deposit contains resources in excess of 70 million tonnes and additional resources have recently been identified. Production in the 2006/07 financial year was about 16 000 tonnes. At present, there are no other known deposits of commercial potential.</td>
</tr>
<tr>
<td><strong>Deposit geology</strong></td>
<td>The Arumpo deposit contains two adjacent large high-quality bentonite deposits that are generally horizontal, up to 10 m thick and extend in a northwest to southeast direction over a distance of about 10 km and a width of about 5 km. These deposits are overlain by fluvial and aeolian sediments and younger bentonite layers. Volcanic ash involved in bentonite formation is inferred to have come from an extensive cluster of highly magnetic concealed pipe-like structures, presumably eruptive centres, in a northeast to southwest structural zone from Wentworth to Booligal. At least two eruptive episodes are thought to have been involved. Younger bentonite formations could be periods of waning eruptive activity.</td>
</tr>
<tr>
<td><strong>Depositional controls</strong></td>
<td>The Loxton–Parilla Sands is a primary host for bentonite owing to diverse geomorphological features that included back barrier lagoons, areas (swales) between numerous barriers, scattered lakes and various drainage depressions. These could have been depocentres of varying importance for sediment accumulation. Also, the Loxton–Parilla Sands covered much of the basin when eruptive activity was most pronounced resulting in this formation receiving volcanic ash over large areas.</td>
</tr>
<tr>
<td><strong>Structural controls</strong></td>
<td>As well as such geomorphological features as back barriers, swales, lagoons or lakes, the Loxton–Parilla Sands has been subject to weak downwarping that might have created more sites for accumulation of eruptive materials. At Arumpo, ash initially settled within a (deeper) graben setting along the eastern side of the Neckarboo Ridge, which is a concealed northeast to southwest basement ridge complex with numerous fault blocks. Ensuing deposition of volcanic ash appears to have occurred in an adjacent, more (structurally) elevated coastal lagoon.</td>
</tr>
<tr>
<td><strong>Alteration</strong></td>
<td>At Arumpo, the earlier, deeper accumulations of volcanic ash are believed to have occurred in more saline water resulting in bentonite with comparatively high Na to exchangeable Mg ratios and high pH values. In contrast, ensuing nearby deposition is inferred to have occurred in more brackish water resulting in bentonite with comparatively low Na to exchangeable Mg ratios and low pH values.</td>
</tr>
<tr>
<td><strong>Weathering</strong></td>
<td>The host Loxton–Parilla Sands at Arumpo show extensive iron oxide discoulouration owing to periods of subaerial weathering.</td>
</tr>
<tr>
<td><strong>Geophysical characteristics</strong></td>
<td>No known characteristics of potential use in mineral exploration.</td>
</tr>
<tr>
<td><strong>Geochemical characteristics</strong></td>
<td>No known characteristics of potential use in mineral exploration.</td>
</tr>
<tr>
<td><strong>Exploration guides</strong></td>
<td>Greenish grey puggy clays intersected during drilling in the Murray Basin, particularly exploration involving the Loxton–Parilla Sands, are potentially bentonitic. Digital Elevation imagery could be useful in locating back-barrier settings, grabens and lakes in which volcanic ash might have accumulated.</td>
</tr>
<tr>
<td><strong>References</strong></td>
<td>See main reference list for Gardam et al. (2008) and Holmes (1983).</td>
</tr>
</tbody>
</table>
## Appendix 2

### Gypsum mineral systems

<table>
<thead>
<tr>
<th>Summary</th>
<th>Gypsum occurs as crystalline, sand- and silt-size deposits of late Pleistocene to Holocene age in continental salt lakes, or playas, within active and preserved groundwater discharge zones. Crescent-shaped dunes (lunettes) of gypsum and/or clay that form rims along their eastern margins developed in response to wind deflation of the salt lakes. Gypsum formation primarily occurred in the late Quaternary (about 25 000 ka to 15 000 ka), when salt lakes shrank to evaporative brine pools during periods of intense aridity. Phases of lake floor deflation and clay dunef ormation have intermittently occurred since then.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographic extent</td>
<td>Although there are numerous lakes across the Murray Basin, all sites do not have gypsiferous sediments. Gypsum deposits are associated with discharge zones, generally inactive, in the western margin of the Riverine Plain. In western New South Wales, groundwater discharge areas are probably related to the drying out of Lake Bungunnia.</td>
</tr>
<tr>
<td>Host formation</td>
<td>Yamba Formation. Minor gypsum is associated with the Blanchetown Clay.</td>
</tr>
<tr>
<td>Geological age</td>
<td>Quaternary, mainly late Pleistocene to Holocene.</td>
</tr>
<tr>
<td>Resource importance</td>
<td>The Murray Basin is the main source of agricultural gypsum in New South Wales. Gypsum production in this region for the 2006/07 financial year was about 94 000 tonnes.</td>
</tr>
<tr>
<td>Deposit geology</td>
<td>Gypsum deposits within preserved and active saline (brine) lake floors are commonly crystalline but rarely greater than one metre thick indicating that the land surface was relatively stable over large areas during their formation. Gypsite (fine-grained gypsum) associated with lunettes can be locally extensive, of varying purity and several metres or more thick. Most of the gypsum has been derived from shallow regional groundwater entrained in the underlying Pliocene Sands aquifer system. At some places, stratigraphic barriers have forced groundwater into surface discharge zones.</td>
</tr>
<tr>
<td>Depositional controls</td>
<td>Marine aerosols leached into basin-wide aquifers have produced highly saline groundwater which, in the central Murray Basin, has salinities exceeding 100 000 mg/L. Groundwater has undergone additional concentration along discharge zones to produce gypsum-bearing playas. In parts of the Murray Basin, groundwater involved in gypsum formation probably came from other aquifers, notably within the Renmark Group. Gypsum deposits in the northern Murray Basin are probably related to local discharges from Miocene sediments, of groundwater similar in composition to the Pliocene sands aquifer system.</td>
</tr>
<tr>
<td>Structural controls</td>
<td>Gypsum formation probably involved groundwater discharge in drainage features related to minor structural sags, wind deflation zones and interdune depressions or swales. Overall, deflation zones appear of greatest importance. In the central Murray Basin, many gypsum deposits are associated with an extensive north–south zone along the western and northern margins of the Riverine Plain. There, groundwater discharge occurs where aquifers of the Renmark Group, and younger sediments, intersect the Iona Ridge, a concealed basement ridge complex of numerous fault blocks, and inferred fault zones.</td>
</tr>
<tr>
<td>Alteration</td>
<td>No known characteristics of potential use in mineral exploration.</td>
</tr>
<tr>
<td>Weathering</td>
<td>No known characteristics of potential use in mineral exploration.</td>
</tr>
<tr>
<td>Geophysical characteristics</td>
<td>No known magnetic characteristics. Radiometric exploration is potentially of significant use in defining such features as lake boundaries and adjacent lunettes.</td>
</tr>
<tr>
<td>Geochemical characteristics</td>
<td>No known characteristics of potential use in mineral exploration.</td>
</tr>
<tr>
<td>Exploration guides</td>
<td>Digital Elevation Imagery is highly useful in defining lake boundaries and their gypsum deposits. Radiometric data have potential application in distinguishing gypsum-bearing salt lakes from those that are variably covered or buried with alluvial and or aeolian sediments, and possibly in gaining some indication of the thickness of infilling sediments.</td>
</tr>
<tr>
<td>References</td>
<td>See main reference list for Wynn (1965); Bowler (1976); Evans and Kellet (1989); Brown and Stephenson (1991); and Warren (1999).</td>
</tr>
</tbody>
</table>
## Appendix 3

### Kaolin mineral systems

#### Summary
The Murray Basin has extensive deposits of sedimentary kaolin in fluvial and lacustrine sequences of the Riverine Plain. The most important occurrences, near Oaklands, contain high-grade kaolin that is used for various applications. Although numerous salt lakes occur throughout the Murray Basin, they mostly contain gypsum-bearing sediments and are unlikely to host commercial deposits of kaolin.

#### Geographic extent
Kaolin deposits (eastern margin of the Murray Basin) largely represent late Miocene weathering products of basement rocks in adjacent highlands that accumulated in fluvial and lacustrine deposits of the Riverine Plain. Minor deposits of clay that occur on floodplains bordering major drainage, principally the Murray River, have been mined at several places.

#### Host formation
Variably developed, commonly lensoidal deposits of kaolinitic clay, silty clay and sandy clay that occur mainly above, but also within and probably below, sand and gravel deposits of the Calivil Formation. In such modern fluvial systems as the Murray and Murrumbidgee rivers, irregular deposits of clay are associated with floodplain sequences of the Coonambidgal Formation.

#### Geological age
The Calivil Formation is probably late Miocene to early Pliocene. This unit is overlain by the Shepparton Formation, which consists of late Tertiary to Quaternary alluvial deposits of clay, fine sand and gravel. The Coonambidgal Formation is late Pleistocene to Holocene.

#### Resource importance
The Oakland kaolin deposits are an important source of kaolin suitable for such purposes such as brick manufacture, ceramic applications and white goods production. Production in this region during the 2006/07 financial year was about 260,000 tonnes. Other deposits of clay have been used in local bricks although their current importance is unknown but probably small.

#### Deposit geology
The Oaklands deposits consist of a lower kaolin horizon about 20 m thick and an upper kaolin horizon about 6 m thick, separated by intermixed sand and clay. The lowermost kaolin horizon is the main unit of commercial interest. The uppermost kaolin horizon consists of scattered lenses of kaolin within sand- and gravel-dominated sequences. These deposits are overlain by the Shepparton Formation.

#### Depositional controls
The Oaklands deposits probably formed on ancient floodplains or lakes of the Riverine Plain. The dominantly clay-rich nature of the lower kaolin horizon suggests the depositional regime was initially dominated by lacustrine (flooding) conditions. The sandy nature of the upper kaolin horizon and intervening interbedded sand and kaolin units indicate that fluvial conditions became more dominant.

#### Structural controls
Kaolin-bearing sequences are largely concealed at varying depths beneath the Riverine Plain. They are locally exposed at some places, notably Oaklands, which forms a highly distinctive plateau over some 50 km² about 60–80 m above the Riverine Plain and as scattered hills or ridges. Their origin is unclear. They might be remnant deposits left by the erosion of nearby sediments or, alternatively, they could represent isolated masses of sediments tectonically lifted above the Riverine Plain.

#### Alteration
No known characteristics of potential use in mineral exploration.

#### Weathering
The top of the kaolin deposits is characterised by dense brown clay that can grade into top soils consisting of reddish-brown clayey soil.

#### Geophysical characteristics
No known magnetic characteristics. Radiometric surveys might potentially be of use in defining Calivil and Shepparton Formations in some circumstances.

#### Geochemical characteristics
No known characteristics of potential use in mineral exploration.

#### Exploration guides
Digital Elevation Imagery is highly useful in defining plateaus or ridges on the Riverine Plain that might be prospective sites for sedimentary kaolin.

#### References
See main reference list for Pearce (1975); Brown and Stephenson (1991), and Page and Nanson (1996).
### Heavy mineral sands mineral systems

<table>
<thead>
<tr>
<th>Summary</th>
<th>Economic deposits of heavy mineral sands (concentrations of rutile, zircon, ilmenite, altered ilmenite (leucoxene) and accessory monazite) occur as relatively coarse beach placers and fine grained shallow marine deposits in the Loxton–Parilla Sands.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographic extent</td>
<td>The Loxton–Parilla Sands is developed over an area of about 100,000 km² (over half the known extent of the Murray Basin in New South Wales).</td>
</tr>
<tr>
<td>Host formation</td>
<td>Loxton–Parilla Sands. Minor non-commercial accumulations of heavy minerals occur in the Pliocene to Recent Shepparton Formation and the late Miocene to Pliocene Bookpurnong beds. Moderate concentrations of heavy minerals have been found in the underlying Miocene Renmark Group.</td>
</tr>
<tr>
<td>Geological age</td>
<td>The Loxton–Parilla Sands is mainly Pliocene.</td>
</tr>
<tr>
<td>Resource importance</td>
<td>The Murray Basin contains major resources of global-quality, premium-grade rutile, zircon, ilmenite and leucoxene in numerous beach placers and in shallow marine deposits. Production from the Ginkgo mine in 2006/07 financial year was about 874,000 tonnes of rutile, zircon, ilmenite and altered ilmenite.</td>
</tr>
<tr>
<td>Deposit geology</td>
<td>Beach placers range from single accumulations, generally 3 m thick and commonly of high grade (&gt;10% heavy minerals), to stacked deposits that contain up to 30% heavy minerals over 40 m thick and widths of over 500 m. Beach placer deposits commonly attain strike lengths of 5 km to 40 km at depths ranging from near surface to more than 50 m. Fine-grained (WIM-style) deposits are extensively developed in nearby shallow marine settings as irregular accumulations, commonly stacked lenses, of heavy minerals formed during storm activity.</td>
</tr>
<tr>
<td>Depositional controls</td>
<td>Various barrier styles and concentration mechanisms appear to be involved in beach placer formation. They occur as stacked barrier deposits (e.g. Ginkgo deposit) up to 40 m thick that formed in response to episodic sea level rises, notably in the early Pliocene (northern Murray Basin) and single barrier deposits typically 3 m thick associated with prolonged ‘stillstand’ conditions that prevailed during the middle and late Pliocene. Aeolian halos are associated with many deposits. In the central Murray Basin, there are high-grade deposits (e.g. West Balranald deposit) about 3 m thick containing &gt;20% heavy minerals (composite basis) that extend over distances exceeding 20 km. They could be transgressive barrier deposits that formed along locally steepened substrates in processes that involved seaward dispersal of quartz sand and the formation of heavy mineral-rich condensed sections on the shoreface. Extra heavy minerals could have been incorporated in the transgressive barrier from the seafloor and added to a pre-existing heavy mineral deposit.</td>
</tr>
<tr>
<td>Structural controls</td>
<td>The Murray Basin has numerous generally featureless barriers extending over hundreds of kilometres in turn intersected by many shore-normal growth faults. Growth faulting associated with reactivated basement activity played a critical role in beach placer development through the formation of uplifted fault blocks on which beach placers preferentially accumulated.</td>
</tr>
<tr>
<td>Alteration</td>
<td>No known characteristics of potential use in mineral exploration.</td>
</tr>
<tr>
<td>Weathering</td>
<td>Fe-bearing sediments, principally ilmenite, have variably undergone post-depositional alteration to produce such secondary minerals as leucoxene, pseudorutile and anatase. Weathering has provided iron for the formation of abundant ferruginous mottling observed in some deposits.</td>
</tr>
<tr>
<td>Geophysical characteristics</td>
<td>Aeromagnetic exploration has been highly useful in finding relatively deeply buried deposits in the central and southern parts of the basin. The nature of overlying sediments, depth to underlying magnetic basement and the heavy mineral assemblage influence the magnetic response of beach placers.</td>
</tr>
<tr>
<td>Geochemical characteristics</td>
<td>No known characteristics of potential use in mineral exploration.</td>
</tr>
<tr>
<td>Exploration guides</td>
<td>Digital Elevation Imagery is highly useful in defining the northwest to southeast trending barriers of the Loxton–Parilla Sands in much of the Murray Basin and in defining upfaulted blocks that are commonly expressed as distinct ridges and that appear to be preferred sites of beach placer formation.</td>
</tr>
<tr>
<td>References</td>
<td>See main reference list for Brown and Stephenson (1991); Posamentier and Allen (1999); Whitehouse at al. (1999); Roy et al. (2000); Roy and Whitehouse (2003), and Whitehouse (2006).</td>
</tr>
</tbody>
</table>
## Saline groundwater mineral systems

<table>
<thead>
<tr>
<th>Summary</th>
<th>Highly saline groundwater occurs across much of the Murray Basin, particularly within shallow aquifers of the Loxton–Parilla Sands and Calivil Formation. Salt extraction, principally NaCl and MgCl₂, takes place in several parts of the Murray Basin during saline groundwater remediation. In New South Wales, commercial salt extraction using solar evaporation technology is undertaken in the Mourquong Basin salt mitigation site near Mildura.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographic extent</td>
<td>Mainly within shallow aquifers of the Loxton–Parilla Sands.</td>
</tr>
<tr>
<td>Host formation</td>
<td>Loxton–Parilla Sands and Calivil Formation.</td>
</tr>
<tr>
<td>Geological age</td>
<td>Mainly Pliocene</td>
</tr>
<tr>
<td>Resource importance</td>
<td>Commercial salt mining, mainly NaCl and MgCl₂, is an increasingly important part of saline groundwater remediation strategies in the Murray Basin. This involves salt extraction for markets involving food processing and industrial applications. Salt production in this region in the 2006/07 financial year was 18 500 tonnes. Downstream processing could involve manufacture of such materials as MgSO₄, Cl₂, HCl and NaOH (halite fraction), and MgOH₂ and MgO, ‘Sorel cement’ and spinels refractories (Mg-rich bitterns fraction).</td>
</tr>
<tr>
<td>Deposit geology</td>
<td>The main aquifers of the Murray Basin include, in ascending stratigraphical order, the Renmark Group, Murray Group, Loxton–Parilla Sands, Calivil Formation and Shepparton Formation. In New South Wales, the most important groundwater system is the Pliocene sands aquifer system, a composite aquifer of the near surface Loxton–Parilla Sands (western and central) and buried Calivil Formation (east).</td>
</tr>
<tr>
<td>Depositional controls</td>
<td>Groundwater quality, which exceeds 100 000 mg/L TDS in the upper 100 m of the central Murray Basin, is dominated by Na⁺ and Cl⁻ ions, along with varying amounts of Mg²⁺, SO₄²⁻ and Ca²⁺ ions. Marine salt aerosols have been deposited across southern Australia in very large quantities and leached into basin-wide shallow aquifers on a long-term basis, resulting in the saline character of Murray Basin groundwater. Past episodes of high groundwater surfaces and salt entrapment though evaporation have contributed to the progressively saline nature of the shallow aquifers.</td>
</tr>
<tr>
<td>Structural controls</td>
<td>Groundwater is effectively trapped within Murray Basin aquifers systems owing to its structurally confined nature, and can only escape by surface discharge or leakage into river systems.</td>
</tr>
<tr>
<td>Alteration</td>
<td>No known characteristics of potential use in mineral exploration.</td>
</tr>
<tr>
<td>Weathering</td>
<td>No known characteristics of potential use in mineral exploration.</td>
</tr>
<tr>
<td>Geophysical characteristics</td>
<td>Airborne electromagnetic methods could be used to determine spatial distribution of salt-affected areas. Radiometric data might be useful in soil studies.</td>
</tr>
<tr>
<td>Geochemical characteristics</td>
<td>No known characteristics of potential use in mineral exploration.</td>
</tr>
<tr>
<td>Exploration guides</td>
<td>Delineation of areas in the Murray Basin for salt extraction would involve site selection along or near the Murray River to coincide with high rates of groundwater discharge and/or where salt concentration would conceivably also be particularly high.</td>
</tr>
</tbody>
</table>
## Summary
Silica sand occurs mainly in aeolian dunes, fluvial sequences and marine deposits. These have been mined in small quarries or roadside borrow pits.

## Geographic extent
Aeolian dunes cover much of the central and western Murray Basin, while fluvial deposits of the Riverine Plain form the eastern Murray Basin, and as channel and floodplain with such modern drainage systems as the Murrumbidgee, Darling and Murray rivers.

## Host formation
The Woorinen Formation, in the western and central Murray Basin, contains highly variable, locally thick dunes and sandsheets. Sand, gravel, and clay of the Shepparton Formation dominate the Riverine Plain (east). The Coonambidgal Formation is associated with modern stream systems. Equivalents of the Pooraka Formation are represented by aeolian and colluvial deposits or outwash fans. The Loxton–Parilla Sands (alluvial and marine) are important sources of silica sand, mainly in areas outside New South Wales.

## Geological age
The Woorinen Formation is Quaternary, mainly late Pleistocene, with minor reactivation during the Holocene, while the Shepparton Formation is Pliocene to Recent and the Coonambidgal Formation late Pleistocene to Holocene. The Pooraka Formation is mainly late Pleistocene.

## Resource importance
The mainly aeolian Woorinen Formation has large areas of fine- to medium-grained iron oxide-coated quartz sand and sporadic calcrete. The fluvial Shepparton Formation and Coonambidgal Formation have variably consolidated clay, silt and fine to coarse sand and gravel. Production of construction materials in the 2006/07 financial year is uncertain.

## Deposit geology
The Woorinen Formation is characterised by extensive sandsheets developed across the western and central Murray Basin. Clay and silt deposits, with intercalated fine to coarse sand and gravel of the Shepparton Formation, form stream channels and lacustrine deposits derived from tributary highland valleys along the eastern margin of the Murray Basin (Riverine Plain). The Coonambidgal Formation occupies confined floodplains of modern river systems in the Riverine Plain and the Murray–Darling River system.

## Depositional controls
The Riverine Plain consists of numerous palaeochannels and floodplains, and associated aeolian dunes, which formed during prolonged Cainozoic fluvial activity that featured major flood peaks and enhanced deposition of bedload sediments derived from the eastern highlands. Woorinen Formation aeolian dune systems, now largely inactive, developed in response to intense Late Quaternary aeolian activity. Along the margins of the Riverine Plain, mixed aeolian and colluvial deposits or outwash fans consisting of polygenetic soils and sediments, including gravity-transported bedrock fragments of inferred middle to late Pleistocene age, are developed. These materials are comparable to the Pooraka Formation along the western margins of the Murray Basin.

## Structural controls
The arcuate shape of the western margin of the Riverine Plain, including the flow direction of many of the rivers, are primarily structurally controlled, and reflect the arcuate configuration of concealed basement (notably the Iona Ridge). Faults disrupt the modern river systems at various places.

## Alteration
Alteration is largely restricted to variably developed calcrete horizons. No known characteristics of potential use in mineral exploration.

## Weathering
The Shepparton Formation and Woorinen Formation have been extensively modified by pedogenesis and fluctuating groundwater resulting in minor consolidation of sandy units, sporadic calcrete horizons, red–brown palaeosols and humic layers. The Coonambidgal Formation is largely unweathered.

## Geophysical characteristics
No known magnetic characteristics but radiometric data might potentially be of use in defining Calivil Formation and Shepparton Formation in some circumstances.

## Geochemical characteristics
No known characteristics of potential use in mineral exploration.

## Exploration guides
Digital Elevation Imagery is highly useful for defining stream channels, floodplains and dune systems units.

## References
See main reference list for Brown and Stephenson (1991); Page and Nanson (1996); and Colquhoun et al. (2005).
Future papers:

‘Contrasting age and isotope characteristics of volcanic-hosted and skarn-type mineralisation near The Glen, Goulburn, Lachlan Orogen NSW’ by P.M. Downes & D. Phillips

‘A revised Triassic stratigraphy of the Lorne Basin, NSW’ by W. Pratt

‘Review of Cambrian and Ordovician stratigraphy in NSW’ by I.G. Percival, R.A. Glen & C. Quinn

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