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Burial history of Jurassic Gondwana Surface west and southwest of Lake Eyre, central Australia

WOPFNER, H.[1]

(1) Institute of Geology, University of Cologne, Germany

Abstract
The Gondwana Surface evolved during the second expansion phase of the super-continent in Late Triassic and Jurassic times. From an initial time of crustal stability it led up to the formation of expanding rift systems which initiated the final fragmentation of Gondwana in the Early Cretaceous. Along the western margin of the Eromanga Basin the stable phase is reflected by a thick regolith of kaolinised bedrock and the formation of the Gondwana Surface. During the Jurassic the surface was covered gradually by the quartzose and kaolinitic Algebuckina Sandstone, deposited by large, high volume river systems, dominated by low pH, "black water" conditions. Palaeobotanical evidence indicates a generally humid, subtropical climate. Expansion of the rift system along the southern margin of Australia coincided with the marine transgression from the east at the beginning of the Cretaceous. Various near-shore facies of the Cadna-owie Formation, including large individual boulders, attest to labile conditions during transgression. The conglomeratic Mt Anna Sandstone Member of the Cadna-owie Formation, containing well rounded pebbles of Gawler Ranges porphyry, demonstrates the formation of a new rift shoulder simultaneous with the marine transgression. Exhumation of the Gondwana Surface commenced in the Early Tertiary and continued episodically until the present time.

Key words: Gawler Range Massif; palaeosurface; transgression; fluvial sandstone; silicification.

INTRODUCTION

During the Jurassic large parts of Gondwana experienced widespread exposure and morphological stability. Weathering and planation produced a senile landscape. This surface is generally referred to as the Gondwana Surface. In syneclises or regional depressions vast fluvial systems developed and the sand bodies deposited within them gradually covered parts of the Gondwana Surface. In Australia these sandstones (Hutton, Mooga, Algebuckina and equivalents) became important artesian aquifers of the "Great Artesian Basin", now termed the Great Australian Basin of which the Eromanga Basin is part. Well documented exposures of the Gondwana Surface exist at the northern margin of the Eromanga Basin near Mt Isa (TWIDALE and CAMPBELL, 1988) and along the southern basin margin near Tibooburra and Milparinka, where large fields of silicified tree trunks, some in growth position, attest to prolific plant growth. (WOPFNER, 1983). The surface is known also from rift structures and pericratonic basins along the southern margin of Australia, like the Polda Basin and the neighbouring Bight Basin (HARRIS and FOSTER, 1974; GATEHOUSE, 1995) and the early graben developments within the Gambier-Otway Basin (WOPFNER and DOUGLAS, 1971; MORTON et al., 1995). The base of the Barbwire Sandstone in the Canning Basin of Western Australia also corresponds to the Gondwana Surface. Here the surface leads from the cratonic platform down into marine environments of the distensional realm of the West Australian Trough.

In Africa the Gundumi Formation of the Iullemeden Basin in northern Nigeria (KOGBE, 1976), the Jurassic part of the "Continental intercalaire" in North African basins (GUIRAUD et. al., 2005), the base of the Sunday River Beds in eastern South Africa and pre-Cretaceous, current bedded, kaolinitic sandstones of the Luwegu Basin in southern Tanzania, all witness comparable morpho-tectonic histories (WOPFNER, 1983). A similar story is revealed at the base of the "Upper Gondwanas" in Peninsular India (CASSHYAP, 1979; CASSHYAP and TIWARI, 1987).

The burial of the Gondwana Surface thus represents a global event connected with the second distensional phase of Gondwana (VEEVERS, 2000) and the subsequent dispersion of Gondwana fragments. The present paper deals with the development of the western and southwestern Eromanga Basin in Australia, where environmental and tectonic forcing mechanisms are especially well demonstrated.

EXPOSURES OF GONDWANA SURFACE

Positive identifications of the Gondwana Surface has been achieved either in the subsurface, where the contact with overlying deposits has been identified by drilling or along basin margins and the periphery of inliers, where the surface has been exhumed from beneath covering sediments. In the subsurface the Gondwana Surface has been identified in a number of drill holes which penetrated Jurassic and older strata, especially near the margin of the Eromanga Basin, as for instance north and west of Oodnadatta (HESS, 1957; DEMAISON, 1969; WOPFNER, 1970), northwest of Marree (KRIEG et al., 1991) or in Fortville No 1-well close to the southern margin of the

Basin (WOPFNER and CORNISH, 1967), just to mention a few of the numerous intersections of the surface in drill holes within the Eromanga Basin.

Surface exposures are widespread along the western margin of the Eromanga Basin. Near the border between the Northern Territory and South Australia the surface has planed adamellites and granodiorites of the Palaeoproterozoic Kulgera plutonic suite. The surface emerges from beneath a cover of Algebuckina Sandstone west of about 134o 06' E longitude (Fig. 1) and extends westward, where TWIDALE and CAMPBELL (1995) recognised "a Jurassic granite inselberg landscape" in the Kulgera region. In the Northern Territory, where equivalents of the Algebuckina Sandstone are referred to as Da Souza Sandstone, the edge of the emergent surface can be traced along a northeast-striking lineament to Finke Station on the now defunct Central Australian Railway Line, where it is developed on Permian sedimentary rocks (Fig. 1). From there the edge is offset to the north and continues along the northeast-striking Rumbalara Hills, whence it disappears underneath the sand dunes of the Simpson Desert (see WELLS et al., 1970).

South of the Northern Territory/South Australian border the edge of the Gondwana Surface, still expressed on rocks of the Kulgera plutonic suite, extends for about 15 kilometres towards Tieyon Station. About

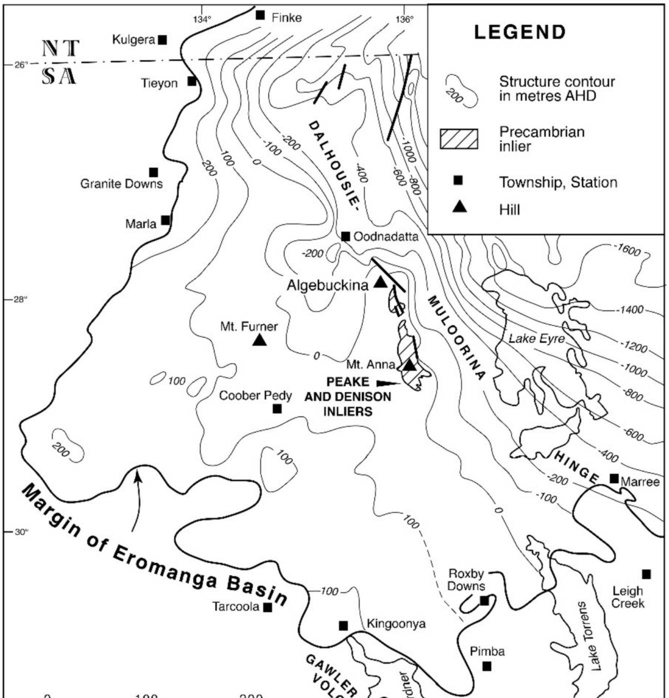

Fig. 1. Generalised structure contour map of base of Mesozoic of southwestern Eromanga Basin; also showing localities mentioned in text. As Triassic strata are absent west of the Dalhousie-Muloorina Hinge, the structure contour lines approximate present subsurface position of Gondwana Surface in that region (modified and expanded after KRIEG et al., 1995).

30 km southwest of Tieyon it is manifested on Early to Middle Proterozoic gneisses of the Musgrave metamorphic complex, before being covered by aeolian sands and other Quaternary materials. It re-emerges again near Granite Downs, but here it has developed on folded sedimentary rocks of Neoproterozoic age. In all the localities mentioned so far the rocks below the Gondwana Surface are intensely altered, all constituents except quartz having been transformed to kaolinite: this zone of chemical alteration may in places exceed 30 metres in thickness. At sites like the Rumbalara Hills deposits of red ochre are associated with the Surface, the formation of ochre resulting from the alteration of pyrite after exhumation.

The antiquity of the pre-Jurassic landscape in that region was recognised by JACK (1915), as pointed out by TWIDALE and CAMPBELL (1993). However, the ledges and mesas covered with siliceous duricrust ascribed by JACK (1915) to pre-Jurassic erosion are now recognised as remnants of an Early Tertiary (Eocene) surface (WOPFNER et al., 1974). In both areas, Tieyon and Granite Downs, the emerging Gondwana Surface is cut at an oblique angle by the Early Tertiary Cordillo Surface and its associated silcrete (Fig. 2). As the weathering processes on both surfaces involved the alteration of feldspars and other silicate minerals, including clays, to kaolinite, the thickness of the chemical alteration zone observed today may represent the cumulative effects of both weathering episodes (WOPFNER, 1964; WOPFNER and WALTHER, 1999).

Very little is known about the Gondwana Surface to the west and northwest of the basin margin. Bevels which are well above the level of Tertiary terraces are fairly common in the Musgrave Ranges in northwestern South Australia. Undoubtedly these bevels relate to an ancient land surface. This conforms to the suggestion of TWIDALE and CAMPBELL (1995) that the lower slopes of the Musgrave and Everard Ranges have been exhumed, "whereas the peaks rose as inselbergs" above the Jurassic fluviatile plains. The fact that Early Tertiary silcretes at the

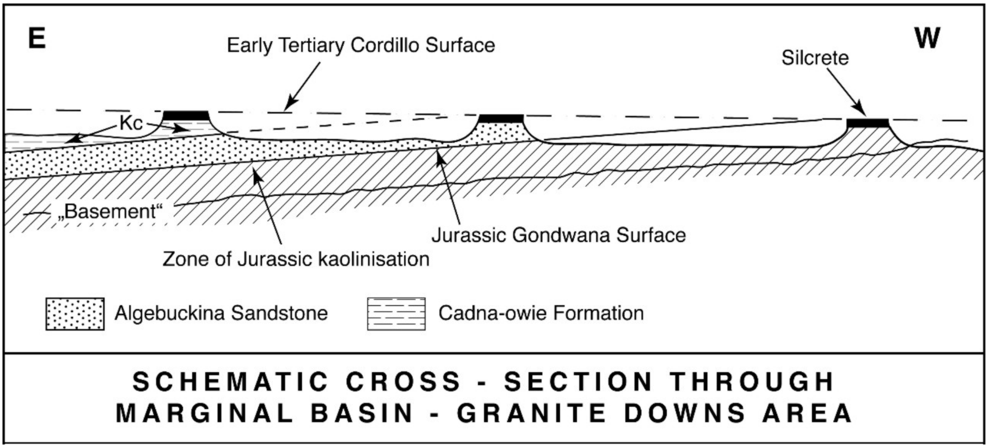

Fig. 2. Schematic cross-section through western margin of Eromanga Basin at Lester's Well, east of Granite Downs, showing present-day relationship between Jurassic Gondwana Surface and Early Tertiary Cordillo Surface (modified from WOPFNER, 1964).

southern margin of the Everard Ranges are only slightly above plain level indicates that the levels of corestones, situated well below the summit surface, resulted from deep chemical weathering of the Gondwana Surface. Obviously there is ample scope for rewarding research in the future.

South of the latitude of Granite Downs exposures of the Gondwana Surface are rare. The surface becomes prominent again at the southwestern margin of the Eromanga Basin, where the basin borders the Mesoproterozoic acid volcanics of the Gawler Ranges. Erosion of the "basal Jurassic sandstone" (JACK, 1931), now recognised as Algebuckina Sandstone and of the Mt Anna Sandstone Member, both of which onlapped the Gawler Ranges, has exposed large tracts of the Gondwana Surface. Within the Ranges themselves the Gondwana Surface is regarded as the precursor of the Nott Surface, *viz.* the ancient etch surface represented by the bornhardt massif (CAMPBELL and TWIDALE, 1991; TWIDALE and CAMPBELL, 1993).

On the southern margin the Gondwana Surface extends on to the Neoproterozoic and Cambrian strata of the Willouran Ranges south of Marree and the Flinders Ranges further to the southeast. On the Curdimurka 1:250,000 geological map KRIEG et al. (1991) noted the widespread subsurface occurrence of deeply weathered pre-Jurassic strata consisting of "greyish white clay passing down to mottled reddish brown clay…". KRIEG et al. (1991) named this zone of deep chemical alteration Bopeechee Regolith and placed it within the interval post-Permian and pre-Jurassic. The regolith is thus an equivalent of the weathering front associated with the Gondwana Surface. Near Copley at the southern end of the Leigh Creek coal basin, Algebuckina Sandstone forms a very prominent mesa. Here the Gondwana Surface is expressed by a low angle unconformity between the Rhäthian/Liassic Leigh Creek Coal Measures and the Algebuckina Sandstone. Silicified stem fragments, up to 30 cm in length are commonly embedded within the current bedded sandstone, indicating episodic input of plant debris. Near Lyndhurst, about 30 km north of Leigh Creek, a regolith consisting of intensely kaolinised, Neoproterozoic strata and large blobs of red ochre, measuring 30 to 80 cm, is ascribed also to the Gondwana Surface.

At the northeastern-most point of the Flinders Ranges, the north-dipping Gondwana Surface is identified by the base of the plant-bearing Algebuckina Sandstone at Mt Babbage (GLAESSNER and RAO, 1955). In earlier literature the sandstone at Mt Babbage was referred to the stratigraphic unit 'Blythesdale Sandstone' (WOODARD, 1955) which induced TWIDALE (2007) to relate the pre-sandstone surface and associated summit surfaces to the Early Cretaceous marine transgression rather than to the Jurassic fluvial event.

In addition to the exposures along the basin margin, the Gondwana Surface is well documented on and around the periphery of the Precambrian inliers of the Peake and Denison Ranges (Fig. 1). This up-faulted basement block is the type area of the Algebuckina Sandstone and the succeeding, Early Cretaceous formations of the Neales River Group (WOPFNER et al., 1970). At Algebuckina Hill, the actual type locality of the Algebuckina Sandstone, the formation rests unconformably on basement of intensely folded Palaeoproterozoic Peake Metamorphics. The basement-rocks which comprise gneiss, migmatite and mica schist have been deeply weathered and kaolinised (Fig. 3). The process which took place prior and during the early stage of deposition of the sandstone has altered all constituent silicate minerals to kaolinite, leaving only quartz and some other resistant minerals unchanged. The altered rocks still preserve

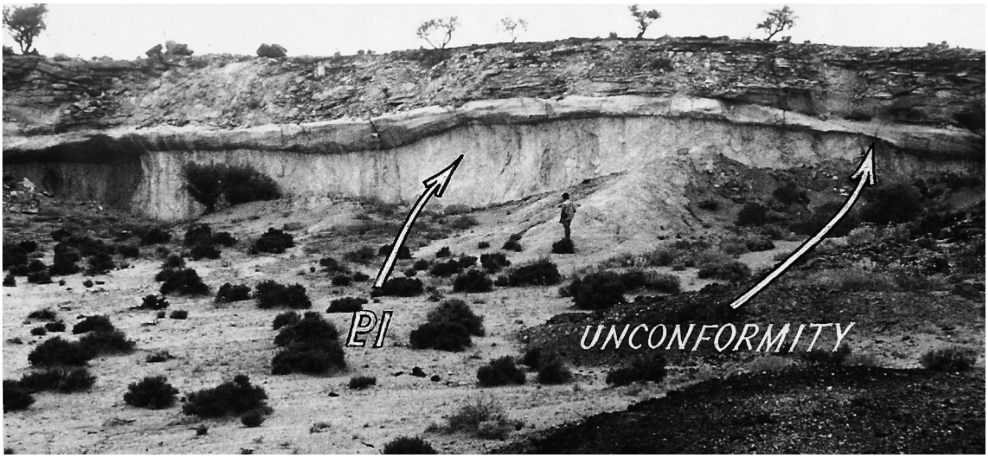

Fig. 3. Unconformity between kaolinised, Palaeoproterozoic migmatite of Peake Metamorphics (Pl) and Algebuckina Sandstone represents the Gondwana Surface. Bold exposure above the unconformity consists of medium-grained, ill-sorted, kaolinitic sandstone. Locality is about 4.8 km west of Algebuckina Hill.

Fig. 4. Completely kaolinised pegmatite, cutting across equally kaolinised migmatite of the Peake Metamorphics is recognizable only by the coarse fabric of remnant quartz. Pebbles of quartz and rip-up clasts of kaolinised basement are recognizable at the very base of the overlying Algebuckina Sandstone.

Fig. 5. Mesas of Algebuckina Sandstone and Cadna-owie Formation at Mt Anna rest on Gondwana Surface. The surface cuts across folded sedimentary rocks of the Neoproterozoic Burra Group, visible in the middle ground of the picture. Mt Anna, recognizable by its white cap of bleached Bulldog Shale (Aptian), is in central background of picture. Silcrete and fossil plant locality is at low mesa furthest to the right.

the fabric of the original rock, which is well demonstrated in the case of a completely kaolinised pegmatite (Fig. 4).

Elsewhere, the Gondwana Surface has been developed on folded and truncated Neoproterozoic sedimentary rocks of the Adelaide System as at Mt Anna further to the south (Fig. 5; WOPFNER and HEATH, 1963; WOPFNER et al., 1970), on Artinskian coal measures of the Mt Toondina Beds west of Algebuckina Hill (FREYTAG, 1965; WOPFNER, 1970) or on Early Permian glacial deposits west of Mt Dutton, the northernmost inlier of the Peake and Denison Ranges (HEATH, 1965). At all these localities the Gondwana Surface is covered unconformably by Algebuckina Sandstone (ROGERS and FREEMAN, 1996).

On palaeo-highs, like the Mt Margaret ridge, Algebuckina Sandstone was not deposited and the Gondwana Surface did not become covered until the Early Cretaceous transgression (WOPFNER, 1968; ROGERS and FREEMAN, 1996). No kaolinisation is discernible at this location, indicating that such “bald heads” had either not been affected by kaolinisation due to denudation or the old regolith had been eroded prior to the transgression.

Until the onset of the Early Cretaceous transgression the Gondwana Surface appears as a stable, senile landscape with occasional inselbergs and low swells.

BURIAL HISTORY

Algebuckina Sandstone

The first sediments to cover the Gondwana Surface were the fluvial deposits of the Algebuckina Sandstone, described by WOPFNER et al. (1970). Within the type area around the Peake and Denison inliers the formation consists of fine to coarse grained, quartzose, current bedded sandstones. It comprises a lower succession characterised by a pore-filling kaolinitic matrix and an upper, generally well sorted and clean sequence. As mentioned above, the Sandstone rests unconformably on older, strongly kaolinised rocks, ranging in age from Palaeoproterozoic to Permian. Commonly a thin, basal conglomerate, consisting predominantly of well rounded quartz pebbles and some rip up clasts occurs at the base of the sandstone. Occasionally, isolated pebbles of kaolinised volcanics or other igneous rocks are observed. West of Algebuckina Hill (Figs 3 and 4), however, the base of the section is formed by 20 cm to 50 cm of massive and resistant, kaolonitic sandstone. On closer scrutiny some relic current structures are discernible but most structures were obliterated by the invasion of pore-filling kaolinite, indicating that the process of kaolinisation and bleaching was not only synchronous with deposition but also continued after the latter had finished.

Kaolinite extends into the lower parts of the formation, which consist of fine to medium grained, kaolinitic sandstones. The dominant sedimentary structures are unidirectional, angular current beds, bounded on bottom and top by quasi-horizontal erosional surfaces, commonly accompanied by lag gravels. The latter are usually only one pebble layer thick, as demonstrated in Figure 6. The direction of the foreset beds is almost invariably within the north to northeast sector. However the proportion of pebble- to cobble-sized clasts varies from locality to locality. At Mt Anna for instance it is considerably higher than at the type section.

The upper part of the Algebuckina Sandstone, with the exception of the uppermost unit, consists of coarse-grained to granule-sized, slightly kaolinitic and generally bimodal, quartz arenites. Kaolinite in

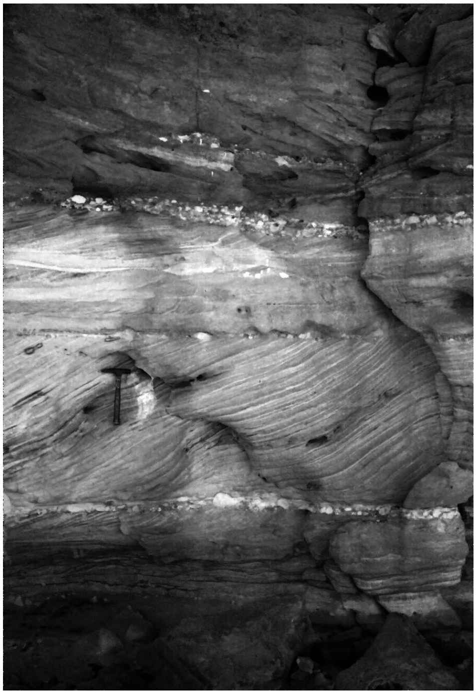

Fig. 6. Typical lithofacies of lower Algebuckina Sandstone, near Mt Anna, consists of planar current beds bounded by level erosional surfaces outlined by lag gravels. The lag gravels consist of quartz and kaolinitic shale pebbles. Climbing ripple marks are recognizable at bottom of picture. The dark sandstone at the top of picture belongs to the coarse-grained, bimodal facies of the upper part of the formation.

the matrix rarely exceeds 5 percent of the pore volume. Aggregates of 8 mm to 10 mm spheres consisting of quartz grains cemented by carbonates and recrystallised kaolinite are common (Fig. 7). The beds of this interval are invariably current bedded, often with concave foresets and cut and fill structures.

The top unit of the formation is formed by fine to medium grained, clean, quartz sandstone. At the Mt Anna section this unit is separated from the preceding units by an erosional surface and a basal granule conglomerate. The unit differs from the sandstones of the lower section by its excellent sorting and by the complete absence of kaolinite or other matrix material. Further characteristics are sigmoidal current beds, dewatering structures as (Fig. 8) and incipient silicifications. At Mt Anna the top 70 cm to 150 cm of this unit have been altered to silcrete, containing well preserved casts of plant fossils (Fig. 9; see WOPFNER and HEATH, 1963; WOPFNER et al., 1970). The silcrete is a typical early diagenetic silcrete formed by quartz overgrowth in optical continuity with the original clastic quartz

Fig. 7. Aggregates of sandstone spheres, consisting of carbonate and kaolinite cemented sand are typical features of the coarse grained sands in the upper third of Algebuckina type section. Coin diameter is 2 cm.

grains (homoaxial overgrowth). Thus, the quartz crystals of the silcrete form a dense and interlocking fabric. They are well oriented along the C-axes (Fig. 10). Homoaxial quartz overgrowth follows the position of the C-axis of the host grain. The orientation therefore reflects the grain orientation of the original sand fabric. This, together with the excellent sorting indicates a steady, quasi laminar flow regime just above the threshold of bed load movement. The existence of quicksand is evidenced by the dewatering structures. Quicksand requires a fabric of random grain orientation and relates to movements at the low energy end of vortex systems. A more detailed discussion of the depositional environment is given below.

The macro-flora of the Algebuckina Sandstone comprises *Cladophlebis* cf.a*ustralis, Hausmannia* cf. *buchii,* (see Fig. 9), several species of *Microphyllopteris, Araucariaceae* and *Cycydites* (HARRIS, in WOPFNER et al., 1970). A review of macro- and micro-floras by ROGERS and FREEMAN (1996) confirmed a Late Jurassic to Early Cretaceous age of the Algebuckina Sandstone, as suggested previously by WOPFNER et al. (1970).

In outcrop the Algebuckina Sandstone rarely exceeds 20 m in thickness, reaching a maximum of nearly 40 m in the region of the Finke erstwhile railway settlement. In subsurface the Dalhousie-Muloorina Hinge separates a western area where the formation generally measures less than 70m, from the region to the east, where the sandstone swells to a thickness of up to 750 m (KRIEG et al., 1995).

Generally the Algebuckina Sandstone extends to the very margin of the Eromanga Basin. However, in the area west of Mt Furner and Coober Pedy (Fig. 1) the Algebuckina

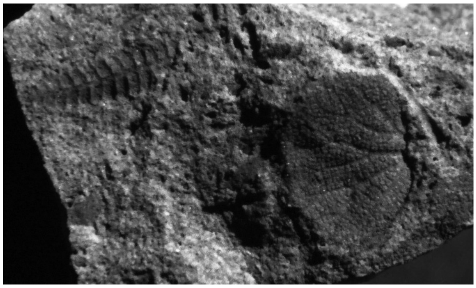

Fig. 8. Contorted folds, symptomatic of the collapse and dewatering of quicksand, are common structures in the uppermost portion of well sorted Algebuckina Sandstone at Mt Anna locality.

Fig. 9. Surface of silcrete with well preserved casts of Cladophlebis cf.australis (upper left) and Hausmannia cf. buchii (bottom right). Specimen is from silcreted Algebuckina Sandstone at extreme right in Fig. 5. Length of Cladophlebis is 34 mm.

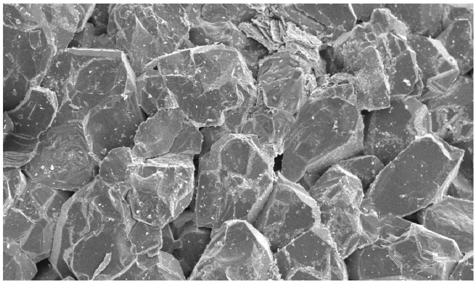

Fig. 10. Scanning electron micrograph of silcrete from the Mt. Anna locality displays a fabric of oriented, interlocking quartz crystals. Surface was obtained by chipping the specimen parallel to the bedding plane. Clear crystal faces are visible at top left of picture. Observations under the optical microscope show that crystal growth took place in optical continuity with well rounded, clastic quartz grains.

Sandstone is overstepped by the Cadna-owie Formation. In a drill hole near Mt Furner, 30 metres of Algebuckina Sandstone were intersected, but in drill holes situated 130 km WNW and 80 km WSW of Coober Pedy respectively, the Neocomian Cadna-owie Formation rests directly on Early Permian coal measures of the Mt Toondina Formation (WOPFNER, 1970). This indicates a morphological high which may have separated two distinct fluvial systems.

Deposition of the Algebuckina Sandstone was a diachronous process. In the rapidly subsiding parts of the basin east of the Dalhousie-Muloorina Hinge, palynological assemblages demonstrate that deposition had begun already in Early Jurassic times, whereas the macro flora at the Mt Anna section is of latest Jurassic to Early Cretaceous age. As some of the main sediment input into the basin was sourced from the cratonic regions exposed to the southwest, west and northwest of the basin, rivers must have flowed across the marginal area for a long time without leaving much sediment. The compressed sections of the Algebuckina Sandstone along the basin margins thus represent a long time of deposition and reworking.

Cadna-owie Formation

The second phase of inundation was introduced by the marine transgression at the onset of the Cretaceous. This event is evidenced in the Cadna-owie Formation. The formation rests with an uneven, erosional surface on the Algebuckina Sandstone. A few lenticular pebble beds are present at the base of the Formation, but generally, a typical rudaceous transgressive facies is absent.

The composition of the Cadna-owie Formation is quite heterogeneous, comprising dark siltstones, carbonaceous claystones, lenses of granule conglomerates and medium to fine grained, feldspathic and micaceous sandstones. Many of the latter are tightly cemented by carbonate, to form hard, calcareous sandstones or sandy limestones. The calcite cement consists of discrete crystals of up to 1cm diameter, poikilitically enclosing the clastic grains. The calcareous nature makes the Cadna-owie Formation an excellent seismic reflector which can be recognised as “C”-horizon across the whole of the Eromanga Basin. Calcareous oolites are commonly associated with the calcareous units, especially at the periphery of “basement” inliers. Pyrite is ubiquitous throughout the Formation, either as botryoidal concretions of up to 10 cm diameter, as fillings of cell lumina of fossil wood or as disseminated small aggregates.

A special feature of the Cadna-owie Formation is the presence of isolated, well rounded cobbles and boulders within calcareous sandstones in the lower third of the formation. The diameters of the clasts range from about 20 cm to 120 cm, but even larger examples, exceeding 2 metres in maximum length have been reported. They consist largely of locally derived rocks, in the case of the Peake and Denison inliers, clasts of yellow quartzite dominate.

Within the upper half of the Cadna-owie Formation, interbeds of medium to coarse grained, feldspathic sandstones with pebbles of purple porphyritic rhyolites are present. At the Mt Anna section the whole upper half of the Cadna-owie Formation (11 m) is made up of such feldspathic sandstones. Thus the sandstone facies has been identified as Mt Anna Sandstone Member of the Cadna-owie Formation (WOPFNER et al., 1970). The unit consists of well sorted, medium to coarse grained, feldspathic sandstones, characterised by concave current bedding with individually graded foreset beds. Conglomerate beds consisting of well rounded pebbles of purple to orange coloured porhyritic rhyolite occur as frequent interbeds (Fig. 11). Petrographic studies have demonstrated that the pebbles of porphyritic rhyolites derived from the volcanic complex of the Gawler Ranges, situated at the southwestern margin of the Eromanga Basin (WOPFNER et al., 1970; CAMPBELL and TWIDALE, 1991; TWIDALE, 2007). This provenance is demonstrated further by increased prominence of the Mt Anna Sandstone Member towards the source area of the Gawler Ranges, where its participation on the total Cadna-owie section is 100 percent (Fig. 12).

The Cadna-owie Formation represents the transgressive event of the Lower Cretaceous Sea. Palynological and palaeontological data indicate a Neocomian to earliest Aptian age (WOPFNER et al., 1970; KRIEG et al., 1995).

Deposition and climate

The most significant features of the succession of the Algebuckina Sandstone are the general absence of silicate minerals except kaolinite and the decreasing participation of kaolinite from the bottom to the top of the sequence. The kaolinisation of the underlying rocks preserving original rock textures and the pore-filling kaolinite of the

Fig. 11. Exposure of current bedded Mt. Anna Sandstone Member at type section. The conglomerate lens incorporated in the sandstone comprises an abundance of well rounded, orange coloured pebbles of Gawler Ranges porphyry.

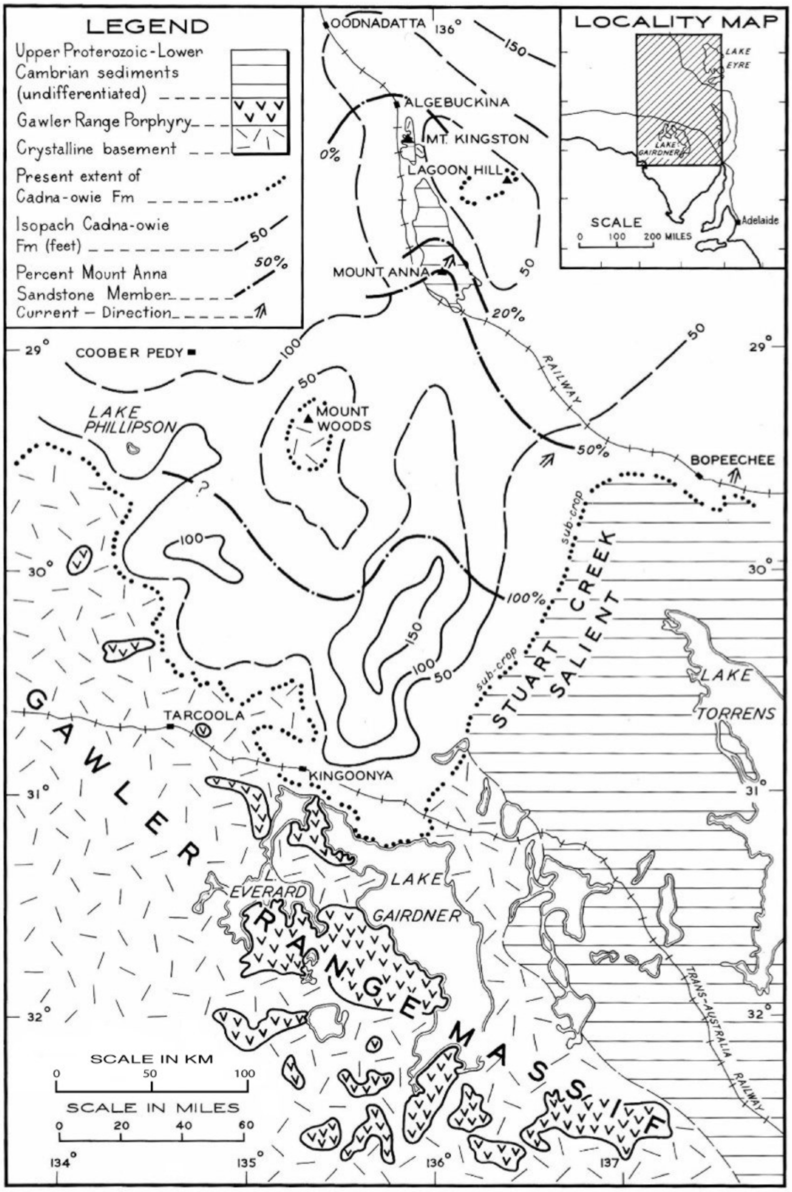

Fig 12. Isopach map of Cadna-owie Formation in feet (1 ft = 30.48 cm) of area between the Peake and Denison inliers and Gawler Ranges, southwestern Eromanga Basin. Thickness of Mt. Anna Sandstone Member, expressed as percentage of total Cadna-owie thickness, demonstrates increased dominance of Mt Anna Sandstone proximal to the Gawler Range Massif (modified after WOPFNER et al., 1970).

lower units of the Algebuckina Sandstone are symptomatic for an aggressive, low-pH pore water system. These pore waters acted within the newly deposited sands as well as within the fluid saturated rocks below and adjacent to the depositional system. KANTOROWICZ (1984) for instance has demonstrated, that pore-clogging kaolinite in Jurassic sandstones of the North Sea is not a depositional component, but was formed during earliest, quasi syndepositional, diagenetic processes in freshwater environments. Neoformation of kaolinite is known to occur in tropical soils (MURPHY et al., 1995) and highly acid conditions within certain rhizospheres are sufficient to transform certain clay minerals into kaolinite (KHADAMI and AROCENA, 2008). Kaolinisation is not only effective in oxic conditions but even more so in reducing conditions. This is evidenced by the abundance of pyrite within the basal Algebuckina Sandstone and the underlying kaolinised basement as for instance in the bore hole Fortville No. 1 (WOPFNER and CORNISH, 1967), and in Early Permian deglaciation sequences (DIEKMANN and WOPFNER, 1996; WOPFNER, 1999).

Conditions as described above exist in so called “black water” rivers. The Rio Negro of the Amazon-Orinoco system in Brazil or the Gordon River in Tasmania may be cited as analogue examples. The waters of the Rio Negro for instance have a pH-value as low as 3.8, caused by high concentrations of organic acids, saponins and other products of plant decay (SIOLI, 1965; GRABERT, 1991). Black water rivers are characterised by high flow volumes. They are further recognised for their paucity of suspended sediment load, the sediment freight consisting primarily of bed load or saltation material.

Conditions of high volume flow regimes with moderate flow velocity and dominance of bed load transport correspond well with the planar current beds, bounded by horizontal lag gravels observed in the lower, kaolinitic units of the Algebuckina Sandstone (Fig. 6). High volume flow regimes are maintained throughout Algebuckina sedimentation but an increase of gradient with locally higher flow energies is indicated in the middle part of deposition, reverting to a steady, high volume regime near the top.

A further characteristic feature of the Algebuckina Sandstone is the decrease in kaolin content from the bottom to the top, leading to a steady increase of chemical maturity of the sediment until pure and well sorted quartz sandstone, consisting of more than 95 percent SiO_2, tops the sequence. This upward improvement of chemical maturity suggests a continuous lowering of the pH to a value where even kaolinite was removed. When Al_2O_3 solubility exceeded that of SiO_2, excess silica crystallised in local concentrations to form the hydraulic silcretes like the plant bearing quartzite at the top of the formation. This process takes place at the level of true solutions (WOPFNER and WALTHER, 1999). Similarly, the silicification of wood, preserving the most intricate details on cell structures, can only be achieved by material exchange on the molecular level, requiring the existence of proper solutions for ion exchange (WOPFNER, 1983).

To maintain such conditions a humid to pluvial climate is required. HARRIS (cited in WOPFNER et al., 1970) from his studies of the palaeoflora deduced a “moist, subtropical climate” which corroborates the sedimentological evidence. KRIEG et al. (1995) and ROGERS and FREEMAN

(1996) reviewed the literature on the fossil flora and deduced a moist and warm to cool-temperate climate.

As mentioned above, the Cadna-owie Formation represents the onset of the Early Cretaceous transgression. Hence it incorporates a great variety of litho-facies expressions, depending on the individual local environment and coastal morphology (see WOPFNER et al., 1970).

One feature which has been subject to discussions ever since their occurrence had been ascribed to glacial transport by JACK (1931), are the pebbles and boulders incorporated in the lower parts of the formation. JACK's (1931) observations referred primarily to the exotic boulders and cobbles which form a cover on all plains between the Gawler Ranges and the Peake and Denison inliers. PARKIN (1956) has pointed out that many of these clasts displaying evidence of glacial transport like soled and striated surfaces were derived from Early Permian tillites of the Arckaringa Basin (see WOPFNER, 1970). Similarly, loose cobbles and boulders of rhyolites have been weathered out from conglomerates of the Mt Anna Sandstone. This explains the origin of most of the exotics strewn on the surface, but the large clasts actually embedded in the lower parts of the Cadna-owie Formation demand a specific interpretation.

WOPFNER et al. (1970) demonstrated that the cobbles and boulders occur at the periphery of basement highs and within specific levels of the Cadna-owie Formation, generally in the lower half of the succession. The clasts consist mainly of local basement material, they are water worn but do not show any typical features of glacial transport and, they diminish in size away from the high. They are always embedded in a stable position, i.e. with the flat side down, whereas labile positions, as observed when emplaced as drop stones from melting ice, are absent. All these features, together with indicators for moderately warm surface waters like calcareous oolites have prompted these authors to refute a glacial origin. They suggested instead that tectonic instability during the transgression combined with near-shore related sedimentary processes like sediment creep, were responsible for the emplacement of the rudaceous elements. Tectonism no doubt was accompanied by earth quakes. Tsunamis activated by earthquakes have to be considered as an alternative mode of emplacement. The omnipresence of pyrite attests to a negative Eh within the sedimentary column, indicating high organic productivity and input of plant material as evidenced by the abundance of fossil wood.

The presence of the boulders within the Cadna-owie Formation and investigations of tree rings of fossil wood have lead FRAKES and FRANCIS (1988) to resurrect the glacial model. The discovery of glendonite pseudomorphs in the overlying marine Bulldog Shale was taken as further evidence for a cool to cold climate during Early Cretaceous deposition in the Eromanga Basin (DE LURIO and FRAKES, 1999). These authors deduced a seasonally freezing climate whereby the boulders were rafted off shore, locked into river ice. In the same paper DE LURIO and FRAKES (1999) supported their argument by recalculating oxygen isotope data published by DORMAN and GILL (1959). Using the assumption that the present isotopic composition of glendonite pore waters are representative of the Early Cretaceous sea water composition and assuming further mixing of high latitude meteoric waters with seawater, DE LURIO and

FRAKES (1999) derived at temperatures between -1° and 5° C, whereas DORMAN and GILL (1959) had obtained temperature values ranging from 13.8° to 16.5° C. Microfloral changes, especially an increase in conifer pollen serves as an additional argument for a cold climate (KRIEG et al., 1995). The present author regards the occurrence of glendonite pseudomorphs primarily controlled by sulphate availability and negative Eh rather than temperature. In this view the question of the palaeoclimate in the Early Cretaceous remains open.

The Mt Anna Sandstone Member is the product of a competent, high energy fluvial system which fltowed from an upland in the region of the Gawler Ranges northeast to enter the transgressing sea in large estuaries and deltas. There its sediment freight was intercalated with marginal marine deposits. The sudden appearance of the sandstone at about the middle of the Cadna-owie Formation requires a substantial increase in gradient ascribed to tectonic uplift of the region of the Gawler Range Volcanics and neighbouring basement complexes, termed the Gawler Range Massif by WOPFNER et al. (1970). The ensuing erosion not only stripped the regolith from the Gondwana Surface but also cut into the fresh rock, laying the foundation for the present morphology (CAMPBELL and TWIDALE, 1991; TWIDALE and CAMPBELL, 1993). Both, WOPFNER et al. (1970) and CAMPBELL and TWIDALE (1991) thought that the Massif had been uplifted along northwest trending fault structures. Considering regional geodynamics however, vertical displacements along latitudinal trending structures may have imposed a controlling influence.

Whatever the temperature may have been in Cadna-owie time, climate was humid, providing considerable transport volumes by pH-neutral waters. The upward fining of individual foreset beds indicates regularly changing flow volumes. These could have been seasonal, but more likely episodic changes in precipitation, whereas the conglomeratic interbeds can be related to storm events.

EXHUMATION

The first evidence for the exhumation of the Gondwana Surface is provided by the ubiquitous presence of well rounded pebbles of silicified wood and amber coloured jaspers in the basal conglomerates of the Paleocene/Eocene Eyre Formation in the eastern Lake Eyre Basin. The provenance of the silicified wood and the amber-coloured jaspers were unquestionable the exposures of Jurassic sandstone and the "fossil forests" in the Tibooburra region in northwestern New South Wales (WOPFNER et al., 1974).

Sandstones of comparable age, intercalated with multiple silcretes at Mt Harvey, 2 km northeast of Algebuckina Hill indicate a similar onset on the western margin of the Eromanga Basin. This is corroborated by the development of silcretes of the Cordillo Surface at the present northwestern boundary of the Eromanga Basin. As demonstrated by WOPFNER and WALTHER (1999) and indicated in Figure 2, these silcretes extend over from the Cretaceous on to basement. The youngest stratigraphic unit on which typical Cordillo Silcrete is developed, are the terminal deposits of the Eyre Formation, hence the first exhumation along the western margin probably commenced also in Early Tertiary times.

The post Eocene – pre Miocene fold movements not only created the large anticlinal structures of the basin but also created new depot centres in the Lake Eyre region. The following period of sedimentation and the formation of ferricretes did not enhance exhumation and the succeeding depositional phase of the Warrina Surface covered large areas of already exposed Gondwana Surface or modified its appearance. The Mt Margaret Surface of ROGERS and FREEMAN (1996) represents the modified or re-emerged Gondwana Surface in the Mt Margaret Range of the Peake and Denison inliers. This is evidenced by remnants of Mt Anna Sandstone with well rounded pebbles exposed on the Mt Margaret Plateau (WOPFNER, 1968). However the surface had been covered by gypsiferous soils of the Warrina Surface and was not exposed until post-Warrina fault movements uplifted the Ranges to their present elevation in Plio-Pleistocene times (WOPFNER, 1968). Figure 13 shows the present exposure of the modified Gondwana Surface at Mt Margaret and the juvenile erosion on the up-faulted (eastern) side of the fault block.

Along the southwestern margin of the Gawler Ranges, the surface may have never been covered to any great extent. The level of the Nott Surface was apparently lower in Early Tertiary times, as indicated by remnants of Cordillo-equivalent silcretes between bornhardts (CAMPBELL and TWIDALE, 1991; TWIDALE and CAMPBELL, 1993). Late Tertiary uplift which elevated the southern rim of the Australian continent by some 200 m was responsible for that final adjustment.

Fig. 13. Exhumed Gondwana Surface cutting across deformed sedimentary rocks of the Neoproterozoic Burra Group now forms the surface of the up-faulted Mt. Margaret Plateau in the Peake and Denison inliers. Direction of view is northwest.

CONCLUSIONS

The Gondwana Surface and its thick weathering mantle of kaolinised basement reflects the crustal stability experienced in Gondwana at the time which followed the termination of the Pangaea depositional phase in the mid-Triassic and the commencement of dispersion of Gondwana fragments in Late Jurassic to Early Cretaceous times. The time interval roughly coincides with the “Gondwana II Extension” of VEEVERS (2000).

During the Jurassic the Gondwana Surface was dominated by large, high volume river systems, leading to gradual burial of the subsiding surface by sand-dominated fluvial and fluvio-lacustrine deposits. Within the study area inflow was from the west and northwest and from the southwest to south. The Algebuckina Sandstone represents this initial phase of burial. Depositional mode, water and soil chemistry and environment were analogous to the present drainage system of the Amazon River.

Northeast tilt of Australia, i.e. away from the rift shoulders, created by the Antarctic–Australia rift system, combined with a rise in sea level, opened the path for the marine transgression in Neocomian times and the deposition of the marginally marine Cadna-owie Formation. Tectonism which became active after the onset of the transgression was responsible for the input of local rudaceous material. The formation of a large basement block in the southwest of the region, the Gawler Range Massif led to the creation of a high energy river system which transported large volumes of sand and rudaceous material into the advancing sea where it interfingered as Mt Anna Sandstone Member with the strata of the Cadna-owie Formation.

The uplift of the Gawler Range Massif was associated with the widening of the rift system between Antarctica and Australia. BOURNE et al. (1974) suggested a northeast tilt of the Gawler Range Volcanics along the northwest-trending Corrobinnie Depression which they interpreted as the surface expression of a fracture zone. They observed a number of minor faults at the edge of the volcanics, but there was no unequivocal evidence for a major dislocation zone concomitant with the surface expression of the depression. On the regional gravity map the complex of the Gawler Range Volcanics and the associated granitoids of the Hiltaba Suite occur as an east-west trending, positive gravity anomaly. A pronounced gravity slope bounds the positive anomaly in the southwest, leading to a substantial gravity low, indicative of a different rock province. This slope combined with a corresponding change of the characteristics of magnetic anomalies support the existence of a northwest striking dislocation zone below the Corrobinnie Depression. From the southern margin of the positive gravity anomaly associated with the Gawler Range-Hiltaba volcanic-igneous complex, a slope leads down to latitudinal-trending gravity depressions and magnetic anomalies along about 32° 30’ S latitude. This is interpreted as an indication for the existence of a further dislocation zone, paralleling older rifts like the Polda Basin and similar structures in the Bight Basin further west. Extensional movements along these two dislocation zones uplifted the Gawler Range Massif, thus creating a north- to northeast-dipping rift shoulder which became the source for the Mt Anna Sandstone. The northwest-trending Corrobinnie dislocation zone would have acted as an accommodation fault. These movements apparently were the final rifting event prior to the onset of drift and distension. This event terminated the history of Gondwana and the Australian continent acquired its own, independent character. Exhumation of the Gondwana Surface was initiated by epeirogenic movements in the Early Tertiary.

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