Bulletin 54

The geology of South Australia
Volume 2 The Phanerozoic

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Issued under the authority of
The Hon. D.S. Baker, M.P.
Minister for Mines and Energy

Newstyle Printing Pty Ltd
1995
towards the eastern margin of the basin indicates that the Flinders Ranges were in existence during deposition.

The difference in elevation between the succession in Lake Torrens and correlative sediments within the Flinders Ranges implies maximum relative post-depositional uplift of the ranges in the order of 100 to 250 m. Greatest subsidence appears to have occurred in the southern portion of Lake Torrens. The distribution of silcretes along the northern and northeastern margins of the basin indicates no relative movement along the Torrens and Norwest Faults since silification. Binks (1972) interpreted uplift of the Ediacara Range to have taken place in the Quaternary.

LAKE EYRE BASIN

R.A. Callen, N.F. Alley and D.R. Greenwood

There is very little record of sedimentation over most of inland South Australia between the Cenomanian and Late Paleocene, when weathering and erosion appear to have prevailed. During the Late Paleocene, tectonic subsidence in northeastern South Australia produced a large, shallow basin, here referred to as the Lake Eyre Basin, in which episodic fluvial and lacustrine sedimentation has taken place until the present (Figs. 10.28, 10.29). Although only the Tertiary

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Fig. 10.27 Cross-sections through Tertiary sediments in the Torrens Basin. Lines of section are located on Figure 10.26. The profile of B-B is also shown on Figure 10.33 to demonstrate the height relationship between the Torrens and Billa Kalina Basins.
sediments are discussed in this section, deposition of some units commenced in the late Tertiary and continued into the Quaternary.

Structure and setting

Like the underlying Eromanga Basin, the Lake Eyre Basin consists of a thick sedimentary succession in a northeastern depocentre and a southwestern part where the sediments are significantly thinner and discontinuous. The basin is bordered on the west by the Peake and Denison Inliers and western margin of the Dalhousie Dome, in the south by the Willouran, Flinders and Olary Ranges, and in the east by the Barrier Ranges. In the north the basin extends into the Northern Territory, Queensland and New South Wales, and is bordered by domes of Mesozoic rocks. The southern margin is sharply defined and faulted as a result of late Cainozoic uplift.

The basin is separated into the Tirari Sub-basin (Krieg et al., 1991) in the west and Callabonna Sub-basin in the east by the Birdsville Track Ridge, expressed in the Tertiary as a series of faulted, duricrust-capped domes (Figs 10.28, 10.30). The stratigraphy of the Tirari Sub-basin (previously named the 'Lake Eyre Basin': Callen and Tedford, 1976; Callen, 1990) is illustrated on Figure 10.31. Stratigraphic units used in the Callabonna Sub-basin (previously known as Tarkarooloo Basin and then Callabonna Basin; Callen and Tedford, 1976; Callen, 1981, 1990) are also shown on Figure 10.31.

Much of the Lake Eyre Basin is close to sea level, with subdued topography and poor outcrop in low cliffs, around salt lakes, or as discontinuous silicified channel remnants between dunes. Tertiary units are commonly covered by Quaternary sediments.
Fig. 10.29 Stratigraphic units in the Lake Eyre Basin, and correlatives in adjacent areas.

Stratigraphy

Deposition in the Lake Eyre Basin occurred in three phases (Krieg, Callen et al., 1990). In the first phase (latest Paleocene to the Middle Eocene), sandstone, carbonaceous clastics and conglomerate of the Eyre Formation and Mount Sarah Sandstone were deposited (Fig. 10.29). There is little evidence for deposition in the Lake Eyre Basin between the Late Eocene and Late Oligocene. According to Wopfner (1974), widespread gentle folding and uplift, including rejuvenation of the Birdsville Track Ridge, initiated the division of the basin into two sectors and produced such structures as the Cooyanna and Gason Domes. The second phase may have commenced in the Oligocene and extended through to the Pliocene; sediments deposited include grey, green and white clay, fine-grained sand and carbonate, with minor conglomerate, of the
Fig. 10.31 East-west correlations across the southern Tirari Sub-basin (B-B) and Callabonna Sub-basin (C-C). Lines of section are located on Figure 10.28.
Etadunna Formation and its correlative Namba Formation, Doonbarra Formation and Cadelga Limestone. The third phase, during the Pliocene to Quaternary, was characterised by deposition of red and yellow-brown sand and sandy clay, and development of gypsum and carbonate palaeosols.

Late Paleocene-Middle Eocene units

Eyre Formation

The Eyre Formation (Fig. 10.32; Wopfner et al., 1974), basal unit of the Tertiary succession and widespread throughout the Lake Eyre Basin, incorporates the Macumba Sandstone (Freytag et al., 1967) and Murnpeowie Formation (Forbes, 1966). The Eyre Formation mostly disconformably overlies Mesozoic sediments, but locally oversteps onto Cambrian and Precambrian rocks; it is overlain unconformably by the middle to late Tertiary Etadunna and Namba Formations and Quaternary sediments. Upper exposed horizons are commonly silicified.

The Eyre Formation consists of mature, pyritic, carbonaceous sand, although the carbonaceous lithologies are often leached in outcrop. Grain size varies from silt to gravel, with clasts up to small cobble size, sand grains usually being subangular to subrounded and polished. Beds of lignite and clay composed of montmorillonite and kaolinite with some illite, sometimes with root horizons, are common; a clay matrix is often present in sand around the basin margins. Polished gravel composed of resistant siliceous lithologies such as yellow, grey and milky quartz, black chert, red jasper, agate, fossil wood and buff and grey silcrete, are a diagnostic feature of the basal horizons, with pebbles of basement rock in some localities. These are a lag of reworked second or third-cycle clasts, derived from Permian and Mesozoic rocks. Pebbles of white and coloured quartz are dominant in palaeochannels on the northern margin of the Olary Ranges.

Wopfner et al. (1974) correlated palynofloras from the formation with the L. balmei to Lower N. asperus Zones, indicating an age range from early Late Paleocene to Middle Eocene. An hiatus encompassing the Early Eocene was believed to be represented as an erosional discontinuity separating older and younger parts of the formation. Alley and Sluiter (in prep.), however, indicate that palynofloras range from latest Paleocene (Upper L. balmei Zone) to Middle Eocene with a relatively short hiatus, perhaps in the late Early Eocene to early Middle Eocene.

Other plant fossils are well preserved in silicified sandstone ('silcrete floras') of the Poole Creek Palaeochannel and include cuticle, algae, fungi, wood, twigs, leaves, shoots, seeds, fruits and flowers. A range of coniferous taxa and capsules of possible Eucalyptus and various other Myrtaceae have been described (Greenwood et al., 1990; Christophel et al., 1992). The only exposure of sediments in which palynofloras and macrofloras occur together is in the lower reaches of Nelly Creek near the southeastern margin of Lake Eyre South. Here macrofossils are preserved in carbonaceous clay lenses as mummified remains and impressions dated palynologically as Middle Eocene (Alley, 1989b), indicating that this is a younger part of the Eyre Formation.

The Eyre Formation was deposited largely by braided streams during epeirogenic uplift of the Olary, Barrier and northern Flinders Ranges, accompanied by subsidence in the Lake Eyre Basin (Krieg, Callen et al., 1990). Extensive erosion of the Eyre Formation during
the early Middle Eocene was followed by fluvial deposition later in the Middle Eocene.

The formation has been correlated with the Glendower Formation of Queensland and Marion Formation of New South Wales (Fig. 10.29), although Whitehouse (1954) and Wopfner et al. (1974) believed the Glendower Formation to be younger.

**Mount Sarah Sandstone**

Barnes and Pitt (1977) defined the Mount Sarah Sandstone from an area west of the main depocentre of the Lake Eyre Basin in the Dalhousie Dome and Stuart Range. Silcrete-capped, massive to cross-bedded sandstone, siltstone and basal conglomerate form a sinuous series of mesas east of the Stuart Range. The basal channel facies containing silcrete, quartz and shale clasts was correlated by Barnes and Pitt (1976, 1977).

The Mount Sarah Sandstone unconformably overlies weathered Cretaceous sediments and is considered to be disconformable on, and/or in part equivalent to, the upper Eyre Formation (Krieg, 1985). Although similar to Eyre Formation, the Mount Sarah Sandstone was thought to be distinguished by its silcrete clasts (Barnes and Pitt, 1977). However, since silcrete clasts are widespread in the Eyre Formation, the two units are indistinguishable. Alternatively, parts of the Mount Sarah Sandstone may be a shoreline facies of the younger Etadunna and Doonbarra Formations (see below).

**Late Oligocene-Miocene units**

**Mirackina Conglomerate**

The Mirackina Conglomerate, a cross-bedded fluvial conglomerate with silcrete clasts and medium to coarse-grained sandstone, occupies the Mirackina Palaeochannel, an eroded Tertiary palaeodrainage system on the western margin of the Lake Eyre Basin. Fine-grained sandy siltstone and shale occur in the upper and distal parts; the top is generally ferruginised and silicified. A Miocene age was inferred by Barnes and Pitt (1976) from the abundance of silcrete clasts. Alternatively, these fluvial sediments may correlate in part with the Eyre Formation. Probable equivalents have been recognised in the ABMINGA and WARRINA map areas.

**Etadunna Formation**

The Etadunna Formation of Stirton et al. (1961), with its type section along the western side of Lake Palankarina, is restricted to the Tirari Sub-basin and usually rests on Eyre Formation or, locally, on Cretaceous strata. The Mampuwordu Sand (Stirton et al., 1961), with a type section at the same locality, is now regarded as a channel facies of the Etadunna Formation. In the southern Lake Eyre region, a basal fine clastic unit has been named the Muloorina Member (Callen and Plane, 1985; Krieg et al., 1991). The Yardina Claystone and Alberga Limestone (Freytag et al., 1967; Wopfner, 1974) may also be members of the Etadunna Formation.

In the type area and westwards to Lake Eyre, the Etadunna Formation comprises white dolomite and limestone overlain by green and grey magnesium-rich claystone and fine sand (Callen and Plane, 1985; Callen et al., 1986). Thickness varies from 25 m in the type section to 35 m beneath Lake Eyre and 80 m in Poonarunna 1 (Fig. 10.31). Intraformational conglomerate and bioturbation are widespread.

The 5-15 m thick Muloorina Member is prominent beneath the Madigan Gulf and Tirari Desert regions (Callen and Plane, 1985) and consists of greenish grey, very fine-grained sand and silt with calcareous intervals. A basal ferruginised sand contains clasts of silcrete and sand reworked from the Eyre Formation.

**Namba Formation**

The Namba Formation was defined by Callen and Tedford (1976) from a type section in Yalkalpo 1, a supplementary section in Wooltana 1, and a supplementary outcrop section on the western side of Lake Tarkarooloo, southeast of Lake Frome. In the southwestern Callabonna Sub-basin, it disconformably overlies Eyre Formation and averages 90 m in thickness but thickens towards the Barrier and Flinders Ranges (e.g. 170 m in Wooltana 1), and thins over the Benagerie Ridge. The unit is similar lithologically to the Etadunna Formation and comprises alternating fine to medium-grained, poorly sorted, angular sand, silt and clay, with thin dolomite and limy, often oolitic, dolomite interbeds. The clay is black due to ferrous iron and manganese, tough and bears slickensided fracture surfaces. Horizontal lamination and small to medium-scale cross-bedding are common in silt and very fine-grained sand. Dolomite frequently contains rod-shaped ooliths and is affected by widespread bioturbation, intraformational brecciation and slump struc-
Late Miocene to Quaternary age (Paten, 1964). Limestone of the Boulia region (Queensland) closely resemble the clastics are a regolith and beach equivalent of the Cadelga Limestone, which incorporates fragments of Doonbara Formation. Sparse gastropods, ostracodes, algae (Chara, Botryococcus), sponges and fish, reptiles, birds and mammals are locally abundant. These have aided in reconstructing palaeoenvironments and in understanding the evolution of Australian faunas (see 'Geological history and palaeoclimate'). The uppermost grey clay contains leaf impressions and sparse palynofloras. Occasional leaf impressions have been found in older parts of the Etadunna, but none have been observed in the lower Namba Formation. The wide-spread distribution of the Etadunna and Namba Formations containing abundant fossils of aquatic animals indicates the development of shallow, brackish to freshwater lakes throughout much of the Lake Eyre Basin.

The age of the Etadunna and Namba Formations may range from (?)-Late Oligocene to Pliocene. A Rb-Sr age of 25 Ma determined on green diagenetic ilillite from the upper Etadunna Formation approximates the Oligocene-Miocene boundary (Norris and Pickering, 1983). A monospecific foraminiferal microfauna of Buliminoides cf. B. chattonensis in Palankarina 1 tentatively suggests a Late Oligocene age (Lindsay, 1987b). This occurrence is enigmatic since Buliminoides, unlike Ammonia or Elphidium, is not recorded as an immigrant or survivor in inland lakes. Age estimates of fossil vertebrates range from Oligocene to Early-Middle Miocene (Stirton et al., 1961; Woodburne and Clemens, 1986; Woodburne et al., 1985). Palynofloras from the formations are sparse but suggest an age range from Miocene to Pleiocene. A possible late Tertiary palynoflora was obtained from the uppermost Etadunna Formation in Palankarina 1 (E.M. Truswell, BMR, pers. comm., 1977), whereas Callen and Tedford (1976) suggested an Early to Middle Miocene age for palynofloras from the Etadunna and Namba Formations. Palynofloras from the Namba Formation in Wooltanji indicate an age range from Late Oligocene to Pliocene (Martin, 1990). Late Miocene palynofloras have been reported from Namba Formation equivalents in the southeastern Callabonna Sub-basin in New South Wales (Morgan, 1977; McMinn, 1981).

### Doonbara Formation and Cadelga Limestone

Wopfner (1974) defined the Doonbara Formation in the north-eastern extremity of South Australia, where it comprises pisolithic and ferruginous fine to medium-grained sand overlying partly silicified Eyre Formation (partly silcreted). The formation is generally 7-10 m thick, but reaches 40 m in the core of the Haddon Syncline. Deposition followed, or was partly contemporaneous with, folding and an enigmatic since Buliminoides, unlike Ammonia or Elphidium, is not recorded as an immigrant or survivor in inland lakes. Age estimates of fossil vertebrates range from Oligocene to Early-Middle Miocene (Stirton et al., 1961; Woodburne and Clemens, 1986; Woodburne et al., 1985). Palynofloras from the formations are sparse but suggest an age range from Miocene to Pleiocene. A possible late Tertiary palynoflora was obtained from the uppermost Etadunna Formation in Palankarina 1 (E.M. Truswell, BMR, pers. comm., 1977), whereas Callen and Tedford (1976) suggested an Early to Middle Miocene age for palynofloras from the Etadunna and Namba Formations. Palynofloras from the Namba Formation in Wooltanji indicate an age range from Late Oligocene to Pliocene (Martin, 1990). Late Miocene palynofloras have been reported from Namba Formation equivalents in the southeastern Callabonna Sub-basin in New South Wales (Morgan, 1977; McMinn, 1981).

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The Cadelga Limestone (Wopfner, 1974) is a pale cherty and dolomitic lacustrine limestone up to 5 m thick, which overlies and incorporates fragments of Doonbara Formation. Sparse gastropods, possible diatoms and algae are present but are not diagnostic of age. On the basis of their similar lithologies, Wopfner (1974) correlated the Cadelga Limestone with the Etadunna Formation and with the Alberga Limestone of the Oodnadatta area. The weathered nature of the sediments and lack of biostratigraphic evidence make correlations with other similar units difficult. However, the Austral Downs Limestone and Noradsite Limestone of the Bulloo region (Queensland) closely resemble the Cadelga Limestone and Doonbara Formation, and are probably of Late Miocene to Quaternary age (Paten, 1964).

### Pliocene-Quaternary units

#### Wipajiri, Tirari and Kutijara Formations

The final phase of Cainozoic sedimentation in the Lake Eyre Basin is characterised by red-brown arenites and dark, fine-grained lacustrine sediments. Aeolian and evaporitic facies are common and dense horizons of calcrite and gypsum developed in soils. Although many of these deposits may range in age up into the Quaternary, the deposits of possible Pliocene age are discussed below. There is no direct evidence of a Pliocene age for any of the rock units in the Lake Eyre Basin.

The Wipajiri Formation, defined by Stirton et al. (1967) from Lake Ngapakalid in the central Tirari Desert, consists of over 1 m of fine-grained sand and silt channel fill cut into the Etadunna Formation. It contains coarser conglomeratic lenses up to 0.3 m thick with intraclasts including siliceous and ferruginous nodules, vertebrate remains and Uranium shell impressions, but their stratigraphic implications are uncertain (Archer and Hand, 1984). The upper part of the section consists of laminated claystone with leaf impressions.

Unnamled black clay and white sand in the Tirari Desert is either Wipajiri Formation or the younger Kutijara Formation. The clay contains well-preserved palynofloras, including Nothofagidites spp., Podocarpidites ellipticus and Phylloclopidites mawsoni, which is suggestive of a late Tertiary rather than Quaternary age. This sequence, characterised by shallow sand-filled channels, is interpreted as a meandering fluvial system or lacustrine delta-fan.

The Tirari Formation, a widespread unit with a type section at Lake Palankarina, consists of 4-5 m of bright red-brown silt with sandy channel deposits and fossil vertebrates, including Diprotodon and short-faced kangaroos. The formation is extensively exposed over the central Tirari Desert and northwards into the Simpson Desert, and is usually cemented with massive gypsum crusts. The depositional environment was probably one of intermittent stream flow under semi-arid conditions. The unit overlies possible Wipajiri Formation at a small lake near Peachawarinna 2 and has been dated there as >0.5 Ma by thermoluminescence methods (Callen and Nanson, 1992).

### Economic geology

The Eyre Formation has been explored extensively for sedimentary uranium, particularly in the Lake Frome area where several deposits have been defined in the Billeroo and Yarramba Palaeochannels. Mining in situ leaching is feasible (Bruni, 1978; Ellis, 1980; Callen, 1990; Curtis et al., 1990). Although lignite has been disclosed by drilling, the beds are thin and of low quality. Sandstone beds form useful aquifers in the Callabonna Sub-basin and are locally pressurised along the western margin of Lake Frome. Zircon and topaz occur locally in significant concentrations in palaeochannels along the southern part of the Callabonna Sub-basin; similar channels elsewhere are potential sources of heavy minerals.

Prospecting for dolomite as blast furnace flux was undertaken in the Etadunna Formation around the margins of Lake Eyre, but the silica content proved to be too high (Whitehead, 1970).

The Namba Formation has been explored for pyrgorskite, a swelling clay used as a catalyst, an ingredient of drilling mud (attapulgite), a dye absorbent, and a sager earth in pottery. However, these investigations have failed to disclose marketable material.

Uranium in a sandy palaeochannel of Namba Formation near Lake Namba (Curtis et al., 1990) is potentially recoverable by in situ leaching at the Beverley Prospect near 'Wooltana'.

Celestite, a mineral with growing demand in the television and economic sources.