Northern Curnamona Province, Regolith Exposures, Tour Guide

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Northern Curnamona Province, Regolith Exposures Tour Guide

Malcolm J Sheard (compiler)

INTRODUCTION

Northern Curnamona Province includes the northern Flinders Ranges, comprising the Mounts Babbage and Painter Inliers (Palaeoproterozoic to Neoproterozoic crystalline basement) and overlying metasediments of the Adelaide Geosyncline (Neoproterozoic). Onlapping these are sediments of the Eromanga Basin (Mesozoic) and the Callabonna Sub-basin of the Eyre Basin (Cenozoic). Weathering profiles have developed in most of the above mentioned rocks, some encompass multiple weathering cycles while others represent only a single weathering cycle. Tectonic uplift during the Cenozoic, repeated episodes of erosion and on-going deposition have together generated a plethora of rock and regolith exposures in this region. These provide excellent opportunities to study key regolith relationships and materials in profile and provide reference sites for comparisons elsewhere. Regional mapping and regolith study in this region since the 1950s have provided much of the information contained herein.

Six sites of significance, at five localities, are presented in this Tour Guide, each provide key profile exposures and reference materials. These are useful in establishing provenance and landscape position (regolith architecture) of potential sample media (especially for lags, duricrusts and colluvium). Sites are described as stand-alone features but can also be visited in a general west to east, or reverse, tour. Regional access for this Tour is via the Strzelecki Track and/or the Arkaroola to Mt Hopeless Road. Pastoral station tracks and the Dog Fence maintenance track provide local access. The specific regolith profiles are situated on these pastoral stations: Murnpeowie-Mount Hopeless and Moolawatana. Permission to visit these sites prior to entering them should be sought from the respective pastoral lease holders and/or their on-site managers. Locations are set out on the regional location plan (Fig. 1) and the more localised 1:250 k topographic map extracts (Figs 2–4). Detailed geology map extracts are provided under each site description. Locations for those are marked on Figures 2–4.

A schematic regional regolith column displaying key regolith relationships including weathering of basin onlap sequences to basement rocks in northern South Australia, is provided in Figure 5.

LOCALITIES

There are 5 sites included in this 'regolith tour guide' (Fig. 1). Sites are in order from north to south, with brief notes regarding their significance.

Site 1

Reedy Springs Gorge, ramp faulted and silcreted Eyre Formation (Site 1): this is the only reference Type Area for the Eyre Formation (Palaeogene) in this region. Localised tectonics have tipped this fluvial sand sequence into steeply dipping beds, now exposed by a cross-cutting fluvial gorge. Pre-tectonic silicification (Palaeogene) and a post tectonic silicification (Neogene) are exposed in the one section, these are at steep angles to each other.

Site 2

Silicified Namba Formation (Site 2): this site is complementary to and just north of Site 1. It exposes part of the Namba Formation (Oligocene to Miocene) where it is intensely weathered, megamottled and silicified to porcellanite (late Neogene). The silicification zone encapsulates part of the megamottle horizon.

Site 3

Bopeechee Regolith, SW of Prospect Hill: extensively developed across much of northern South Australia, this intensely weathered profile is developed here in both Terrapinna Granite (Mesoproterozoic) and Adelaide Geosyncline metasediments (Neoproterozoic). It is overlain by essentially unweathered terrigenous-marginal marine Parabarana Sandstone (equivalent to Cadna-owie Formation). Well exposed, this site offers 3D comparisons of weathering in two very different primary materials and displays how these are incorporated into the overlying sediment.

Site 4

Mulligan Dam Regolith: is a remnant of a more extensive weathering profile and is developed in Late Cretaceous marine shales of the Eromanga Basin, it is therefore younger than the profile exposed at Site 3. This profile, as defined, includes overlying colluvium and silcrete granules-pebbles derived from the underlying weathering zone. Mulligan Dam regolith underlies or interdigitates with the Eyre Formation, and is therefore early Palaeogene in age.

Site 5

Parabarana ramp faulted and silcreted regolith: there are two separate sites to visit here within a few kilometres of each other. Site 5a: is at the Parabarana Sandstone Type Section, just east of Parabarana Hill, where tectonically folded-ramp faulted Cretaceous sandstone is intensely silicified along the crest of the exposure but not below the overlying Cretaceous Bulldog Shale. Site 5b: is ~350 m north of Site 5a and forms part of the same tectonic feature. Here Eyre Formation overlies Parabarana Sandstone and Bulldog Shale but it is the Eyre Formation that has been intensely silicified to silcrete (~5 m). Erosion of the ramp faulted sequence has provided cliff exposures – particularly of the complex silicification zone. Comparisons between the two sites regolith can be easily made.

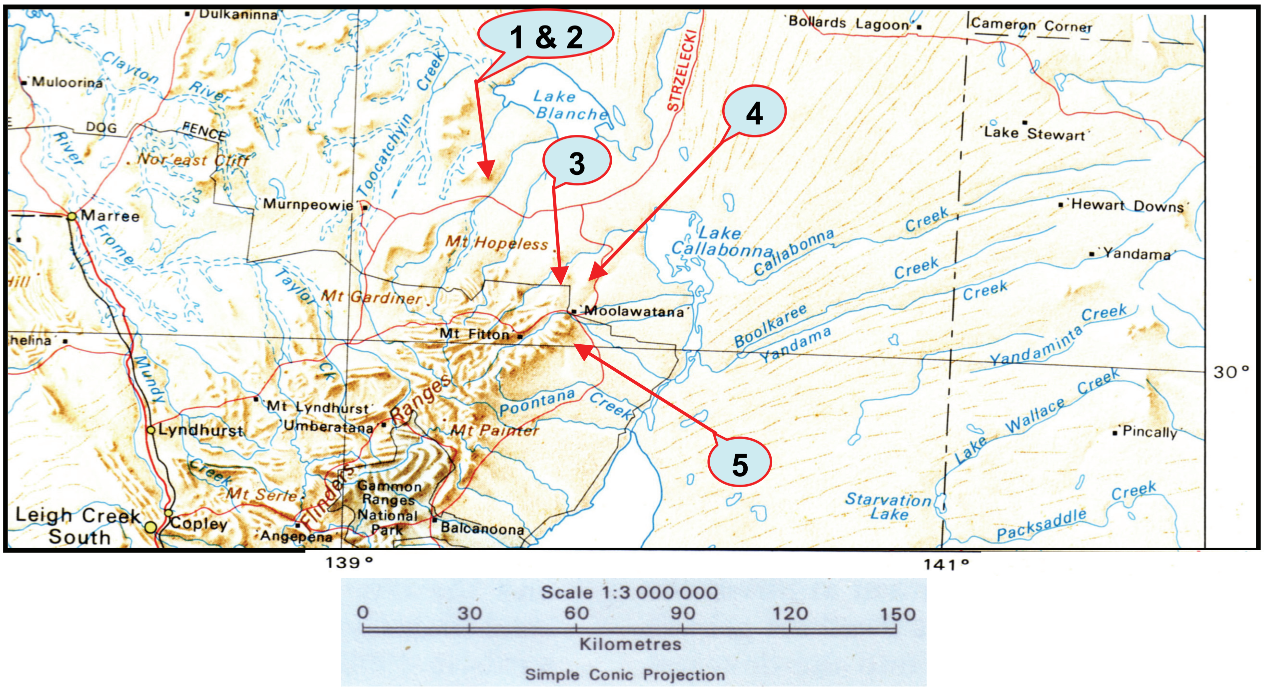


Figure 1. Regional location map showing roads, villages and key topographic features for the northern Curnamona Province (after Griffin and McCaskill, 1986). Numbered arrows indicate the approximate locations of tour sites.

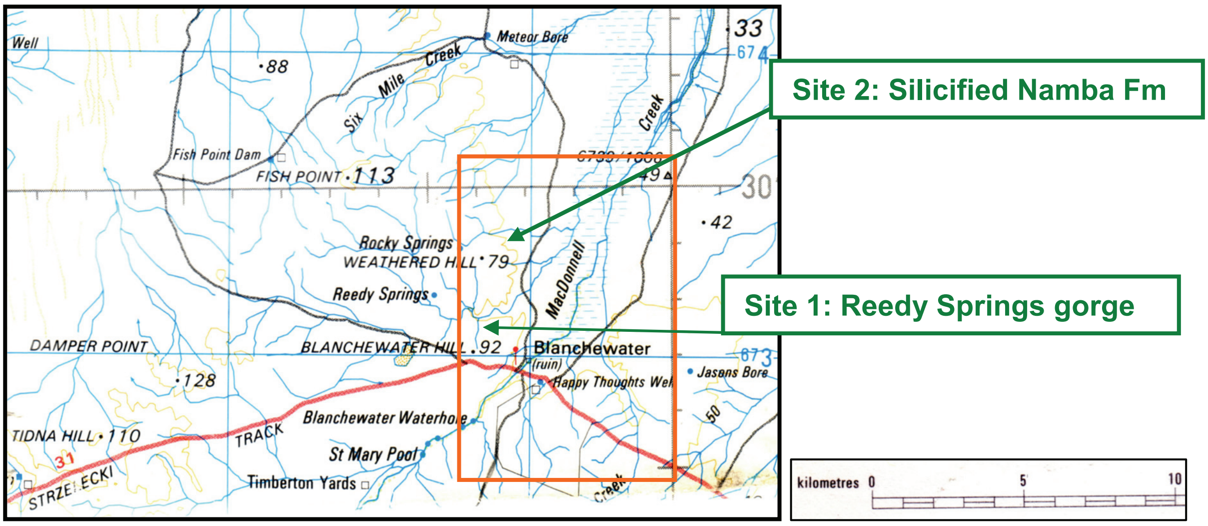


Figure 2. An extract from MARREE 1:250 k topographic map, ~mid-east side. The orange outline box indicates the location for Figure 6 showing geology for the Reedy Springs gorge Eyre Formation (+ silcretes Site 1), and nearby silicified Namba Formation (Site 2) outcrop. Main access is via the Strzelecki Track, turn off at Blanchewater Ruins.

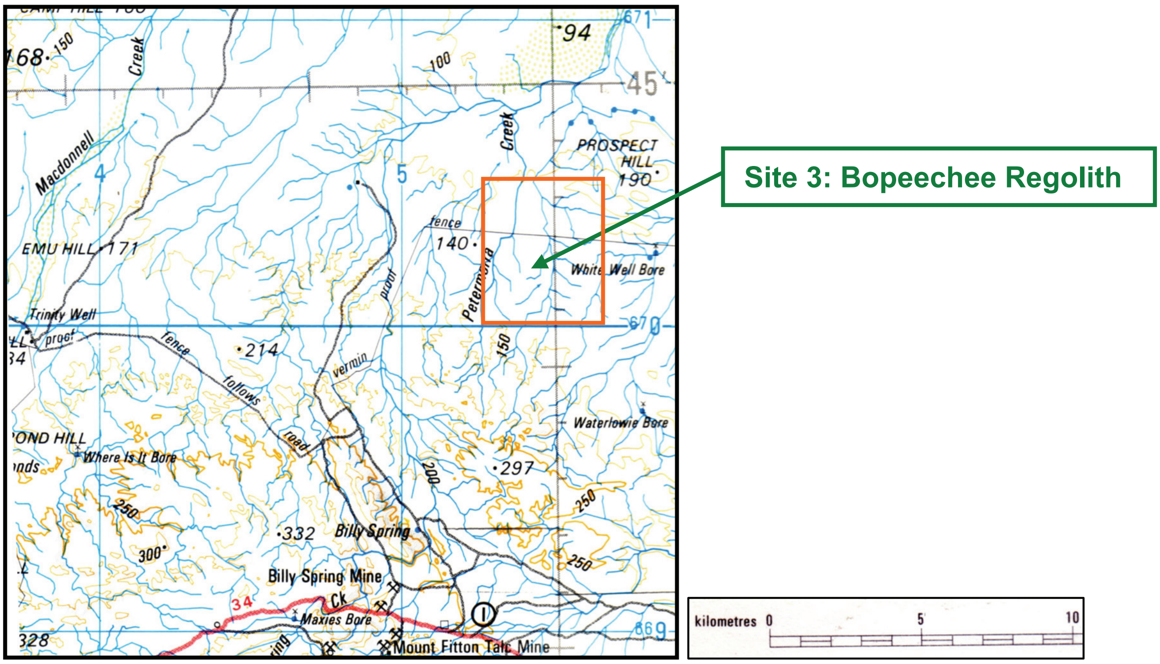


Figure 3. An extract from MARREE 1:250 k topographic map, SE corner. The orange outline box indicates the location for Figure 10 showing geology for the Bopeechee Regolith (Site 3) outcrop. Main access is via the Strzelecki Track, east along the Talc Road and track to Trinity Well, then east along the Dog Proof Fence track towards Prospect Hill.

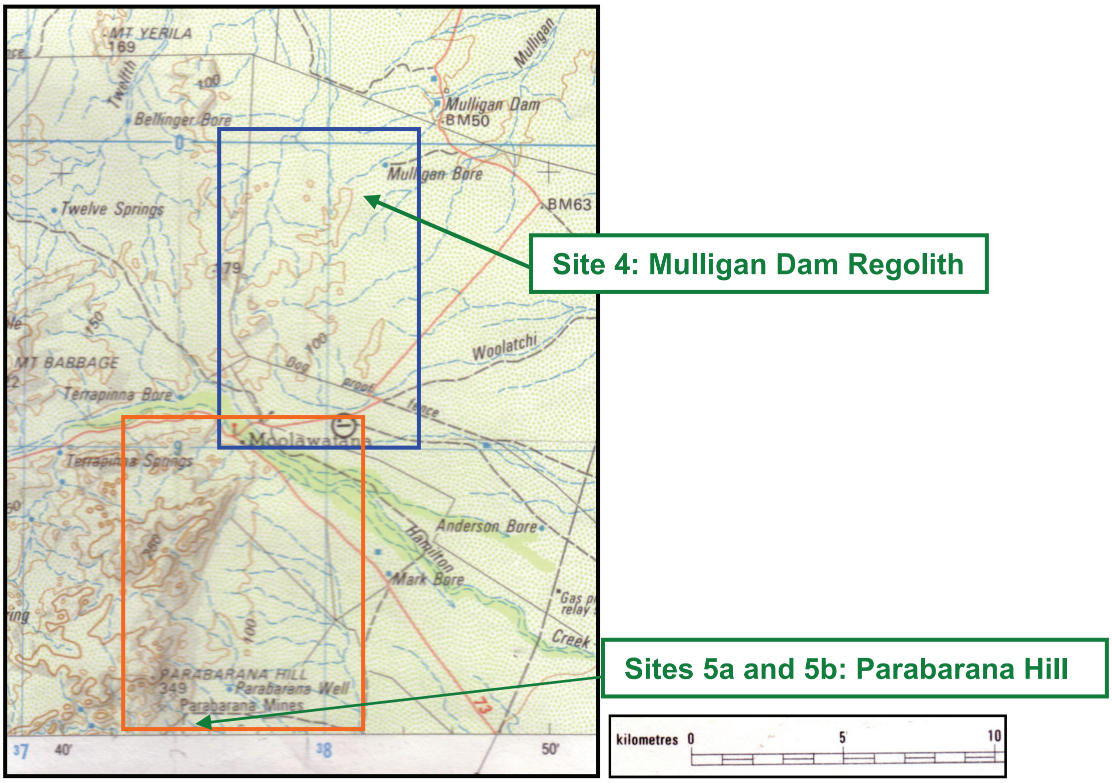


Figure 4. An extract from CALLABONNA 1:250 k topographic map, SW corner. The outline boxes indicate the locations for Figures 12 and 15 showing geology for: Mulligan Dam Regolith outcrop (blue box), and Parabarana ramp faulted and silcreted regolith outcrop (orange box). Main access is via the Arkaroola to Moolawatana Road or via the Strzelecki Track and south along the Mt Hopeless to Moolawatana Road.

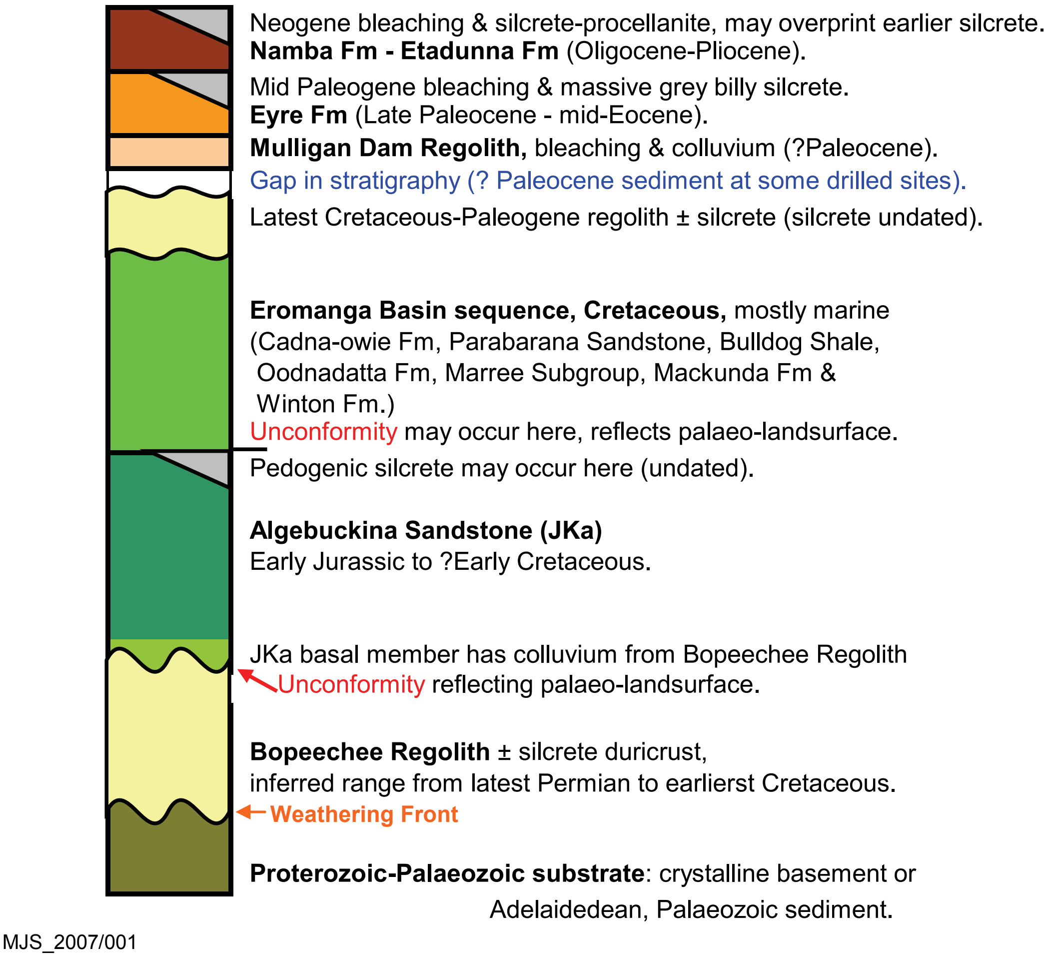


Figure 5. A schematic composite column displaying the late Palaeozoic to Late Jurassic deep weathering profile (Bopeechee Regolith) + Jurassic sediment and silcrete + the latest Cretaceous to Palaeogene sediments with deep weathering and silcrete + the Neogene sediment with profile weathering and silcrete

Reedy Springs gorge, ramp faulted and silcreted Eyre Formation (Site 1)

(after Sheard et al., 2000; White et al., 2000; Wopfner et al., 1974; Forbes, 1966)

Location

Reedy Springs gorge is located ~1 km north of the Strzelecki Track and Blanchewater Ruins, and ~2.3 km west of MacDonnell Creek. This gorge exposure forms one of six reference sections for the Eyre Formation and is the only one within northern Curnamona Province. The gorge is centred on: Lat. 29°31’46”S, Long. 139°25’47”E; [GPS: Zone 54J, 348276 E, 6731466 N (GDA 94)] (Figs 1, 2). Access is via the Blanchewater Ruins turn off from Strzelecki Track (north side) close to MacDonnell Creek crossing. A northerly trending station track to Meteor Bore can be driven along near to the gorge but a fence precludes vehicle access to the gorge. Excellent cliff outcrop occurs to the west on both sides of the gorge and several prominent hard bars within its floor provide additional strike aligned exposures. This area is depicted on the Blanchewater 6738 (1:100 k scale) and MARREE SH 54 5 (1:250 k scale) geological map sheets. The Reference Section is best observed by starting at its western end, and proceeding east (up section). It is worth noting here that faulting has thickened the Eyre Formation here considerably, a feature not fully appreciated by Wopfner et al. (1974) or by Forbes (1966), (Fig. 6).

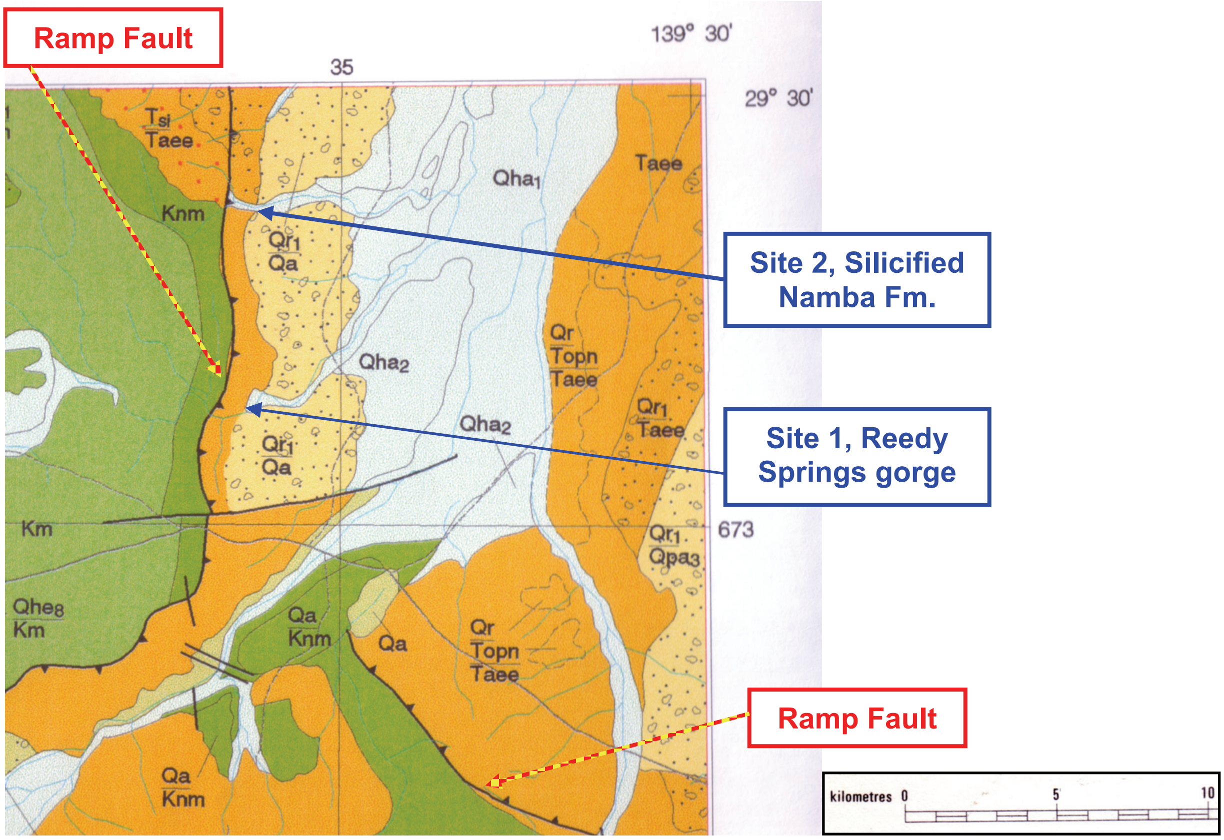


Figure 6. An extract from the Blanchewater 6738 (1:100 k scale) geology map (Sheard et al., 2000). The Eyre Formation Reference Section along Reedy Springs gorge, the ramp fault and the silicified Namba Formation sites are indicated. Relevant symbols are: Kmb = Bulldog Shale, Km = Marree Subgroup (undifferentiated), Knm = Mackunda Formation, Taee = Eyre Formation, Topn = Namba Formation, Tsi = Cenozoic silcrete (undifferentiated), Qr = Quaternary colluvium-alluvium, Qr1 = Quaternary gibber mantled colluvium, Qpa3 = Pleistocene high level alluvial fan, Qa = Quaternary alluvium (undifferentiated), Qha1 = Holocene channel alluvium, Qha2 = Holocene terrace alluvium. Grid lines are: Zone 54, 350000 E, 6730000 N.

Lithology

Eyre Formation exposed in Reedy Spring gorge is mainly composed of a quartz arenite with interbeds of siltstone. The exposed rocks are mostly bleached and variably secondarily calcified, ferruginised and silicified. Pale colours of this section are in contrast with darker hues of fresh sediment in subsurface samples. Sorting in the sandy sediment is good to moderate (estimated). Grains are subangular to rounded, polished, and of irregular shapes. Sands commonly display a bimodal sorting in the basal coarse-grained beds; the coarse fraction ranges from very coarse-grained sand to gravel and pebble sizes, and the coarse sand to granules are highly polished. Milky, clear and grey quartz grains, black chert-chalcedony, and rare volcanics, jasper, agate and silicified wood grains-granules are present, and commonest in the lowest part of the sequence. The upper finer-grained beds are generally well sorted, less polished, and more angular. Bedding ranges from thick plane beds to laminations. Cross-bedding is common, consisting generally of planar foresets and angular toesets. Complex cross-stratification occurs in the middle section.

The top of the section is marked by a thick columnar pedogenic silcrete which dips at 80 degrees east, in conformity with the steep bedding. Bedding here has been tipped (partly folded) to steep angles by ramp faulting after deposition ceased and section top silica duricrust had developed. The relationship of this silcrete to other local silcrete duricrusts is displayed in Figure 7. A second generation silcrete has also developed here but this one post dates Eyre Formation tipping because it roughly parallels the current landsurface (almost orthogonal to the bedding parallel silcrete). East of mid-section, this second generation silcrete displays a complex spheroidal aggregate form (previously described as “Ants Nest Silcrete”), and tongues of this type have also penetrated deeply along porous beds and bedding planes (Figs 7, 8). The spheroidal silcrete form is stained a hematite-red at the section’s eastern end but east of mid-section it remains an unstained grey to pale yellow-brown. Although appearing a weaker form of silcrete, because of its contained voids, it is actually very tough and hard to break – even with a large mallet.

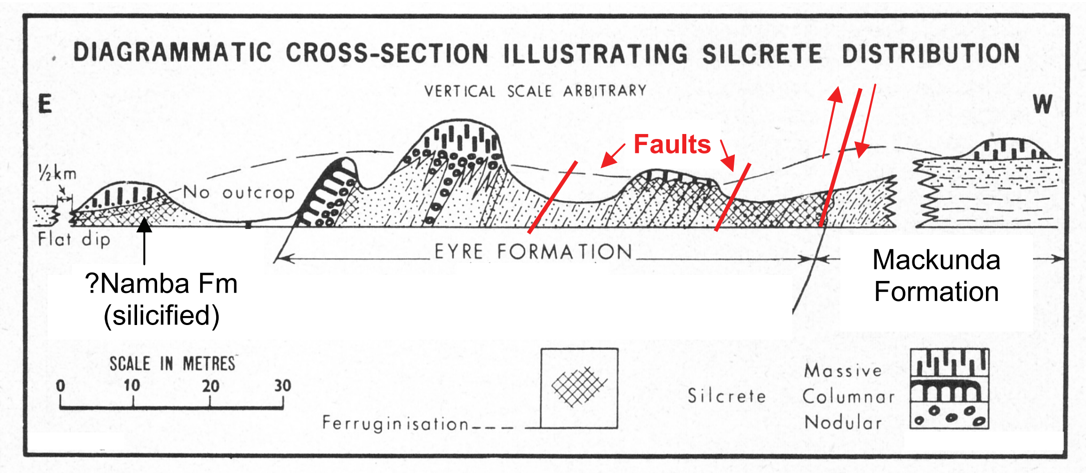


Figure 7. Schematic cross-section through Reedy Springs gorge, modified from Wopfner et al. (1974). Section measurements by M. Sheard and M. White during regional mapping in 1996 indicated that some repetition of the Eyre Formation has occurred through bedding parallel faulting. A significant ramp fault separates the Eyre and Mackunda Formations, this is marked in red, with throw directions indicated. Drag folds associated with this structure occur within the Mackunda Formation shales and clay. Additional faults within the Eyre Formation are also marked in red but throw directions were not measurable within the sand-gravel beds. Two distinct silicification episodes are evident: the 1st (oldest) is at the Eyre Formation top (section E end) and is bedding parallel, this has been subsequently tilted by faulting; the 2nd is near parallel with the current landsurface and cross-cuts both bedding and the 1st generation silcrete. This silicification also invades the Eyre Formation bedding by downward migration of silica along porous beds (mid section) yielding tongues and ‘fingers’ of silicified sand-gravel.

Age

Eyre Formation has been dated using, palynomorphs and plant leaf fossils. These have indicated an age range spanning Late Paleocene to mid-Eocene with a possible short hiatus during the Early Eocene (Callen et al., 1995).

Silcrete ages, based upon host strata stratigraphy plus dating minima and maxima, indicate the following likely time frames: first phase Eocene, and second phase ~latest Miocene to Early Pliocene. Dating of silcrete from this particular area using K-Ar or Rb-Sr or palaeomagnetic methods has not been attempted. Note: this outcrop presentation of distinctly separate pedogenic silicification episodes, separated by localised tectonic activity, is quite rare in South Australia.

Landscape and development environment

Eyre Formation was deposited largely by braided streams in a cool humid climate and on a well vegetated landscape, where relief was varied but vigorously developing in response to epeirogenic uplift of the Flinders Ranges. Fast flowing streams drained the new ranges and formed abundant complexes with occasional lakes-marshes out on the lowlands. Quartz-rich sand ± gravel, along with intermittent basal lignite seams, and rare silty clays were deposited (lignites, known from drilling).

During a time of limited or no deposition, coinciding with landscape stability, silicification of this quartz-rich porous profile took place. Strong seasonality and/or intense climate change promoted deep weathering and very acid soils. Those conditions induced the repeated (?seasonal) dissolution of silica in pedolith moisture and its redeposition nearby as pedogenic silcrete. This significant duricrust (columnar to massive) has been named the Cordillo Silcrete – after the CORDILLO 250 k map sheet where this silcrete reaches >6 m thick.

Following deposition and silicification, continued tectonic activity associated with mid-Cenozoic uplift of the ranges, induced new compressional stresses to develop within surrounding basin onlap sediments. Those stresses were released within compliant sediments via decollement slippage and ramp faulting. Mesozoic and Cenozoic sediments were pushed away from the uplifting ranges, resulting in breakage of stiffer strata and their ramping up on more plastic formations. The result is steeply dipping sand-rich strata, part folded and over-riding drag folded clay-rich strata, where the bedding and fault dips are typically facing out from the ranges. However, ~500–900 m either side of the ramp fault, dips revert to near regional alignment. This tectonism occurred post Eyre Formation silicification and some minor erosion, but the adjacent Namba Formation is only slightly tipped up. In this local area it is unclear whether or not Namba Formation was ever deposited on the silcrete clad Eyre Formation. Further away, exposures and drilled sections make that stratigraphic relationship more obvious. Later erosion again exposed the Eyre Formation to a second phase of pedogenic silicification. This second silicification phase cross-cuts the earlier tipped beds, and is at 70–90 degrees to the first silcreting episode; as well as having selectively migrated down permeable beds (Fig. 7 mid gorge section; Fig. 8). Second phase silcrete style also differs from the first, i.e. 1st episode is columnar and nodular; the 2nd episode is massive or “ants nest” spheroid aggregates or nodular. Continued erosion has uncovered the current exposure.

a

b

c

Figure 8. Silicified Eyre Formation.

a. Silicified subvertical sand and gravel beds, exposed in gorge floor.

b. ‘Ants Nest’ silcrete, aggregated silcrete spheroids with rough exteriors, stained by hematite, this form is very hard and resistant to hammer blows. Occurring as bands-horizons 100 mm to 2 m thick at the gorge eastern end and mid-section (non ferruginous there). Lens cap scale is 50 mm diam.

c. Cliff exposure, part of the 2nd generation silicification (~mid gorge section, S side) displaying alternating tongues of massive + spheroidal silcrete + sheet-like cavities, all roughly parallel to subvertical bedding. Hammer scale is 300 mm long.

Boundaries and correlation

Eyre Formation rests disconformably on the Mesozoic succession in this region but more locally is known to rest conformably upon or interdigitate with Mulligan Dam Regolith. The upper boundary can be complex: where silcreted the boundary with overlying strata is disconformable, but where not silcreted the upper boundary is unconformable with the Namba Formation or later Cenozoic and Quaternary sediments. Eyre Formation has been correlated with the Glendower Formation in Queensland, and the Marion Formation of New South Wales (Callen et al., 1995).

Silicified Namba Formation (Site 2)

(after Sheard et al., 2000; Sheard and White unpublished field notes, c. 1996)

Location

This site is located ~2 km north of the Strzelecki Track and Blanchewater Ruins on the track to Meteor Bore, and ~2.5 km east of MacDonnell Creek. Outcrop centre is: Lat. 29°31'S, Long. 139°27'E [GPS: Zone 54J, 348704 E, 6734194 N (GDA 94)]; Figs 1, 2, 6). Access is via the same track as indicated for the Reedy Springs gorge (see above). Proceed north for another ~1 km past the gorge stop, then walk west for about 1.5 km, a fence precludes vehicle access to the outcrop. Regolith exposure is quite small (<0.3 ha) and not readily displayed on a 1:100 k scale map. Outcrop forms part of a creek bank, is shallowly dipping east and comprises silicified megamottled weathered Namba Formation clays. Bank erosion on three sides has exposed the profile, most of which is beneath Quaternary alluvium. There are numerous shrubs and small trees clumping around and overhanging this site.

Lithology

Outcrop base at this site consists of pallid upper saprolite – a kaolinite dominant material, where visible quartz sand grains are absent and original bedding is not obvious (Fig. 9a). Saprolite merges into a pallid plasmic zone (lower pedolith), although a distinct boundary is not visibly recognisable. Megamottling affects both saprolite and pedolith, where mottles are red to red-brown or dark maroon (100–200 mm across) and composed of hematite ± clay-rich regolith. Many megamottle interiors display breccias of the host regolith and/or pseudo-brecciation due to an incomplete ferruginous overprinting (Fig. 9b–d).

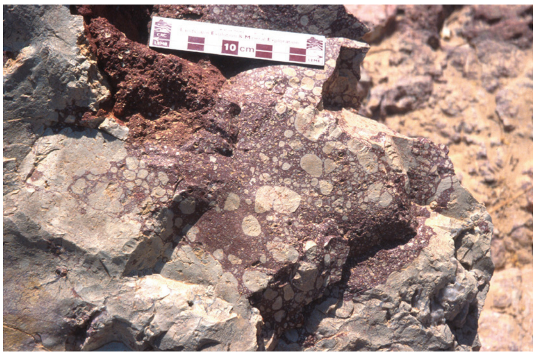
Pedogenic silicification of the upper 1–1.5 m includes a lower incipient porcellanite interval that incorporates ferruginous megamottles without obvious change in mottle structures from those below. Above is a more intense (hard and brittle) porcellanite that also includes ferruginous megamottles similar to those below the silicification. The top silicification unit is a massive silcrete horizon ("grey billy") ~300–500 mm thick, where megamottles have either not been retained or were never developed.

Boundaries and correlation

The Namba Formation exposed surface at this location is extremely weathered, megamottled and silicified. It is not possible to estimate its full thickness here, nor be sure where in the recognised formation this exposure actually fits (too weathered for fossil preservation). Therefore it is possible that erosion may have removed some or a considerable percentage of its original thickness. An unconformity occurs with the overlying Quaternary alluvium. The Namba Formation silcrete upper surface has a slope of ~5 degrees to the east, suggesting this may reflect a palaeo-landsurface slope or conversely it represents post development tilting. Namba Formation unconformably overlies the Eyre Formation regionally, although the actual contact here is hidden by Quaternary alluvium. Wopfner et al. (1974) suggest that an inferred fault contact occurs further south (between these two Cenozoic units) but no evidence for that or an unconformity was discovered by M. Sheard and M. White during regional mapping in this area in 1996. A fault relationship is also unnecessary to explain rapid dip changes (folding) where ramp faulting occurs, and especially where an unconformity is demonstrated elsewhere.

Another good section of Eyre Formation (mostly sands) is exposed further up stream in the main creek where a near vertical northern bank provides ready access for observations. Walk up stream (north and then west) from the silicified Namba outcrop towards the ramp fault. The white peak of "Weathered Hill" will be easily seen, off in the distance. Ramp faulting has tilted the exposed sands into steeper east dipping angles nearer the fault. There is no silcrete developed within Eyre Formation in this particular creek section.

a


b


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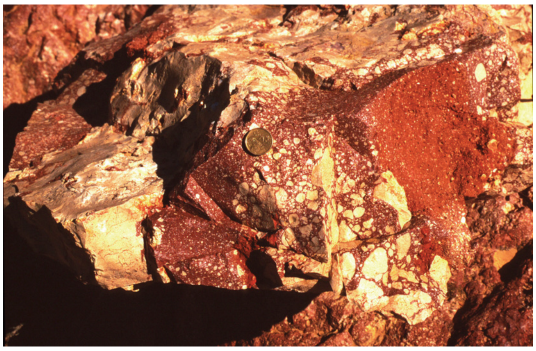

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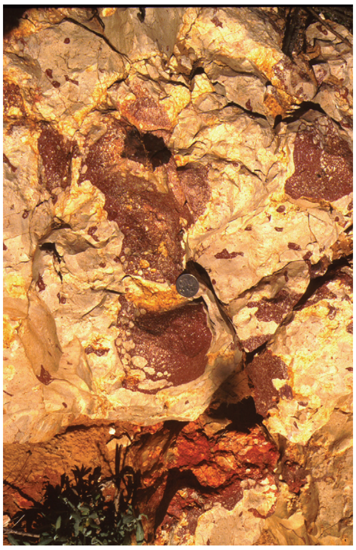


Figure 9. Silicified Namba Formation.

a. View east of creek bank exposure (~2 m high) just south of the creek incision through slightly tilted siliceous duricrust. Regolith zones are indicated on RHS of image.

b. Complex megamottles within pallid pedolith, extremely weathered Namba Formation clays and silts. Megamottles display brecciated and pseudo-brecciated inner fabrics.

c. As per image ‘b’ but within the porcelanitic portion of the silicified zone. Silicification has incorporated megamottle hematite and interior structures without further disruption to the fabric. Coin at centre is 20 mm diam.

d. Similar to ‘c’ but nearer the massive silcrete horizon. Here the porcellanite is hard enough to splinter into razor-sharp shards when struck by a hammer. Coin at centre is 28 mm.

Age

Namba Formation stratigraphic position and dating by palynomorphs, plant impressions and vertebrate fossils, these indicate an age range spanning Oligocene to Pliocene with Oligocene to Miocene most commonly expressed (Callen et al., 1995). A Rb-Sr age of 25 Ma was determined for green diagenetic illite from the upper Etadunna Formation (Eyre Basin equivalent to the Callabonna Sub-Basin Namba Formation) and that approximates the Oligocene-Miocene boundary (Norrish and Pickering, 1983).

Silicification of an extremely weathered clay-rich profile has taken place and must have occurred post Namba Formation deposition. It therefore follows that the silcrete-porcellanite horizon is of latest Miocene to Pliocene age.

Landscape and development environment

Namba Formation was deposited in a cool humid climate and a well vegetated landscape with very low relief where meandering sluggish streams and swamps abounded, allowing clay ± silt ± organic matter ± reduced Fe-Mn oxides to deposit. After deposition, tectonic activity associated with ongoing Cenozoic uplift of the Flinders Ranges, induced stresses to develop within surrounding basin onlap sediments. Those stresses were released within compliant sediments via decollement slippage and ramp faulting. Mesozoic and Cenozoic sediments were pushed away from the uplifting ranges, resulting in breakage of stiffer strata and then ramping up against more plastic strata. The result is steeply dipping sand-rich strata ramped upon drag folded clay-rich strata, where the bedding and fault dips are typically facing away from the ranges. However, ~500–900 m back from the ramp fault, dips revert to being near regionally aligned again. This tectonism occurred between deposition and silicification of the Eyre Formation and post deposition of Namba Formation. Intense weathering of Namba Formation produced pallid saprolite–pedolith + megamottling, and conditions were acid enough to allow a pedogenic silicification overprint to develop. Subsequent burial by alluvium with later erosion has uncovered the current exposure.

Bopeechee Regolith, SW of Prospect Hill (Site 3)

(after Sheard et al., 2000; White et al., 2000; Sheard and White unpublished field notes, 1996).

Location

This area is ~5 km SW of Prospect Hill, adjacent to and south of the Dog Fence (older mesh type, a few 100 m south of the new electric wire strand fence). Access is via the Dog Fence maintenance track which can be entered either from the east via Moolawatana Pastoral Station tracks; or from the west via the Strzelecki Track intersection with the Dog Fence. For those driving in along the northern side of the Dog Fence there is a gate through it, ~5 km SE of Prospect Hill trig point, that will give access to the fence' southern side. This reference area covers ~4 km^2 centred on Lat. 29°46'00"S, Long. 139°29'50"E (Figs 1, 3, 10). It includes both weathered Mesoproterozoic granite and Neoproterozoic metasediment basement terranes. Erosion has either variably uncovered the in situ weathered basement or provided mesa escarpments where the overlying Cretaceous Parabarana Sandstone remains in place. This area is a key reference location because exposure is excellent and offers 3D views, different parent rock types (granite vs slate), and the regolith profile is relatively thin (<2 to <4 m).

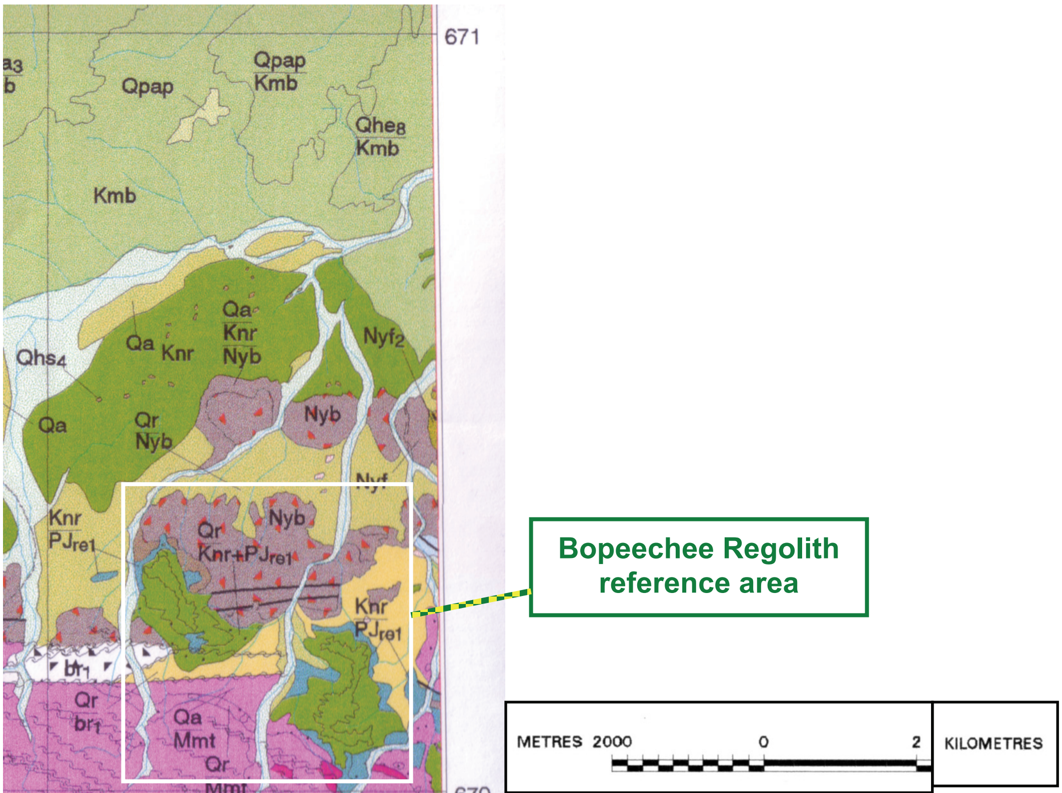


Figure 10. An extract from the Blanchewater 6738 (1:100 k scale) geology map (Sheard et al., 2000). The Bopeechee Regolith reference area is boxed. Relevant symbols are: Mmt = Terrapinna Granite (Mesoproterozoic), Nyb = Bolla Bollana Tillite (Neoproterozoic), Nyf = Fitton Formation (Neoproterozoic tillitic shale), PJre1 = Bopeechee Regolith (Permo-Jurassic in situ weathered), Knr = Parabarana Sandstone (Cretaceous), Qr = Quaternary colluvium-alluvium, Qa = Quaternary alluvium (undifferentiated). Grid lines are: Zone 54, 350000 E, 6700000 and 671000 N.

Lithology

There is typically little or no saprock development. Saprolite is mostly highly weathered and commonly very leached (pallid: white, cream, yellow to brownish), it ranges from <1 m to ~4 m thick in this area, although it may attain >20 m elsewhere. The saprolite is kaolinite and quartz dominant, with original rock textures and/or metamorphic fabric preserved via resistate mineral patterns. Some ferruginising is present as ghostly megamottles or as coatings on resistate minerals or clasts. This zone can be discontinuous due to post-development erosion, however in some locations, it may be traced for many kilometres (Fig. 10).

A pedolith zone overlies the saprolite, and consists of a basal pallid plasmic to arenaceous interval, still kaolinitic, and sometimes containing several bands of scattered ferruginous pisolites or irregular segregations (Fig. 11). An upper clast-rich—waste mantle, ranges from <0.1 to <0.5 m thick and can grade into the overlying Mesozoic sandstones. It is similarly coloured to the underlying saprolite-pedolith but with more iron present (yellow and brown colours predominate). This is a colluvium—slope debris consisting of angular fragments, mostly unsorted, with pseudo-layering (Liesegang banding) to crude sedimentary layering at its top. Clast type and matrix strongly reflect the underlying parent rock and saprolite materials, or if developed from metasediment then clast angularity is similar; both types indicating a short transport history. Where on or close to saprolitic granite the clasts usually include a high proportion of variably kaolinised feldspar crystal fragments (5 25 mm) and quartz (gruss). Best exposures and reference sections are SW of Prospect Hill (S of Dog Fence; Figs 10, 11), underlying the Parabarana Sandstone mesas and developed within the Terrapinna Granite, and further west, below a remnant Parabarana sandstone mesa, and developed in Bolla Bollana Tillite. The full aerial extent of this palaeo-regolith for the northern Flinders Ranges can be seen on the “Northern Flinders Ranges Geology” map (Sheard et al., 1996).

Boundaries and correlation

Bopeechee Regolith was defined by Krieg et al., (1991) for the CURDIMURKA (SH 53-8) map area. This is a widespread in situ weathered profile (saprolith ± pedolith) often overlain by a mechanically derived debris (pedolith-colluvium). This regolith occurs immediately beneath the Mesozoic succession in outcrop and drillcore. Bopeechee Regolith is extensively developed over much of the Gawler Craton and is exposed at the northern edges of the Curnamona Province–Flinders Ranges, within Mesoproterozoic granites and Neoproterozoic Adelaide Geosyncline metasediments (Figs 10, 5, 11).

Age

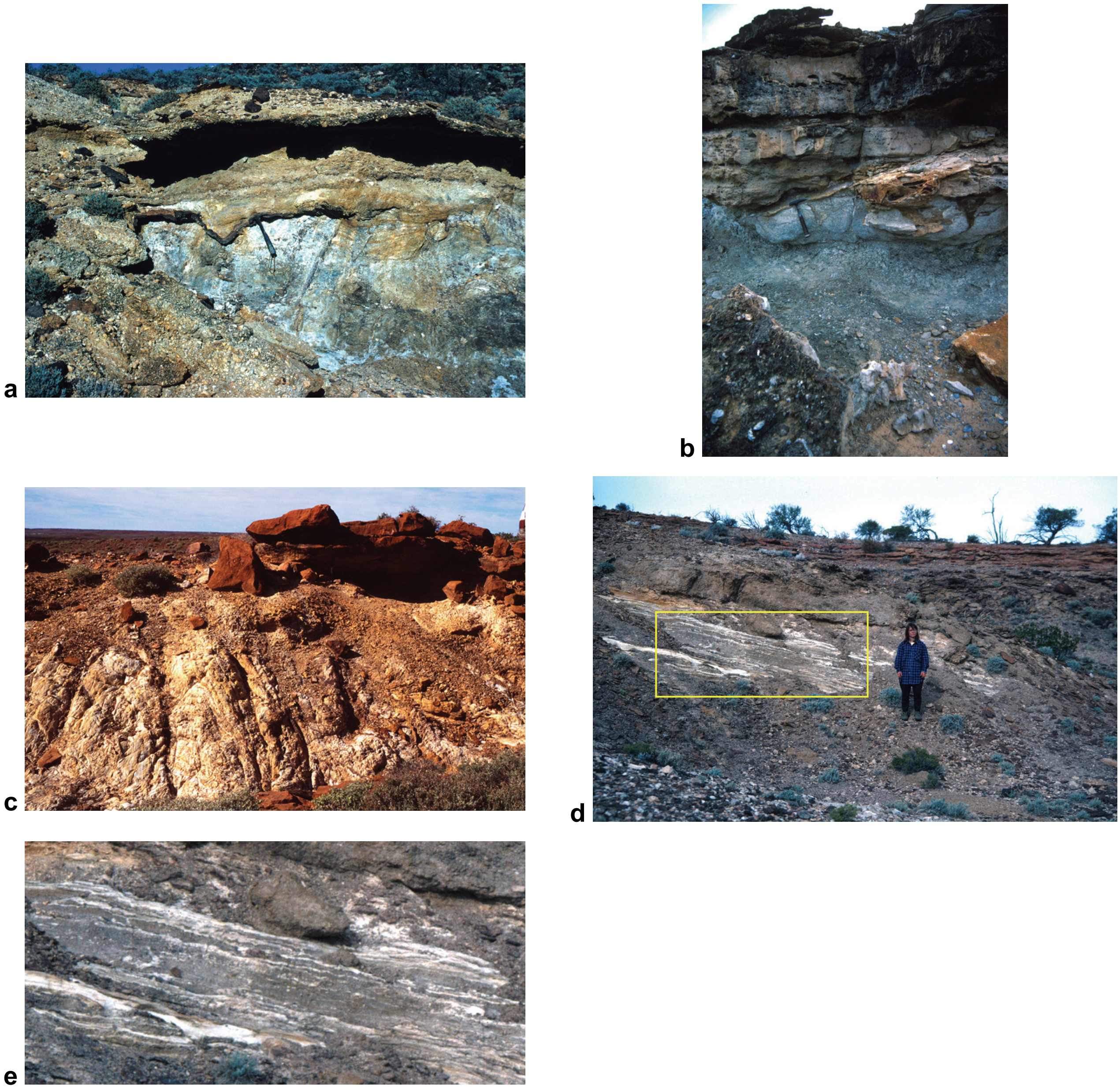
The age of the Bopeechee Regolith and its concomitant deep weathering episodes cannot be determined directly – a feature common with many palaeo-regoliths. However, from stratigraphic and palynological evidence using underlying and overlying strata as time limits, on CALLABONNA, MARREE, CURDIMURKA and WARRINA 250 k map sheet areas, a time range of latest Permian to latest Jurassic is suggested (Krieg et al., 1991; Rogers and Freeman, 1996a, b) cf. Figure 5.

Landscape and development environment

Substantial glaciation of South Australia took place during much of the Permian. Throughout that glaciation most if not all previous deep weathering profiles appear to have been planed off by ice. A significant, widespread weathering profile developed soon after glaciation ceased in rocks of demonstrated latest Permian to latest Jurassic age (Bopeechee Regolith; Fig. 5). That in situ profile was formed by intense weathering processes during a long period of continental tectonic stability, when erosion and deposition were minimal. Those processes promoted removal of coloured oxides—hydroxides (Fe and Mn) leading to bleached profiles enriched in Si and Al. There is increasing global evidence for significant climate changes occurring repeatedly from the Permo-Triassic boundary (251 Ma) to the late Jurassic. Those changes may have initiated the lowering of soil pH and a marked increase in reducing Eh conditions, promoting intense deep weathering of exposed rocks. Many of the deeply weathered profiles have silicified duricrust cappings (Fig. 5); that property applies to the Bopeechee Regolith west of Flinders Ranges but is not part of its profile around the Ranges northern and eastern edges.

Typically the overlying sediment has a basal component derived from reworking of Bopeechee Regolith materials. This juxtaposition suggests a relatively sudden resumption of sedimentation involving some initial surficial disturbance – erosion. Sedimentation resumption was not uniformly timed everywhere, in some places the Jurassic Algebuckina Sandstone overlies Bopeechee Regolith, while around northern Flinders Ranges the exposures are overlain directly by Cretaceous

Cadna-owie Formation/Parabarana Sandstone or more rarely by Bulldog Shale; suggesting a much later start to sedimentation resumption there. A commonality of the covering transported regolith is that whatever its timing, that sediment has a basal component derived directly from reworking of Bopeechee Regolith (Fig. 11). This occurrence suggests a relatively quick resumption of sedimentation involving some initial surficial disturbance (Krieg et al., 1991; Callen et al., 1992; Krieg, 1995; Sheard and Callen, 2000).



a b c d e

Figure 11. Bopeechee Regolith SW of Prospect Hill and the Dog Fence

a. Below hammer is west facing saprolith developed in Terrapinna Granite; above hammer is a colluvium rich in kaolinite and quartz. This is unconformably overlain by basal Parabarana Sandstone.

b. A similar profile to ‘a’, east side of same mesa exposure, a thicker pallid kaolinitic saprolite is developed.

c. A remnant of calcite-cemented Parabarana Sandstone unconformably lying on deeply weathered subvertical Neoproterozoic pelitic metasediment.

d. Pedolith component displaying bands of ferruginous granule-like segregations (5–10 mm). Yellow outlined area is enlarged in plate ‘e’.

e. An enlarged outlined part of image ‘d’. Dense but irregular ferruginous granule bands are separated by near-white kaolinite-rich amorphous plasmic bands.

Mulligan Dam Regolith (Site 4)

(after Sheard, 1996, in prep.; Sheard and Callen, 2000)

Location

Mulligan Dam is located 12.5 km NNE of Moolawatana Pastoral Station Homestead on the Mt Hopeless to Moolawatana Road. Type Section is ~4 km west of Mulligan Dam (centred on: Lat. 29°51’18”S, Long. 139°45’58”E; Figs 1, 4). Access is westerly via a station track to Mulligan Bore and off-road from there. Outcrop stretches S and SE towards Moolawatana Station airfield and is ramp fault bounded for much of its exposure. This palaeo-regolith unit is depicted on the Moolawatana 6838 (1:100 k scale) and CALLABONNA SH 54 6 (1:250 k scale) geological map sheets. The Type Section is best observed by starting at its northern end, and proceeding south, then southeast along its numerous creek sectioned exposures adjacent to the steep reverse ramp fault (Fig. 12).

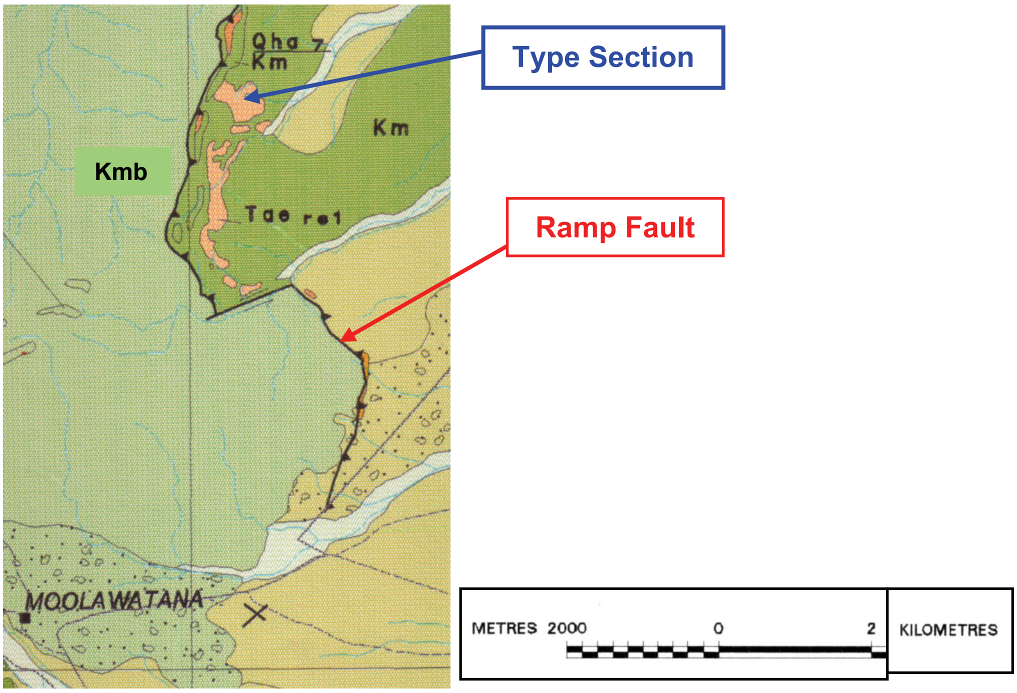


Figure 12. An extract from the Moolawatana 6838 (1:100 k scale) geology map (Sheard, 1996). The Mulligan Dam Regolith Type Section, outcrop extent and ramp fault edge are indicated. Relevant symbols are: Taere1 = Mulligan Dam Regolith, Kmb = Bulldog Shale, Km = Marree Subgroup (undifferentiated), Qha7 = Quaternary scree. Grid lines are: Zone 54, 380000 E, 6690000 N.

Lithology

Forming a small remnant of a once more extensive regolith, the outcrop mantles a palaeo-land surface and consists of two main components: (i) a basal pallid blotchy to megamottled pedolith–saprolith zone (1–2 m thick) developed as a weathering profile within Marree Subgroup shale. The megamottled zone passes into a second unit (ii) an overlying massive to indistinctly bedded, gravelly to pebbly sandstone (Figs 13, 14). The boundary between these is either an angular unconformity or in some places a transition interval dominated by colluvium (150–300 mm thick) composed of a mixture of sub-rounded to angular quartz sand-grit to gravel and reworked pedolith fines ± fragments. The basal in situ weathered zone consists of clay-rich or silt-rich saprolith–pedolith (light greyish olive [5Y 6/3] to moderate yellowish brown [10YR 5/4]) with moderate reddish brown [10R 4/4] mottles 50–200 mm across and spaced 150–250 mm apart. Cavernous weathering of cliff outcrop, associated with incipient case hardening, is exhibited by the megamottled zone. A brownish weathering rind is present on most of the outcropping regolith. Sand comprising the main upper interval is poorly to moderately sorted and of low maturity (quartz

Figure 13. Mulligan Dam Regolith components.

a. Basal remnant at northern end of outcrop. Just above hammer and continuing below is unit 1 of mottled pedolith (weathered Marree Subgroup). Brown material above hammer is colluvium-alluvium of unit 2.

b. Mid profile, silcrete-clasted gravel and pebble beds exposed half way along the ~N-S outcrop.

c. Sample of poorly sorted gravelly colluvium-alluvium from the lower half of the transported regolith unit, Most gravel clasts are derived from an eroding silcrete duricrust. The quartz grit and sand, plus the silt and minor clay are derived from other source materials.

d. Silcrete columns from the soil profile developed on/in the sandstone transported regolith of unit 2.

e. Sectioned silcrete columns from the soil profile developed on/in the sandstone of unit 2. These have entrapped quartz gravel to small pebbles, and the columns display draped concave growth banding similar to that observed for cave stalagmites.

f. Sectioned silcrete mini columns from the soil profile developed on/in the sandstone unit of Mulligan Dam Regolith. These display a basal pebble growth-nucleus, and internal convex curved draped banding.

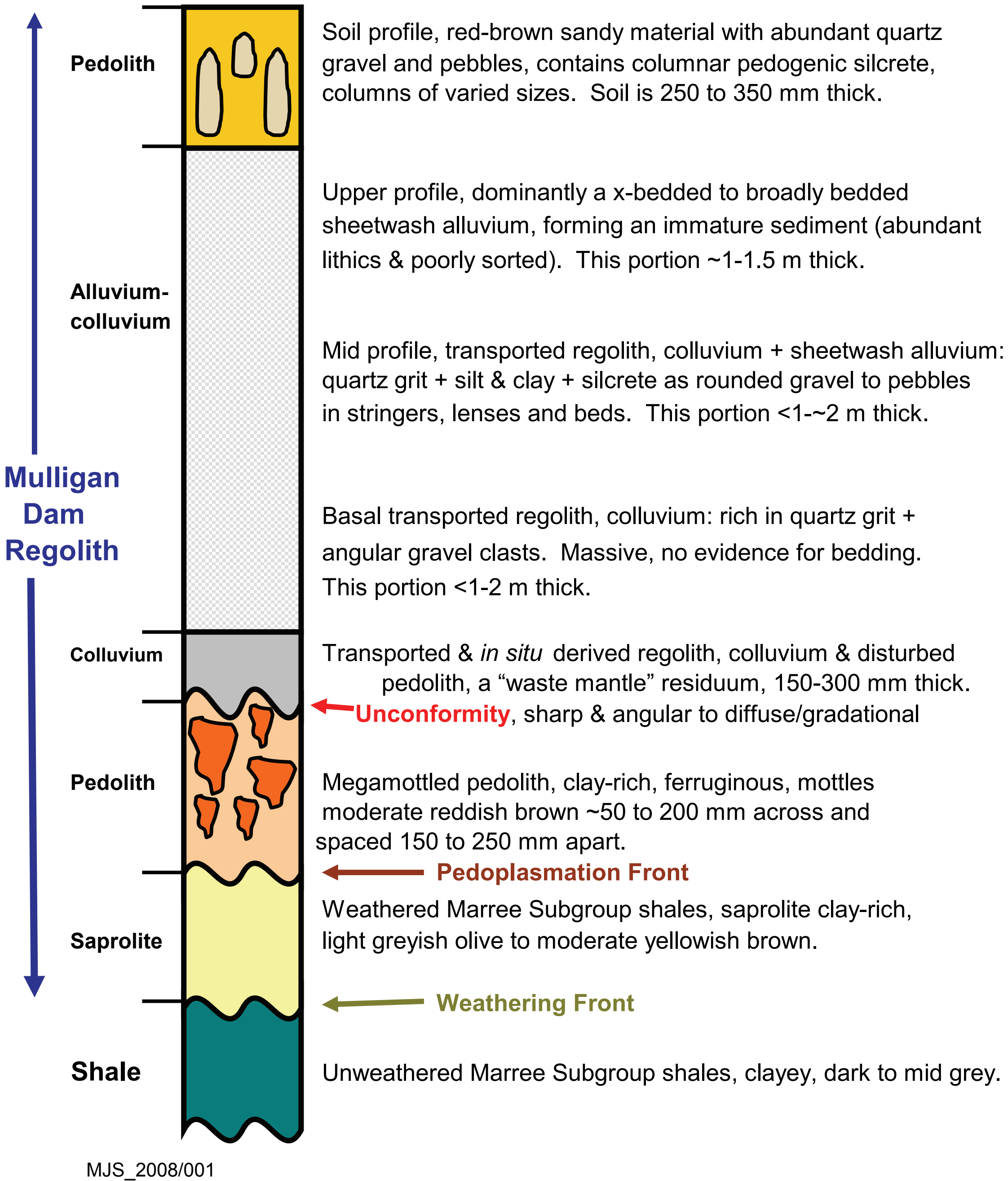


Figure 14. A schematic composite regolith column for Mulligan Dam Regolith from the Type Area. Total profile ranges from ~5 m at the north to ~9 m in the SE.

+ lithics) towards the base but grades upwards into a well sorted but semi-mature fluvial sand. It is conspicuously cross-bedded towards the top (mid to southern exposures) and variably cemented to a moderate competency. Clasts range from angular to rounded with low sphericity. Sand grains comprise milky to grey quartz + lithics (mainly silcrete) with a bulk sample colour of light greyish yellowish brown [10YR 6/3 (dry), 10YR 6/2 (wet)]. Regional dips in the upper sandstone beds range from ~5-10o NE to SE. Pebble and gravel clast stringers to lenses contain abundant well-rounded pedogenic silcrete fragments (in mid section). Abundant silcrete clasts here indicate the presence of an eroding silcrete duricrust relatively nearby at the time of deposition.

In the current soil profile (Late Cenozoic), developed within Mulligan Dam Regolith, are abundant pedogenic silcrete columns. Individual columns range from >300 mm long x 120–50 mm wide to mini-columns 40 mm long x 6–15 mm wide. Many columns encapsulate quartz fragments, gravel and pebbles, while the mini-columns appear to grow up from a basal quartz pebble (stalagmite-like) as if the pebble formed a permeability barrier to downward percolating silica-rich moisture (Fig. 13d–f).

Boundaries and correlation

Mulligan Dam Regolith has its lower boundary within Marree Subgroup shale (mid Cretaceous). The in situ weathered unit is separated from the colluvial-fluvial upper unit by an unconformity, which is in part angular, but at other locations is transitional. At the outcrop southern end, just north of Moolawatana Station airfield, the regolith top interdigitates with or conformably underlies the basal Eyre Formation (latest Palaeocene to early Eocene; Callen et al., 1995). These boundary relationships, and the presence of abundant silcrete clasts within the sediment unit, imply that an eroding silcrete duricrust must have existed in this area prior to Eyre Formation deposition. There are no other known equivalents to this regolith from adjoining map sheets in South Australia.

Age

Stratigraphic position suggests an Early Cenozoic age, i.e. early-mid Palaeocene, although a latest Cretaceous age cannot be ruled out. The underlying unweathered Marree Subgroup shale is mid Cretaceous based upon palynological, marine microfossil, plant cuticle and mollusc evidence. Moreover, the megamottled basal component (lowest pedolith) may have begun to form during the Late Cretaceous and continued into the Palaeocene, a case for this is presented by Benbow et al. (1995). No fossil evidence for its age has been found, although the depositional environment was probably not conducive to fossil preservation. Radiometric dating has not been attempted.

Landscape and development environment

An elevated weathering surface developed in exposed Mesozoic strata. The onset of erosion caused quartz as sand and gravel with silcrete clasts to shed down a gentle slope via colluvial and incipient fluvial sheetwash processes. A south to east thickening, up to >5 m, of this transported regolith wedge suggests erosion and deposition progressing in a similar direction. Sedimentary structures consistent with fluvial processes became dominant over colluvial processes, this occurs in a southwards direction and up-section. The basal saprolith—pedolith zone is relatively consistent in thickness and is similar to weathering profiles developed in a humid environment. Subsequent widespread fluvial activity developed in response to uplift and climate change, leading to deposition of Eyre Formation sands and burial of Mulligan Dam Regolith. A partial silicification process has lead to columnar silcrete development in the soil-palaeosol profile. Exhumation and erosion in response to later tectonics, has re exposed the Mulligan Dam Regolith.

Parabarana ramp faulted and silcreted regolith (Site 5)

(after Ludbrook, 1966; Sheard, 1996, in prep.; Sheard and Callen, 2000).

Location (Site 5a)

Parabarana Hill is located ~8 km SSW of Moolawatana Pastoral Station Homestead, west of the road to Arkaroola and is part of the Mt Painter Inlier—Flinders Ranges uplands. The Parabarana Sandstone (Cadna-owie Formation equivalent) Type Section is ~1.5 km SSE of Parabarana Hill, in the vicinity of the abandoned Parabarana Copper Mines ore processing and camp area (Lat. 29°58’14”S, Long. 139°42’25”E; Figs 1, 4).

Access is via a westerly running station track to Parabarana Bore and west from there following old mine and exploration tracks. Parabarana Sandstone outcrop intermittently stretches north towards Moolawatana Station. This Cretaceous rock sequence is depicted on the Moolawatana 6838 (1:100 k scale) and CALLABONNA SH 54 6 (1:250 k scale) geological map sheets in green and by map symbol Knr. The Type Section is best observed by entering the small amphitheatre exposure south of where the old mine access track cuts through the steep reverse ramp fault escarpment (Figs 15, 16). Park vehicles where safe and walk to cliff exposures but beware of old fence lines and loose fencing wire scattered about the amphitheatre floor. A hard hat should be worn when working close to the cliff exposure.

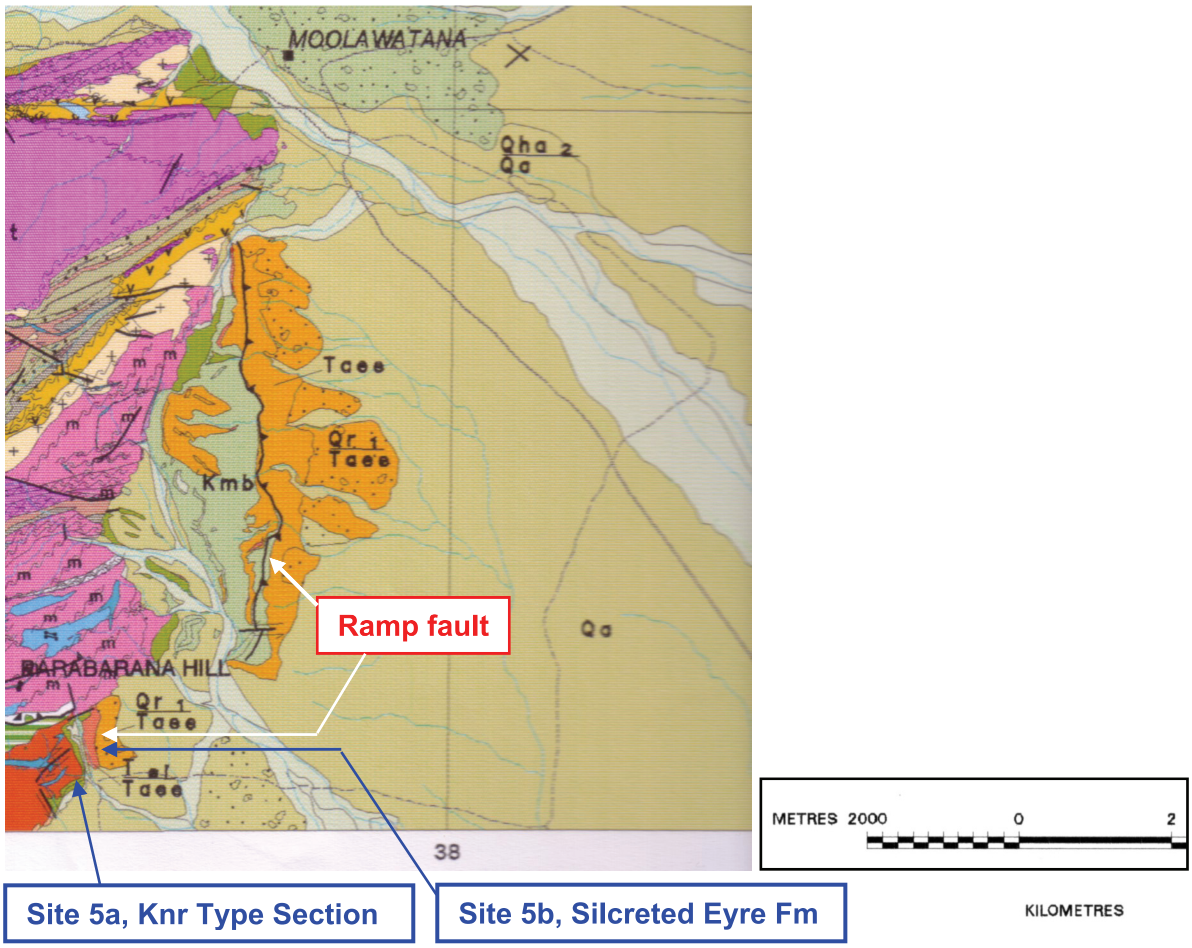


Figure 15. An extract from the Moolawatana 6838 (1:100 k scale) geology map, SW corner (Sheard, 1996). The Parabarana Sandstone type section is indicated (Site 1). Outcrop of silcreted Eyre Formation nearby is also indicated at Site 2 and is well exposed further north along the marked ramp fault. Relevant symbols are: green (Knr) = Parabarana Sandstone, Kmb = Bulldog Shale, Taee = Eyre Formation, Tsi = silcrete, Qr = Quaternary colluvium-alluvium, Qa = Quaternary alluvium (undifferentiated). Grid lines are: Zone 54, 380000 E, 6690000 N.

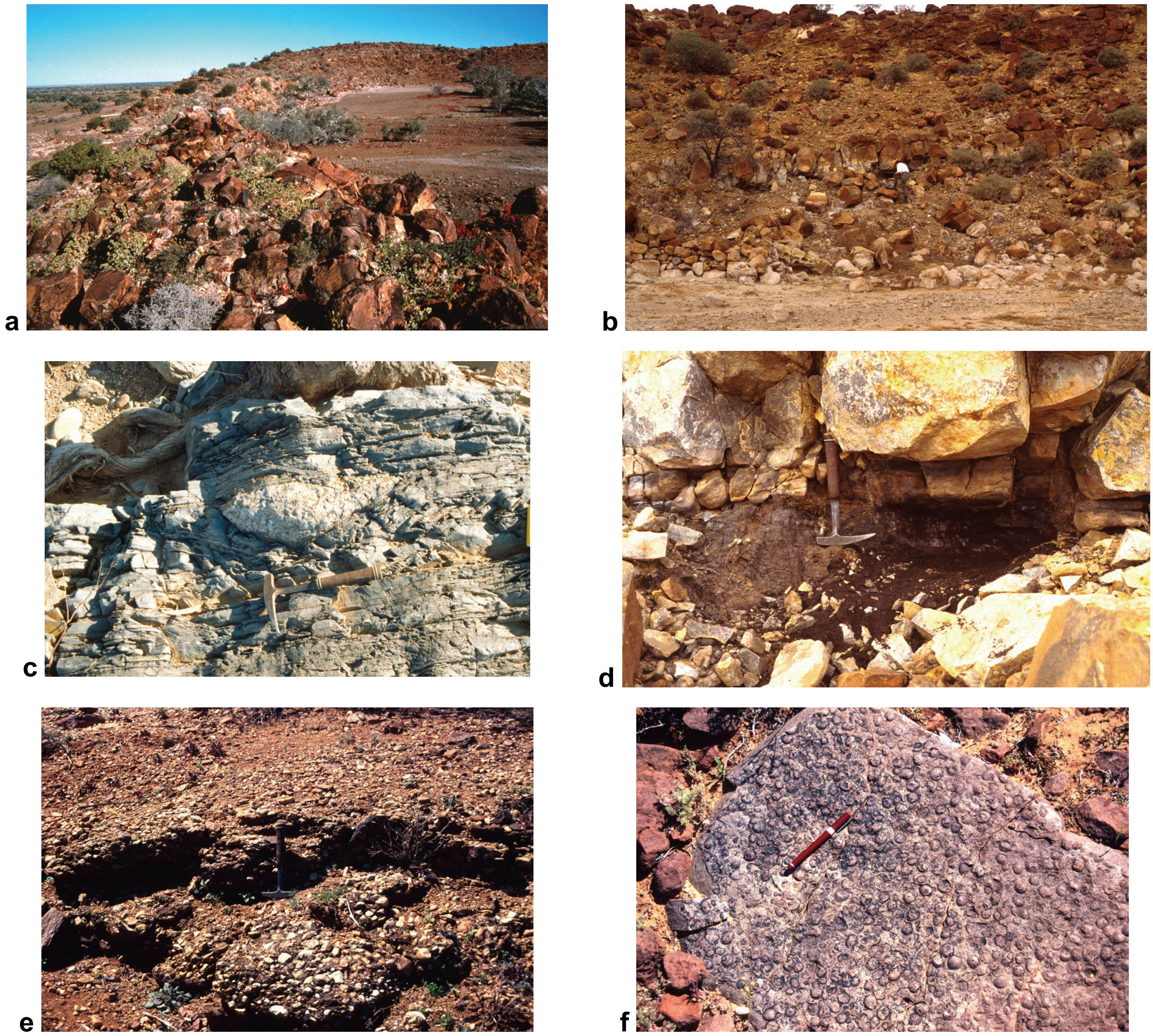


Figure 16. Parabarana Sandstone, Site 5a.

a. View of ramp fault anticline structure at the Type Section amphitheatre exposure, view ~S from atop the escarpment's northern end.

b. Escarpment eastern face, within amphitheatre, displaying ~21 m of sandstone.

c. Laminar bedding within unit 2, weakly carbonaceous here.

d. Hammer rests upon the grey carbonaceous sand top of unit 2 and above is more competent calcareous-micaceous sandstone of unit 3.

e. Basal conglomerate, exposed ~1 km south of the amphitheatre in eroding terrain, hammer scale at centre.

f. Upper surface of silcrete horizon, atop the escarpment southern end, displaying silicified fossils of bivalves: *Lingula subovalis* and *Cyrenopsis* sp. (estuarine facies; c.f. Ludbrook, 1966), pen scale 120 mm.

Lithology (Site 5a)

Parabarana Sandstone is a quartzitic, calcareous, and in places a fontainebleau sandstone containing shelly fossils (estuarine facies bivalves) and terrigenous plant impressions. The beds dip ~12–70° E to SE due to localised ramp faulting but are near flat lying to gently dipping only 500 m behind the steep escarpment.

Parabarana Sandstone units at the Type Section (total thickness 21.3 m), in upward sequence are:

1. At the base of exposure; a poorly exposed sequence of grey carbonaceous sands and gravels ~2 m thick, and black carbonaceous sands and shale, ~0.3 m thick. South of the Type Section a basal conglomerate is exposed, ~1 m thick, (Fig. 16).
2. Light grey, with dark grey patches, weathering to grey-brown, laminated medium- to coarse-grained quartzite, finely micaceous, and weathering into hard blocks in a low cliff, 1.2 m thick, (Fig. 16).
3. Cream-white calcareous sandstone, micaceous, relatively soft but weathering hard and light to dark brown on the surface. Interval partly obscured by talus, 8.5 m thick. Light grey, weathering to red-brown, calcareous medium-grained sandstone with plant stem impressions, forming a ledge dipping at ~12° E, 3.65 m thick, (Fig. 16).
4. Above the ledge of unit 3, calcareous sandstone, ferruginised and partly silicified, weathering in large blocks, with quartz and quartzite pebbles up to 75 mm in diameter: bedded on the eastern side, beds ranging in thickness from 50–450 mm, unit thickness is 3.65 m.
5. Coarse-grained quartzite with subvertical ?plant stem impressions. This unit is densely silicified to silcrete, preserving bivalve shelly fauna near the top and occasional u shaped burrows mid-unit. Dip is ~45-70° E, thickness is 1.82 m, (Fig. 16).

Boundaries (Site 5a)

At this locality the sandstone basal contact with underlying Mt Neill Granite is obscured close to the escarpment toe by soil and talus but the angular unconformity surface can be observed in the amphitheatre floor where exposed basement is weathered to saprock and saprolite. Silicification of the sandstone upper unit to silcrete has occurred here post faulting, this duricrust preserves fossils and has maintained a cliff exposure.

The upper surface conformably underlies Bulldog Shale, a greyish to grey-olive, low competence shale to clay-silt-rich material where unweathered, but is brown to yellow or pale yellow with ferruginous staining where weathered. Bulldog Shale is variably bedded and/or laminated, contains dark grey limestone concretions and irregular lumps-lenses of yellowish cone-in-cone limestone. There are also occasional shelly fossils and trace fossil burrows in some beds. At the amphitheatre escarpment crest the Bulldog Shale is eroded away leaving the silcreted Parabarana Sandstone exposed, but down slope, where the track enters the amphitheatre, the contact relationship can be observed.

Age (Site 5a)

Parabarana Sandstone (Cadna-owie Formation equivalent) has been dated using palynomorphs, dinoflagellates and forams, these indicate an age range from Neocomian (Valanginian) to Aptian (Early to Mid Cretaceous) (Krieg and Rogers, 1995). The ramp faulting occurred post deposition (post Cretaceous). Silicification of the sandstone to silcrete along the ramp fault crest has occurred post tectonic displacement and does not occur below the Bulldog Shale nor does it involve the shale at this site. Silcrete here is presumed to be Cenozoic because further north along the same fault structure silicification only affects the Paleogene Eyre Formation overlying unaffected Parabarana Sandstone (see Site 5b description below).

Landscape and development environment (site 5a)

Parabarana Sandstone lower third to half is of terrigenous origin and mostly represents a back-barrier fluvial-lacustrine-paludal sediment, deposited on a surface gently sloping away from the basement highlands. The upper half to two thirds represents a transgressive marginal marine (estuarine) to beach facies sediment, where conditions near the top of formation were conducive for phosphatic and aragonitic shelled molluscs to live. Conditions changed to fully marine where the mud facies Bulldog Shale conformably overlies the Parabarana Sandstone. There is a stratigraphic break in the rock record after that time. Silicification of the sandstone occurred post tectonic tilting because only the tipped sandstone is silicified, while sandstone underlying the Bulldog Shale remains unaffected. There may have been subsequent burial of this area by later sediments but evidence for that and what those may have been has been removed by on-going erosion.

Location (Site 5b)

Tilted silicified Eyre Formation, escarpment and mound outcrop ~350 m NE of Site 5a (Fig. 15). Access is in part by the same old mine and exploration tracks as for Site 5a, then on foot. This outcrop extends northwards for ~1 km where it terminates against basement granite with a subvertical cross fault, now occupied by a creek gully. A continuation of this outcrop and ramp faulting occurs ~2 km ENE of that termination, and continues north towards Moolawatana Homestead and beyond (see Figs 15, 12).

Lithology (Site 5b)

Eyre Formation here, in an uncemented form (typical), is not well exposed due to abundant silcrete fragment scree and talus. However, small scree windows and small erosion gullies expose variably well bedded to cross-bedded mature sediment (Fig. 17). Well sorted and well rounded sand and gravel sized quartz clasts dominate. Lithic gravel sized clasts include red, green and black jasper, amorphous chalcedony, agate and silicified wood. There are virtually no fines (clay or silt) in this sequence.

a 

b 

Figure 17. Eyre Formation, Site 5b.

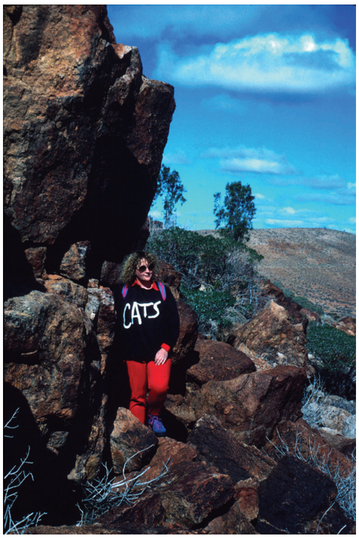
a. Bedded and cross-bedded channel sand and gravel.

b. Strongly cross-bedded sand beds composed of finer-grained sand than in ‘a’.

A substantial silcrete duricrust caps the Eyre Formation along this exposure. Silcrete ranges from massive to “cannon-ball” styles, where nodules (50–>200 mm diameter) form distinct horizons up to a metre thick. Those horizons can be bounded top and bottom by massive silcrete (Fig. 18). Nodules typically have rinds displaying concentric lamellae where these tend to be asymmetrical, i.e. thicker and more abundant on their original top side (geopetal; (Fig. 18). There are also occasional silcrete columns present in the upper most horizon, these are mostly 100–200 mm long and 80–120 mm broad, contain concentric banding and may have an unstructured–amorphous core (Fig. 18). Silicification parallels bedding and has been folded upwards with the ramp faulting process, elsewhere it is near flat lying where the beds are similarly arranged.

Boundaries (Site 5b)

At this locality the Eyre Formation basal contact is totally obscured by talus however, the underlying Parabarana Sandstone can be observed protruding that talus wedge near the outcrop northern end. The lower boundary is a major unconformity, occasional gully exposures further north towards Moolawatana display this relationship well. No upper boundary with overlying sediment is observable along the tilted strata.



a

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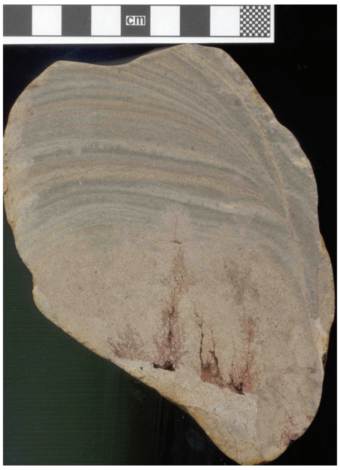

e

Figure 18. Silicified Eyre Formation Site 5b.

a. Silcrete duricrust >5 m thick, developed within tilted Eyre Formation. Both massive and nodular forms occur in this horizon.

b. Pedogenic “canon-ball” silcrete (~1 m thick) developed below massive silcrete (~1 m thick) in dipping Eyre Formation. There are a number of these coarse nodule horizons developed within this duricrust.

c. Canon-ball—nodular silcrete horizon, further along same exposure as ‘b’.

d. Sectioned pedogenic silcrete nodules displaying a massive inner core and a finely banded outer rind. The right nodule has a more complex interior suggesting two or three growth phases – possibly involving down slope movement.

e. A sectioned pedogenic silcrete column displaying massive inner core, a finely banded upper zone and a complex RHS edge.

Age (Site 5b)

Eyre Formation has been dated using palynomorphs, plant cuticle and macrofossils. These indicate an age range from latest Paleocene to mid-Eocene (Callen et al., 1995). Localised ramp faulting occurred post deposition (post mid-Eocene). Sedimentation forming the Eyre Formation regionally has been ascribed to uplift of the Flinders Ranges, beginning in the Paleocene (Callen et al., 1995; Quigley et al., 2007). Silicification of the sandstone to silcrete occurred pre-tectonic tilting. The silcrete duricrust here may include a Miocene silicification overprint, as well as the Eocene silicification imprint, but because there is no Miocene strata preserved here, that assumption is not proved.

Landscape and development environment (site 5b)

Eyre Formation was deposited largely by braided streams in a cool humid climate and on a well vegetated landscape, where relief was varied but vigorously developing in response to epeirogenic uplift of the Flinders Ranges. Fast flowing streams drained the new ranges and formed abundant braided complexes. Quartz-rich sand ± gravel was deposited.

During a time of limited or no deposition, coinciding with landscape stability, silicification of this quartz-rich porous profile took place. Strong seasonality and/or intense climate change promoted deep weathering and very acid soils. Those conditions induced the repeated (?seasonal) dissolution of silica in pedolith moisture and its redeposition nearby as pedogenic silcrete.

Following deposition and silicification, continued tectonic activity associated with mid-Cenozoic uplift of the ranges, induced new compressional stresses to develop within surrounding basin onlap sediments. Those stresses were released within compliant sediments via decollement slippage, ramp faulting and localised folding. Mesozoic and Cenozoic sediments were pushed away from the uplifting ranges, resulting in breakage of stiffer strata and their ramping up on older rocks. The result is steeply dipping sand-rich strata, part folded, where the bedding and fault dips are typically facing out from the ranges. This tectonism occurred post-Eyre Formation silicification and some minor erosion. In this local area it is unclear whether or not Namba Formation was ever deposited on the silcrete clad Eyre Formation. Further away, exposures and drilled sections confirm this stratigraphic relationship. Continued erosion has uncovered the current exposure.

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