Tertiary and Plio-Pleistocene Geomorphology and Neotectonics of the Nilpena Area, Western Flinders Ranges

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Chapter 1 Introduction

1.1.1 Location

The area studied is situated approximately twenty kilometres north east of Parachilna in the Nilpena Hills, an outlier of the western Flinders Ranges, South Australia. It is about ten kilometres north-south by two kilometres east-west and situated on a pastoral property called 'Nilpena', consisting of low hills grading to slightly elevated platforms and alluvial fans intersected by several creeks. The area studied mostly lay west of Dead Man Creek.

1.1.2 Aims, Significance and Previous Work

Little previous work has been done on the Cainozoic geology of the area with most attention being focussed on Neoproterozoic rocks and the associated Ediacara fauna and local Early Cambrian exposures (eg. Sprigg, 1947; Jenkins, 1975). Work by Leeson (1970) as part of the 1-mile Beltana geology sheet (Leeson, 1966) forms the basis for the background geology of the area. Much of the work done on Cainozoic geology in the Flinders Ranges focuses on the western piedmont of the Flinders Ranges and their associated pediments. Much work has been done by Twidale and others, presented in numerous articles, describing pediments and outwash deposits along the western margin of the Flinders Ranges. Twidale et al. (1996) also discusses the importance of various ancient land surfaces, varying in age from Triassic to Eocene. Pediments and alluvial fan generation and their relationship to lithology are discussed by Bourne et al (1998). The aims of this project are fairly broad and are:

- To map and describe various ancient land surfaces and determine their relative ages and the possible environments linked to their formation.
- To determine the role of various faults in relation to these land surfaces.
- To determine the spatial distribution of local Quaternary lake sediments and the age of other associated sediments.
- To describe the stratigraphy and sedimentology of the lake sediments and fossil soils.
- To determine a depositional environment and climate for the lake sediments.

By achieving these aims it is hoped that the understanding and knowledge on Cainozoic tectonism and climate will be improved both locally and perhaps regionally.

1.2 Regional Geology

1.2.1 Pre-Cainozoic geology

The principal geological structure associated with the Flinders Ranges is the Adelaide Rift Complex. This embraces an ancient geosuture that represents the junction between the older western part of Australia, the Australian Shield, and the newer eastern parts, collectively known as the Tasmanides. The age of rocks in the Adelaide Rift Complex is Neoproterozoic and Cambrian (Preiss, 1993). Rocks of younger age are also found in the Flinders & Mount Lofty Ranges but are unconformable above those of the Adelaide Rift Complex. The latter is associated with two key tectonic elements. The Torrens Hinge Zone represents its western margin. The Stuart Shelf, situated to the west of the Flinders Ranges, represents an ancient continental shelf that formed a shallow apron of sedimentation during the Neoproterozoic and Cambrian. The Adelaide Rift Complex has a basement made of sialic crust and the oldest included sediments are the Callanna Group, which include the Arkaroola and Curdimurka Subgroups. They date from the older Neoproterozoic. The youngest sediments in the Adelaide Rift Complex are in the Lake Frome group, which are part of the Early to Middle Cambrian Moralana Supergroup.

The Proterozoic rocks in the study area fall into the Wilpena group and mostly consist of the Wonoka Formation and Pound Subgroup rocks. The Pound Subgroup, which consists largely of quartzites and sandstones, is latest Neoproterozoic.

Cambrian geology in the Flinders Ranges consists almost entirely of sedimentary rocks which can be divided up into three groups: the Hawker Group, and a combination of the Billy Creek Formation and the Wirrealpa Limestone, and the Lake Frome Group (Preiss, 1987).
Permian geology is restricted to a very small patch of glacial diamictite (Lemon, 1996).

Mesozoic geology consists of small basins associated with diapirs. Coal deposits formed in association with these basins during the Triassic. The Jurassic and Cretaceous comprise thin fluvial sands and marine sediments.

1.2.2 Palaeogeography, Palaeotectonics and Palaeoclimate of the pre-Cainozoic

For most of the Neoproterozoic, only mild tectonism is evident in the Flinders Ranges. Sedimentary records in the Adelaide Rift Complex are extensive as this structure acted as sediment sink, burying thousands of metres of detritus. The northern and south parts of the Adelaide Rift Complex appear to have been open to the ocean, whereas the central zone was flanked by the Gawler Craton in the west and the Curnamona Cratonic Nucleus in the east. This central zone has been considered a failed rift (Lemon, 1996). The Adelaide Rift Complex can be considered to have many of the characteristics of a rifted margin that later became a passive margin. The major orogenesis of the Adelaide Rift Complex occurred during the Early Cambrian through the Ordovician and is termed the Delamerian Orogeny. The Delamerian Orogeny resulted in very little sedimentary record for most of the Palaeozoic.

This was due to the orogenesis and denudation that occurred. During the Jurassic and Cretaceous a widespread marine transgression occurred (Benbow et al. 1996).

1.2.3 Tertiary and Quaternary geology

Cainozoic geology in the Flinders Ranges largely consists of pediments and alluvial deposits. Lacustrine deposits are also found such as those associated with the palaeo-lake, Lake Brachina (Cock et al., 1999). The Flinders Ranges were significantly elevated enough to prevent marine ingressions occurring locally. The Cainozoic was also the time of most of the uplift of the present Flinders Ranges. Very few of the sedimentary rocks from the Cainozoic in the Flinders Ranges are strongly consolidated, with the exceptions being sandstone such as the Eyre Formation, various conglomerates and chemical sediments including silcrete and calcrete. There are no igneous or significantly metamorphosed rocks visible on the surface.

1.2.4 Palaeogeography, Palaeotectonics and Palaeoclimate of the Cainozoic

The earliest uplift that made the present Flinders Ranges probably began in the Eocene (Benbow et al. 1996). The uplift probably continued until the late Oligocene. The major phase of uplift which occurred in the late Pliocene to Pleistocene resulted in extensive alluvial fans. During the Palaeocene and Eocene, the environment in the Flinders Ranges was one of fluvial deposition with a temperate and wet conditions. There is some evidence for tropical conditions in South Australia during this time with the presence of tropical plant taxa (Benbow et al., 1996). During the late Eocene, there was a marine transgression over much of the southern margin of Australia and the environment around Flinders Ranges became much more flood plain and fluvial dominated. The climate cooled but still remained wet.

During the early Oligocene there was a sharp fall in global sea level. In the late Oligocene a sharp marine transgression flooded the St.Vincent and Western Murray Basins. The climate warmed throughout the late Oligocene and into the Miocene. Shallow lakes developed around the margins of the Flinders Ranges. The climate was much wetter than today at this time (Benbow et al., 1996).

During the late Miocene and through into the Pliocene there was an increase in aridity and the lakes surrounding the Flinders Ranges decreased in size. The climate became progressively more arid during the Pleistocene until it reached its present state.

1.2.5 Silcretes and laterites in the Flinders Ranges

Silcretes and laterites are often of geological importance because they may be used as geological markers signaling distinctive climatic events. There are considered to be two main phases of silcrete formation in the Flinders Ranges, and for Australia in general, during the Cainozoic. There are silcretes that are at least early Miocene and others of Pleistocene age (Hutton et al. 1972; Alley 1977). According to Alley (1977), Tertiary laterites in the mid-north of South Australia formed before the Eocene. These are termed the southern Flinders Ranges laterites.

1.3 Local geology

The local geology was first formally mapped by Leeson (1966) in the form of the Beltana 1:63,360 geology sheet. This map has not been updated since. The Neoproterozoic rocks of the area consist of the Bunyeroo Formation, Wonoka Formation and the upper and lower members of the Pound Subgroup now renamed the Bonney Sandstone and Rawnsley Quartzite. The Wonoka Formation does not outcrop well in the study area but is considered to have similar structural trends to the Rawnsley Quartzite. The Rawnsley Quartzite strikes in a north to north-north-east direction with a dip of about ten degrees east-south-east. The only evidence for folding is in the Cambrian rocks which form an anticline just west of the Nilpena homestead.

There is only limited outcrop of Cambrian rocks in the area belonging to the Parachilna Formation, an argillaceous sandstone and shale, and the older part of the Ajax Limestone.
There are small exposures of silcrete and laterite which have been given an imprecise age of Tertiary by Leeson.

Quaternary geology consists of the Nilpena Limestone, a non-marine limestone containing fossil gastropods (Leeson, 1970). Whether this is the true basal unit of the lacustrine sediments is debatable as clay sediments were found beneath parts of the limestone. This may just represent thin layers of clay within the limestone, or more likely, be recent redeposited clays from further up section. Other sediments consist of slope and scree deposits as well as several overlapping alluvial outwash fans.
Sand dunes are found in the northern part of the area.

1.4 Palaeosurfaces and lakes

1.4.1 Palaeosurfaces in the Flinders Ranges

There are many remnant land surfaces throughout the Flinders Ranges. Some of them have been buried and then exhumed while others have never been buried. Many of the land surfaces in the Flinders Ranges have been preserved because of a combination of climate and composition. Silcrete and laterite surfaces are especially prone to becoming preserved land surfaces. The oldest land surfaces that have been exhumed date from the Late Jurassic and were covered with Early Cretaceous sediments deposited by the advancing Cretaceous sea (Twidale et al. 1996). This surface is known as the Woodard Surface. Palaeosurfaces in the Cainozoic were formed much more by the dissection of Mesozoic land surfaces by rivers. Valley floor remnants such as the Proby Surface and the Willochra Surface are examples of this (Twidale, 1966; in Twidale et al., 1996). Many of these valleys probably also contained lakes at times.

1.4.2 Palaeo-lakes in the Flinders Ranges

The most prominent example of a palaeo-lake in the Flinders Ranges is the Pleistocene Lake Brachina. This was recently studied by Cock et al. (1999). The age of Lake Brachina is similar to the likely age of the lake in the study area. The lithology of the sediments deposited in Lake Brachina are more arenaceous than the lacustrine sediments in the study area. The thickness of sediments is similar in both cases. Lake Brachina was formed, in part, by blockage of Brachina Gorge.

1.5 Assumptions and Hypotheses

To make some decisions about how each of the studied surfaces in the Nilpena Hills relates to each other in time it is necessary to make some assumptions, linked to the observation that the regional dip of the Pound Subgroup in the area of interest at 11° east is closely similar to the dip of the presumed oldest recognizable Cainozoic land surface, viz 9° east. Based on this, the several assumptions are:

- There has been uplift and tilting in the Nilpena hills, which has not reversed direction during the post Palaeozoic and/or Cainozoic time.
- In order to discriminate events in time it may be assumed that the uplift has been at a more or less constant rate for an appreciable part of the Cainozoic.
- The Pre-Cainozoic strata were never sloping in the opposite direction to which they are today, and their general accordance of dip at 11° east is all related to post Palaeozoic movements.

- None of the described surfaces are simply slope deposits. This can be concluded because of the similar dip of the 'oldest surface' when compared to the Pre-Cambrian strata dip, and because of the mature nature of the surfaces indicating they must have been formed in a sub-horizontal position.

Based on these assumptions, inferences can be made such as:

a) A surface with a high slope will be older than a surface with a low slope.

b) A surface with no slope will be very young.

c) Surfaces with similar slopes can be regarded as having similar ages.

d) No surface of Cainozoic age can have a slope greater than the slope of Pre-Cainozoic (Proterozoic bedding) surfaces or strata.

Based on this last statement, a limiting slope can be placed on the slope of Cainozoic surfaces. This slope was taken by measuring the slope of several good outcrops of Pre-Cambrian strata and finding the average slope. The dip of the Precambrian strata was found to be 11° towards the east (map reference G 3.8). This is close to the maximum dip for any post Palaeozoic surface, which was 9° towards the east.

This also suggests that there was not much time between the first uplift of the Precambrian strata, and the formation of the first Cainozoic surface. Therefore, most of the uplift of the Precambrian strata must have occurred significantly post-Palaeozoic and presumably mainly during Cainozoic times.

1.6 Methods and Fieldwork

1.6.1 Mapping and surface measurements

The slope of discernible palaeosurfaces was calculated by sighting along the plane of surface and measuring both a determined vertical and a horizontal distance from the vertical marker using a tape measure.

It was estimated that the accuracy of the method was ±1°. Several measurements were made on each surface until a maximum slope was found and the direction of this was also determined using a compass.

Problems encountered when measuring the slope of surfaces included the unevenness of some surfaces, and the small size of others, which meant that repeat measurements could not always be made. Vegetation also contributed to possible errors.

Mapping of surfaces was done using an air photograph of scale approximately 1:6666. Marking of surface limits was done directly on to the air photograph and later transferred into an electronic format. Stereoscopic images were also used to aid in the identification of surfaces and their extent. The main inaccuracies in this method are in the possible mis-identification of similar surfaces on the air photograph. However, surface locations were carefully checked. The extent of some surfaces is, unclear, even with careful observations on the ground.

As well as measuring the slope of each surface, a description of each surface was made. The description consisted of matrix and clast lithology, the roundness of the clasts, whether the surface was matrix or clast supported, the size of clasts and whether the matrix was calcareous (see Appendix 2).

1.6.2 Section construction

Several cross-sections were constructed to demonstrate local stratigraphy and the nature of the lake sediments. The sections were made by either using a level sight or tape measure. Because of the weathered nature of many of the outcrops it was difficult to obtain an accurate vertical profile. Due to these uncertainties and difficulties in measuring boundaries of layers, the thickness measurements can only be considered correct to a precision of 90%. The strata were described and tested for any special properties such as responding to acid.

1.6.3 Analytical and lab methods

Thin sections of a few samples were made for examination under a petrological microscope. The sections were made mainly to be able to determine the mineralogy of conglomerates including the cement type.

X-ray diffraction was chosen to determine the broad composition of various unknown poorly consolidated sediments and to provide confirmation of assumed composition (see Appendix 1).

Chapter 2. Findings and results

2.1 Stratigraphy

2.1.1 Stratigraphy and sedimentology

The study area can be divided into four clearly defined, tectono-sedimentary zones or regions. Each of these regions has a specific characteristic in either tectonics and/or sedimentology, which allows it to be differentiated. The regions may and indeed probably do have sediments or surfaces that are co-temporal with those of other surfaces.

The oldest of these regions is the silcreted highland surfaces. This region includes the oldest post-Palaeozoic surfaces and is found between the main topography of the Nilpena Hills and the lowlands to the east. The extent of this region can only be defined in terms of the surfaces that it contains. These surfaces are patchy and poorly defined. The region is linked to an early phase of tilting of the Nilpena Hills. All of the surfaces contained in the zone, of which there are at least three, have slopes between four and ten degrees in an easterly to south-easterly direction.

The next oldest region includes the lake deposits. These are primarily glauconite and gypsum rich clays. The Nilpena Limestone underlies these clays. The limestone may be the results of a low sedimentation phase, early in the lake's history. The lake may have become saline at a later stage permitting the formation of glauconite. There is evidently a second limestone that formed at the top of the lake deposits. This seems to have later been calcretised to form the current calcrete (not the mottled calcrete).

The lake deposit region may overlap in time with the next zone, which is the Northern Dune region. The Northern Dune region has a basal laterite and various pre-dune platforms built on it. This zone is significantly elevated in comparison to the lake deposits and may be more involved with the uplift of the main Nilpena Hills. Locally the laterite may have formed by extreme weathering of uplifted lake deposits or it has simply formed directly from weathered Wonoka Formation, where it is particularly iron rich.

The fourth zone consists of all the recent and Pleistocene outwash fans, alluvial deposits and floodplain deposits. They are generally flat lying except in the case of outwash fans. There has been some disturbance of the sediments by faults that are particularly evident in Deadman Creek near the station.

In the general study area are various sediments previously described as lacustrine in origin. The described sediments consisted of named and unnamed units. Unnamed units consisted of various clays and gypsiferous units. The lowest unit, except for poorly exposed clays exposed in the area that formed part of the lacustrine sediments, is a fossiliferous limestone. This appears to be the previously described Nilpena Limestone (Leeson, 1970). There are gypsiferous clay units that possibly lie beneath the limestone but they are poorly outcropping.

The Nilpena Limestone appears to be the oldest post-Palaeozoic water-laid, fine grained sedimentary unit in the area. Above the Nilpena Limestone are a series of gypsiferous clays with occasional concretionary and nodular layers of calcrete. The clays vary from green to pink to white clays. Gypsum was most common in the green and white clays. A complete X-ray diffraction analysis of a section through the lake sediments was done. For more information on the mineralogy of the lake sediments see the X-ray diffraction results in appendix 1. On top of the clays was a crust of calcitic gypsum (**Plate 1.d**). This crust appears likely to be a recent weathering feature and it is commonly associated with the mottled 'large honey comb' calcrete described later. This crust could also grade into a hard calcrete in some areas and lacks gypsum. It is possible that the hard calcrete is actually a calcretised limestone.

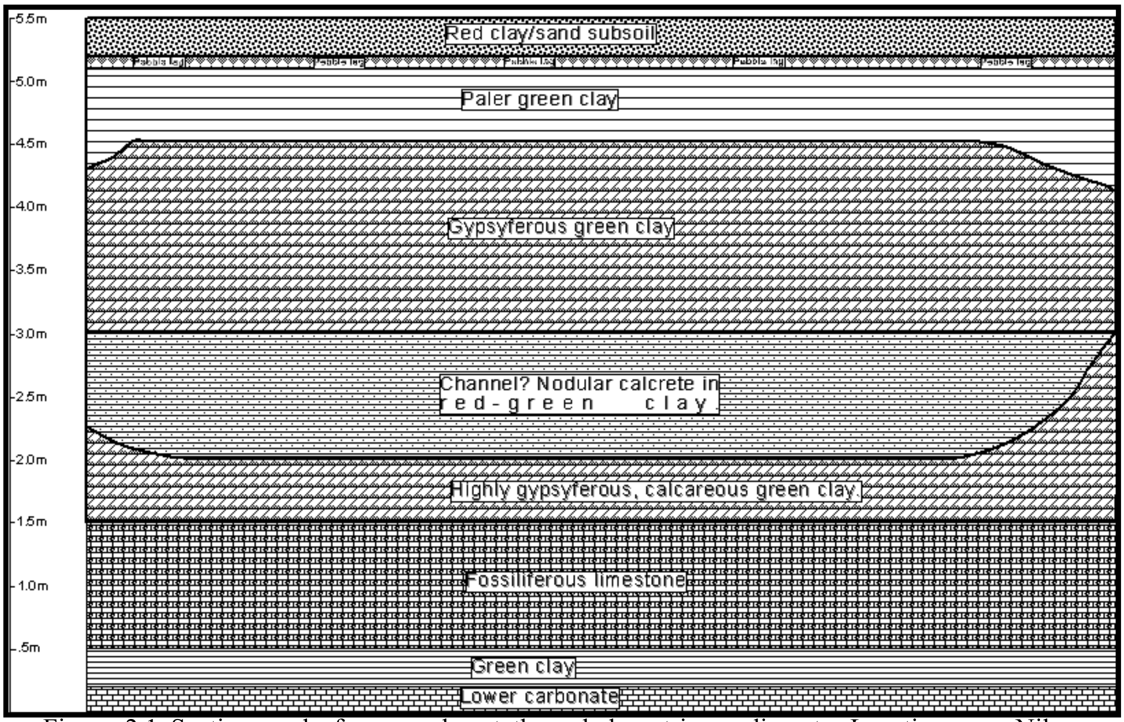


Figure 2.1 Section made from creek cut through lacustrine sediments. Location near Nilpena station (map reference T 3). Note the presence of a clay layer between the fossiliferous limestone (Nilpena Limestone) and a lower carbonate. The lower carbonate is probably a less fossiliferous part of the Nilpena Limestone. The width of the channels cut in the clay is approximately 5 to 10 metres.

Leeson (1966) describes high-level dissected piedmont gravels. It was found that in many areas, immediately adjacent to these high level surfaces, there were lake deposits on top of the Nilpena Limestone. The Nilpena Limestone and lake deposits as a whole were at a similar altitude to the high level surfaces indicating either a similar time of formation or very little uplift between the formation of the high level surfaces and the combined Nilpena Limestone/lake deposits. The high-level dissected piedmont gravels commonly lie as a sheet on top of the gypsum crust or hard calcrete. Much of the present day landscape is dominated by expansive alluvial fans and fluvial floodplain deposits, which lie above or lap onto the other sediments. It would seem that these would be the latest deposits with the exception of scree and possibly a conglomerate found in Deadman Creek.

The conglomerate found in Deadman Creek is different to other conglomerates found in the area in that it has much larger clasts, some as large as ten centimetres in diameter, and occasionally has clasts within clasts. This seems to discount the possibility of the conglomerate being very recent because for the recycling of conglomerate to occur, there would have to be two cementation phases or one long cementation phase. The conglomerate also differs from other conglomerates because it has cement almost totally composed of calcite. The conglomerate contains clasts of sandstone, quartzite and siltstone that have come from Precambrian and Cambrian rocks or surfaces containing rocks of those ages. The clasts are well rounded.

Other conglomerates found in the area have much smaller clasts (<1cm) and are likely to be much older because they are found at much more elevated levels than the Deadman Creek conglomerate.

The laterite (**Plate 2.d** and **2.a**) that exists in the Northern Dune zone has red-orange pisolites that have weathered to kaolinite in places (see Appendix 1 – XRD Results).

2.1.2 The mottled 'large honey-comb' calcrete

A calcrete horizon can be found that can be best described as having a 'large honey-comb' structure (see **Plate 1.a**). This particular layer was found in a variety of localities and initially appears to be a distinct and restricted horizon. On closer examination, it is found to be near the surface of any section that contains it and it often is located *at* the surface forming a crusted patchwork of white calcrete. It is quite soft and friable. It appears to be related to the carbonate content of the lower rocks or regolith. It is found in isolated patches in sections of areas containing only Precambrian rocks. From this it can be concluded that it is a very recent element and is part of the present day soil.

2.2 Surfaces

2.2.1 Surface descriptions and locations

The slopes and directions of each of the localities where discrete surfaces were recognized and slopes were measured can be seen in figure 2.2.

LOCALITIES	DESIGNATED SURFACE	LOCATION DESCRIPTION (ALSO SEE MAP)	SLOPE	DIRECTION	MAP REFERENCE
1	A	East slope, Eastern Twin Peak	≈9°	Approx. east	B 4.3
2	G	Calcrete surface west of station	≈1.5°	East	S 2.2
3	G	East of south hill	≈1°	Approx. east	O 1.1
4	G	On top of White Bluff	≈1°	Approx. east	M 2.8
5	G	Near large station tank	≈1°	Approx. east	S 4.4
6	I	Near corner of fence, east road	≈1°	Approx. east	P 5.0
7	E	Above high creek cut, Great Divide	≈2.5°	Approx. East	C 5.2
8	E	High surface near camp	≈2°	Approx. East	O 2.6
9	E	See map	≈1.5°	Approx. East	R 1.4
10	B	See map	≈7.5°	≈70 mn	G 5.2
11	B	See map	≈6.5°	≈70 mn	H 5.1
12	B	See map	≈6°	≈70 mn	H 5.2
13	I	See map	No discernible dip	-	O 4.7
14	I	See map	No discernible dip	-	P 4.6
15	I	See map	No discernible dip	-	P 4.3
16	E	See map	≈1.5°	Approx. East	Q 1.9
17	H	See map	≈1°	Approx. East	S 2.9
18	H	See map	≈1°	Approx. East	R 3.3
19	D	Northern dunes, south side	≈3°-4°	Approx. South	B 1.8
20	C	South west of Sugar Loaf	≈4°	Approx. east	L 3.6
21	C	See map	≈4.5°	≈150 mn	
22	H	Northern dunes, south side	≈1°	Approx. South	B 0.9
23	C	See map	≈3.5°	≈75 mn	F 5.5

Figure 2.2 *mn = magnetic north. Note that surface F, the sub-dune platform surface does not appear in this table because no slope estimate was made.

2.2.2 Relationships of surfaces

It is unlikely that any of the surfaces described can be directly related to previously described surfaces because of the isolation of the area from the main Flinders Ranges. None of the surfaces can be related to the most prominent land surface in the Flinders Ranges, the Woodard Surface, due to the lack of Cretaceous sediments and the relatively low altitude of all of the surfaces. The local surfaces could possibly be comparable to, and probably are, Cainozoic surfaces such as the Willochra surface and others, but the isolation of the surfaces makes drawing any direct comparisons difficult. Most of the surfaces found, cannot be directly related to one another because they do not directly contact one another. Relationships can be derived by qualities such as lithology, slope and position relative to specific markers such as the Nilpena Limestone and a laterite found near the Northern Dunes. The best direct example of how various surfaces relate can be found in the Northern Dunes. This is detailed in figure 2.3. The surfaces have already been loosely grouped, mainly if they had similar slope or clastic/pedological associations. They can be grouped further by taking a broader look at their characteristics.

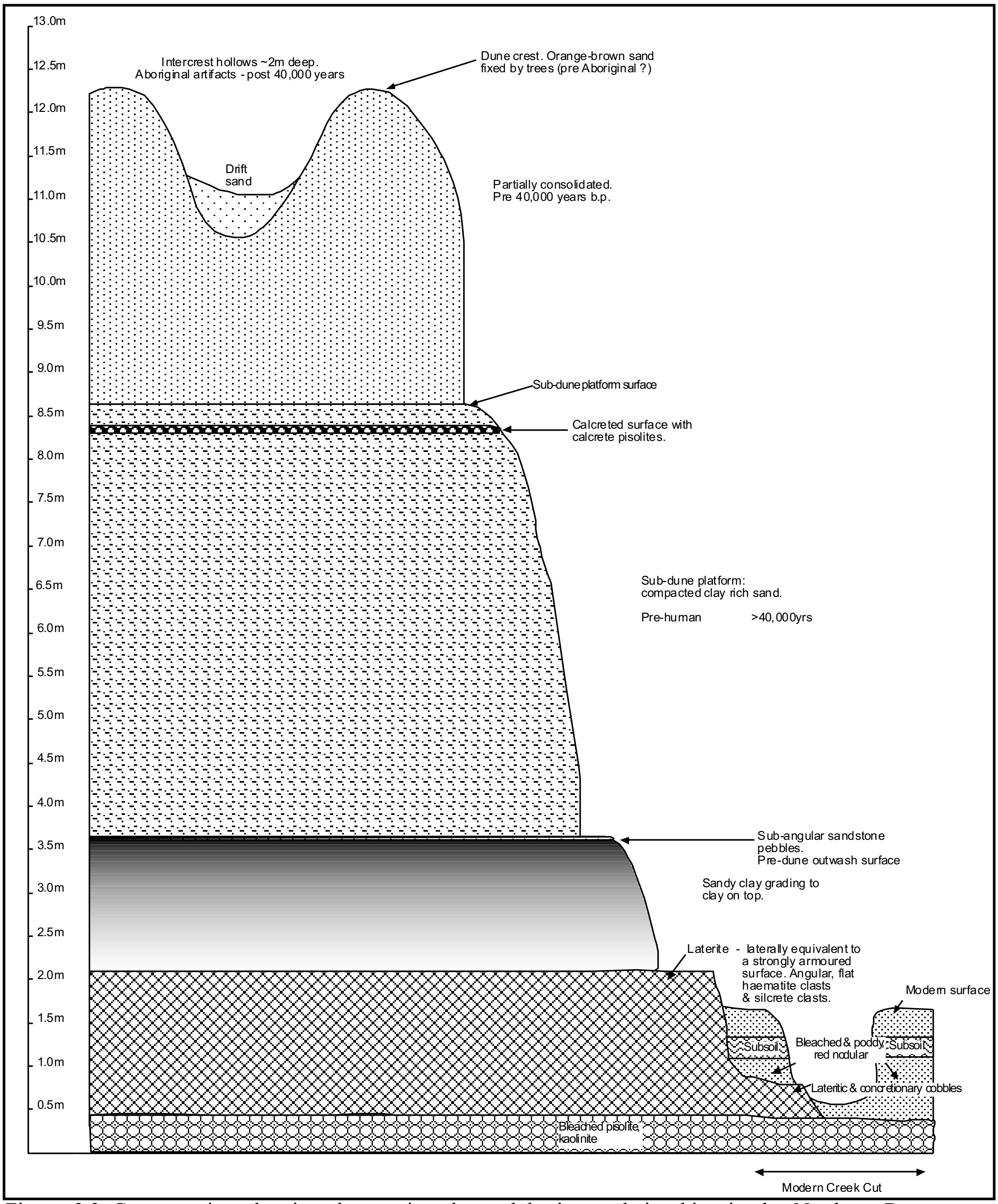


Figure 2.3 Cross section showing the stratigraphy and horizon relationships in the Northern Dunes area. Horizontal scale has been compressed. Approximate horizontal scale is 30 metres.

2.2.3 Specific surface relationships

Of the three recognized silcreted surfaces, A, B and C, in the silcreted highland surface region, surfaces B and C are the most similar. Surface A (**Plate 1.b**), the earliest surface, has much more silcrete than surfaces B and C. The isolated nature of all of the silcreted highland surfaces, makes drawing direct spatial relationships difficult. This is probably due to the age of the silcreted highland surfaces. Surface A has only one example (grid reference B 4.3). Surface B has three examples (G 5.2, H 5.1 & H 5.2). Surface C has three examples (F 5.5, O 0.8 & L 3.6). Surface D has only one example (B 1.8). This is the laterite surface. This has a dip of three to four degrees which is similar to a rough dip measurement made on the dip of the Nilpena Limestone. This would indicate that the laterite was formed at about the same time as the Nilpena Limestone but it does not indicate whether the laterite was formed over or from any of the lacustrine sediments. Surface E is part of the fourth region, the Pleistocene zone. This surface has a slope of approximately two degrees, which is twice the dip of the current floodplain deposits. This suggests that this is the earliest Pleistocene surface. This surface is also commonly greatly elevated and sits on top of the lake sediments. Faulting, and not uplift is probably responsible for the altitude of this surface and the fault blocks were probably rotated as they were uplifted. There are four examples of this surface (C 5.2, O 2.6, R 1.4 & Q 1.9). Surface F is the sub-dune platform. A slope measurement on this is difficult, but it can be assumed that it is Pleistocene in age. Surface G is part of zone four, but was formed at a much later stage is has been uplifted by much more recent faulting. It includes such lithologies as a gypsum layer and a hard calcrete layer. There are four examples of this surface (S 2.2, O 1.1, M 2.8 & S 4.4). Surfaces H and I both have very little slope. Surface H has a slope of approximately one degree and largely consists of armoured cobble/ironstone stained surfaces elevated half a metre above the surrounding surface. There are three examples of surface H (S 2.9, R 3.3 & B 0.9). Surface I has been strongly dissected by faults and this may be the reason for the formation of the surface. Like surface H it consists totally of strongly armoured cobble/ironstone stained surfaces. There is negligible slope. Since the surface is only found on elevated fault blocks it may be possible that the surface formed post faulting and hence is very recent. The surface may have formed during the current arid period. It is possible however that the surface may have formed pre-faulting and the lower portions of the surface have been eroded. The best examples of surface I fall in the region on the map of grid reference P 4.6 to P 5.0.

Surface J is the surface which forms most of the lowlands and consists of floodplain deposits. It is weakly sloping towards the east which indicates tilting is still occurring. Surface K is the most recent surface and includes any of the surfaces formed by the cutting action of modern creeks and rivers.

2.3 When each surface formed

Working with the model that the surface with the greatest slope must be the oldest, Surface A can be considered the oldest. Continuing on, the relative ages of the surfaces must be (from oldest to youngest):

SURFACE	DESCRIPTION	TECTONO-SEDIMENTARY REGION
A (oldest)	Silcreted surface	Region 1
B	Silcreted surface	Region 1
C	Silcreted surface	Region 1
D	Laterite	Region 3
E	Earliest, elevated Pleistocene surface	Region 4
F	Sub-dune platform	Region 3
G	Gypsum and Calcrete crusts	Region 4
H	Western ironstone armoured surface	Region 4
I	Eastern ironstone armoured surface	Region 4
J	Floodplain surface	Region 4
K (youngest)	Current creek cut surface	Region 4

Figure 2.4

2.4 Faults

2.4.1 Fault locations and descriptions

The main regional fault in the area is the Ediacara fault, which runs along the western margin of the Nilpena and Ediacara Hills. It separates the Beltana Sub-basin from the Torrens Basin (Leeson, 1970). Various previously unnamed and undocumented faults occur in the area, all of them being normal faults as far as can be determined.

The most prominent fault in the study area is a fault, which runs coincident with Deadman Creek. The east side of the fault is higher than the western side by about one to two metres but sometimes as little as fifty centimetres. From various intersections between the creek and the fault, it is determined that this is a normal fault. The path of the fault can be seen on the map (plate 4).

In the southern area are a series of graben structures, which converge with the Deadman Creek fault. The graben structures are restricted to the east side of Deadman Creek fault.
The offset in these graben structures is about one metre (see plate 2.c.). The horst surface associated with these grabens made up of ferruginised pebbles and can be considered as an armoured surface. The surface at locality 6 is an example of one of these.

Other faults which are not easily seen but which can be inferred are found to the west of Deadman Creek. The main one runs parallel to the Deadman Creek fault until the creek diverges from the hills. This fault may have formed the margin for the palaeo-lake that existed. Exact offsets on the fault are difficult to determine, but on the basis of the amount of sediment infill it appears to be at least five metres, and probably more than ten metres. This fault may be the same one that was evident in the southern part near the area termed the Amphitheatre (S 1.6). Another fault that runs through the area is one at the western end of the Northern Dunes. This fault is identifiable on air photographs but is very difficult to see in the field.

2.4.2 Fault groupings

There are three distinct faults or fault sets. The first set has by far the greatest number of faults. It includes all the faults that make up the graben structures seen in the south-east portion of the area. The second fault is Deadman Creek fault. The third fault runs parallel to Deadman Creek fault. The main difference between the faults is in the probable age with set one being the youngest and set three being the oldest. These last two group of faults are most likely to be reactivations of much older faults, probably as old as the Precambrian.

2.5 Lab and analytical results

2.5.1 Thin sections

The only sample analysed that was of any use was a conglomerate. The conglomerate had clasts consisting mainly of quartz with occasional albite. The conglomerate analysed was the stream conglomerate found as a horizon at the base of Deadman Creek (R 3.8). The cement was fine grained calcite. All remaining samples were too fine grained to provide any useful information.

2.5.2 XRD

The XRD results confirm the field appraisal of the composition of most samples. Of particular exception is one sample from the northern dunes, which was suspected to be a silcrete. Instead, it was found to be mainly composed of kaolinite. It appears that it is just a leached example of the laterite.

The composition of a ‘strange black calcrete’ was confirmed to have no detectable traces of other minerals so the black substance is probably some organic material, possibly charcoal. The other XRD results are detailed in appendix A.

Chapter 3. Discussion

3.1 Palaeoenvironmental reconstructions

3.1.1 Tertiary

The various surfaces and sediments found in the area provide a record of the different environments through time. This record is in no way complete, nor does it provide a temperal account of the environmental history of the area.

The oldest surface, a silcreted surface (locality 1.) is part of the silcreted highland surface zone. Silcretes most commonly form in a warm wet climate and are most likely to form in valleys or small depressions. This means that at the time of formation of the oldest surface, the climate was warm and wet and there must have been some surrounding elevated ground. Whether this elevation was uplift associated with the initial tilting of the Nilpena Hills or was part of the main body of the Flinders Ranges is debatable. It seems likely that the topography that created these valleys or depressions was probably part of the initial uplift of the Nilpena Hills, mainly because the uplift of the main Flinders Ranges is too remote in relation to the silcreted surface. If the valley forming topography was related to the main Flinders Ranges it would be expected that elevated silcreted surfaces could be found further to the east of the Nilpena Hills. The preferred assumption is that it was the initial uplift of the Nilpena Hills which provided the necessary hill and valley topography to allow deposition of silcrete. The fact that the silcreted surface is made up of silcrete skinned, rounded boulders and cobbles probably points to the valley being a river valley containing a fairly energetic river.

There are at least two other silcreted surfaces in zone 1. These may be redeposited, which means their relative ages cannot be determined using the high slope equals old age hypothesis, or they may be primary surfaces. Similarities in lithology and sedimentological structure of these surfaces and the earliest silcrete surfaces points towards these surfaces having similar formational modes to the earliest surface. Since the availability of zones of deposition is likely to have remained relatively constant throughout tilting, it seems reasonable to ascribe these silcreted surfaces to at least two further warm and wet climate periods.

The earliest sediments deposited in zone 2, the lake deposit zone, are carbonates which make up the Nilpena Limestone. The presence of small gastropods in the Nilpena Limestone and the thickness of the beds indicates that the body of water in which the limestone was deposited must have been permanent. Although the presence of glauconite in the succeeding argillaceous sediments would indicate a shallow marine setting, this seems very unlikely considering the absence of any mention of marine incursions during this time in the literature. It could, however, be possible that remnants from the last marine incursion during the Tertiary, resulting in saline or brackish conditions in associated lakes. The presence of alkaline lakes has been indicated on the western side of the Flinders Ranges in the Miocene (Benbow et al., 1995). The Nilpena Limestone also indicates a low input of sediment from terrestrial sources. This may show that runoff was low, and therefore the climate was dry, or there was no topography to provide sediment. Due to the presence of the Flinders Ranges and the Nilpena Hills, it seems unlikely that lack of topography was the cause of low sedimentation. Therefore the climate must have been dry enough to not allow much sediment transport, but wet enough to disallow the complete evaporation of the lake. Other factors such as vegetation may have also prevented a large sediment input but still have allowed a wet climate. This could be analogous to the present day Great Barrier Reef of the coast of Queensland.

The sudden transition into clay sediments indicates an increase in runoff and a possible increase in chemical weathering. This shows that the climate became significantly wetter. The source of the clay sediment is likely to be the Wonoka Formation. The Wonoka Formation is a calcareous siltstone so it seems reasonable that the Wonoka Formation could undergo extreme weathering resulting in many clay-sized particles as well as a significant amount of carbonate minerals. The Wonoka Formation is poorly outcropping in the area when compared the Rawnsley Quartzite and this could be due to its major role in providing sediment for the lake.

The increasing amount of gypsum that occurs up-sequence in the lake sediments may also indicate and increase in the amount of time that the lake underwent intermittent evaporation. This culminates in a relatively hard gypsum crust at the top of the clay sediments that may indicate the final period of the lake’s flooding. The gypsum crust is not always found above the clays but this may be due to later erosion by Quaternary rivers (**Plate 2.b**). In the northern dune zone, the only sediment that can be possibly assigned to form in the Tertiary is the laterite (**Plate 2.a**). It should be noted that no evidence of a complete laterite weathering profile can be seen. The main characteristic of this laterite should be taken as pisolites of secondary oxides of iron or aluminium. Laterites form in similar climatic conditions to silcretes, but need significant drainage so are unlikely to form in valleys. The laterite probably formed due a combination of climate and fault related uplift. The precursor sediments for the laterite are possibly early lake sediments that got isolated by uplift, or erosion of the Wonoka Formation. The likely precursor for the laterite depends on the relative altitude of the laterite and the lake sediments. The highest lacustrine sediments are at an altitude of between 110 metres and 130 metres whereas the laterite is at an altitude between 140 metres and 150 metres (Department of Lands, 1990). Either the precursor lacustrine sediments for the laterite were uplifted much higher than the highest uplift of the lacustrine sediments seen currently, or the precursor material for the laterite was the Wonoka Formation. The Wonoka Formation lies

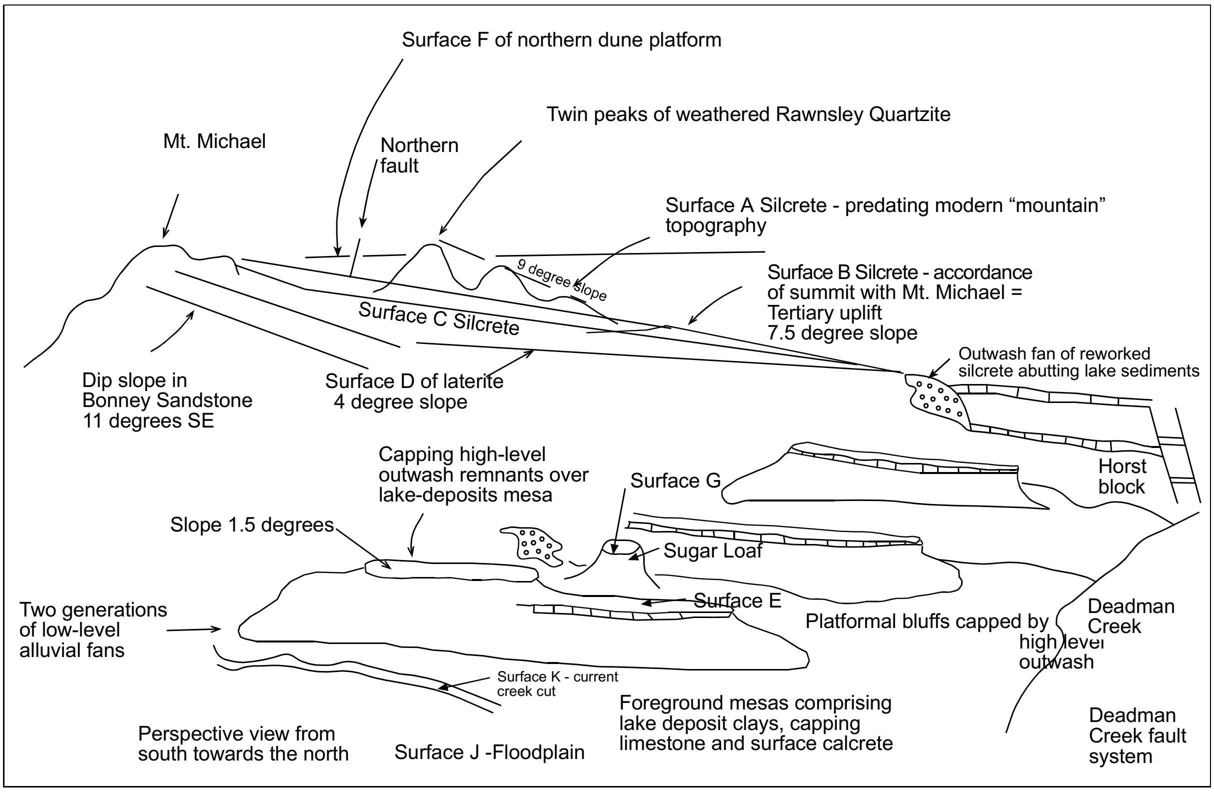


Figure 3.1. Perspective drawing showing relationship of various palaeosurfaces. Not to scale.

at the same elevation to the laterite and therefore seems a much more likely candidate for the precursor material, especially as it is bevelled by the lateritic surface at locality 22 (B 0.9). Much of the above is illustrated on plate 3.

3.1.2 Quaternary

The Quaternary geology consists largely of pediments and floodplain deposits. This indicates a climate in which rainfall was relatively low, but the landscape was not arid. Pediments can be deposited in an arid climate due to a sudden influx of water from occasional storms, but the presence of alluvial sediments indicate significant fluvial action. Fanglomerates are common indicating a combination of river derived sediments and mountain derived sediments. These pediments and floodplain deposits are the main constituent of tectono-sedimentary zone four.
Quaternary geology of the Northern Dune zone is focussed around the development of sand dunes, which also coincide with most of the outcrops of the laterite. The Northern Dunes are likely to be evidence of a drier and more arid climate. The reason the dunes form where they

do is probably because of the prevailing wind direction and the blocking nature of the Nilpena Hills which prevented further migration of sand southwards.

There are at least two phases of dune construction. The first has been largely eroded and forms a semi-consolidated dune platform. The second phase is the more recent and is responsible for the present dunes. The dunes are no longer active except for small blowouts and drift sand deposits (**Plate 1.c**). These drift sand deposits contain Aboriginal stone tools and so are no older than 40,000 years old (assuming Aboriginal occupation for no more than 40,000 years). The first and second phases of dune formation have no visible Aboriginal tools and are therefore likely to be older than 40,000 years. The two phases of dune formation illustrate at least two periods of arid climate prior to, or including the present.

3.2 Age

Going by the model of the oldest surface has the largest slope, surface A can be concluded to be the oldest. Surface B was either a result of a later silcreting event or reflects a redeposition of silcreted clasts derived from surface A. Most silcretionary events in the Flinders Ranges during the Tertiary occurred during the Eocene (Callen, 1983). It seems that this would be a likely age for surface A considering its slope. Surface C is more likely to be younger and may represent a redeposition of an older silcreted cobbles.

The timing of all the of the Northern Dune surfaces seem unclear. It may be irrelevant to use the high slope = old argument, because that area is not discernibly tilted. However it is cut by a north-south trending fault which bounds a significant area of stream denudation, signifying that the substructure of the dunes and main dune development are relatively ancient. Therefore any surfaces in this area are very hard to date. Surface D, the oldest surface in the Northern Dune zone, is a laterite and must have formed by weathering of an elevated fault block. This constrains its age to a warm and wet time. Surface F, the sub-dune platform is probably pre 40,000 years old, due to the lack of Aboriginal stone tools.

Parts of surface E shown signs of silcrete, but is likely to partly indicate redeposition of silcrete from another source.

The age of the Nilpena Limestone has previously been described as early Pleistocene (Leeson, Beltana map). This may be possible, but it would have to have been deposited very early in the Pleistocene, before the latest phase of uplift because it seems to have a relatively high slope of four degrees. If the Nilpena Limestone is early Pleistocene, then the lacustrine clays must be younger.

The remaining surfaces G, H, I, J and K are probably all recent to sub-recent. This can be concluded because of the low dip of the surfaces and they probably reflect the late Pleistocene and Holocene climatic conditions.

If it is assumed that surface A has an age of middle Eocene, and it is also assumed that tilting has occurred at a constant rate after the formation of surface A, then it is possible to ascribe model ages to subsequent surfaces. These ages are shown in figure 3.2.

SURFACE	MODEL AGE (MA)
A	44
B	37-30
C	17-<5
D	20-15
E	12-7
F	No measured slope so no model age
G	7-<5
H	<5
I	<5
J	<5
K	<5

Figure 3.2 Surface model ages. Accuracy is limited by slope accuracy so is only accurate to five million years

3.3 Tectonics

3.3.1 Tectonic history

The general tectonic regime of the area appears to be one of extension. This is probably the result of the rotation and flexure of the crust about a pivot point somewhere to the east of the Nilpena Hills. The uplift of the Nilpena Hills would have resulted in a significant amount of normal faulting along their edges. This is expressed firstly in fault group three and later in Deadman Creek fault. The graben structures that intersect but do not cross Deadman Creek fault may represent some recent or sub-recent transverse movement in a sinistral sense along Deadman Creek fault. A bend along Deadman Creek fault may cause the graben structures and this may explain why the grabens do not persist further north (see figure 3.3)

3.3.2 Implications for sedimentation

The fault that runs parallel to Deadman Creek fault was probably the most important fault with regards to sedimentation. It appears that it provided the necessary topography so that a lake could form and sediments could be deposited. There is an apparent increase in the amount of glauconite near to the fault which may indicate this was where the shallowest waters were. This fault may also have provided the necessary topography to provide sediments for the lake. Glauconite is normally formed in a shallow marine setting. Whether the lake had any marine influence or behaved in a chemically similar manner is difficult to say. Glauconite formation is often due to changes in oxidity, particularly fluctuations between sub-oxic and oxic conditions, which would perhaps reflect climate change (pers. comm., Gammon, P.).

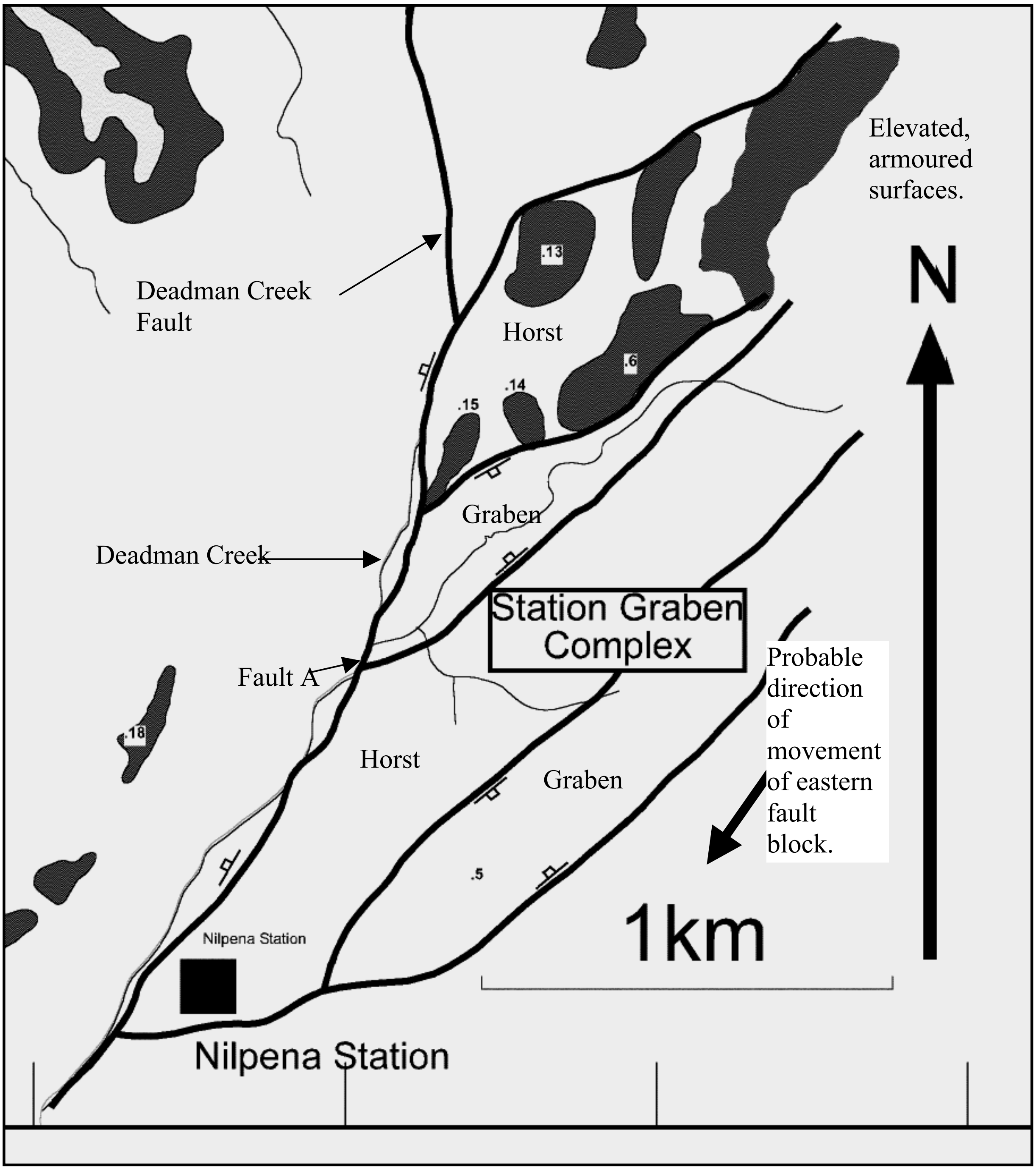


Figure 3.3 Extensional fault zone near station. Extensional faults may be due to a combination of stress field direction and underlying anisotropical weaknesses in the rock. The absence of faults in the northern section may be related to the kink in Deadman Creek Fault. The faults were discovered by examination of creek cuttings and interpretation of topography. See also the map.

Deadman Creek fault appears to be relatively recent and as such has had little impact on past sedimentation. There is present day erosion, which can be linked to the Deadman Creek fault.

There are also significant erosion gullies on the eastern side of Deadman Creek fault, which are contributing to present-day deposition.

An erosion surface in parts of the green clay can be seen in parts of Deadman Creek. This erosion surface is probably related to the faults that form the graben structures as these faults appear to be quite recent (**Plate 2.b** and **2.c**).

Chapter 4 Conclusion

The development of various armoured surfaces has been the most important factor in allowing any study of the development of the land surface to occur. The oldest armoured surfaces are mainly silcrete, in particular silcrete skinned - cobble quartzite surfaces. Other armoured surfaces such as ironstone and laterites have also been important palaeosurface indicators, particularly in the Quaternary.

Faults are also important in the preservation of the land surfaces as they allow elevated blocks to develop armour, as with the ironstone stained surfaces, or they create the necessary topography so that silcrete can form in valleys. They also facilitated the formation of a laterite.

The lake sediments are confined by the Nilpena Hills to the west and their eastern extent is unknown. Judging by past work it seems likely that the lake would have become shallower and more marshy, the further east it went.

The lowest of the lake sediments, the Nilpena Limestone, was deposited in a warm, wet climate in a low sediment input environment. It is likely that there were significant amounts of vegetation around the shores of the lake when the Nilpena Limestone was forming. The clay sediments probably formed in a significantly more arid climate while the oxidity of the lake was varying significantly from sub-oxic to oxic.

There are three faults or fault sets. At least two of these were originally active during the pre-Cainozoic. The other set, the Nilpena station graben complex, has greatly influenced the development of Quaternary ironstone surfaces in the southern part of the study area.

The climate has gone through at least four warm and wet phases, with the development of a laterite and silcretes during each phase. A drier phase, possibly during the late Pleistocene, resulted in a decrease in vegetation and an increase in terrigenous input of sediment into the lake. This resulted in the cessation of limestone formation and the deposition of significant amounts of clay minerals. The increase in terrigenous input may continued until a further phase of limestone deposition occurred, or the lake dried up. Which of the two occurred is not clear because the exact nature of this later limestone is difficult to determine. It may be simply be a recent calcrete. It is likely that it is only a recent calcrete, due to the lack of any evidence to the contrary, and would therefore indicate that the climate has become continuously drier since the cessation of the deposition of the Nilpena Limestone.

Plate 1

(**a**) Mottled 'honey-comb' calcrete. Near locality 7 (C 5.2). 2 metre pole for scale.

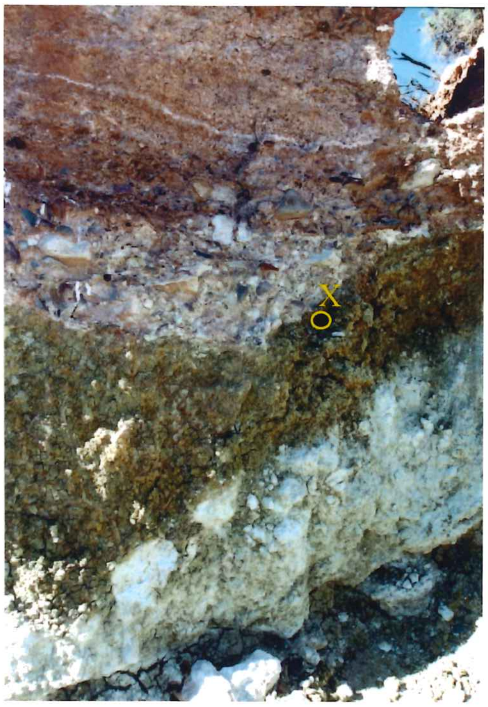
(**b**) View of twin peaks looking north. Right slope indicated by line is surface A (locality 1 – B 4.3)

(**c**) Modern dune blowout in Northern dunes. 300 metres west of Twin Peaks

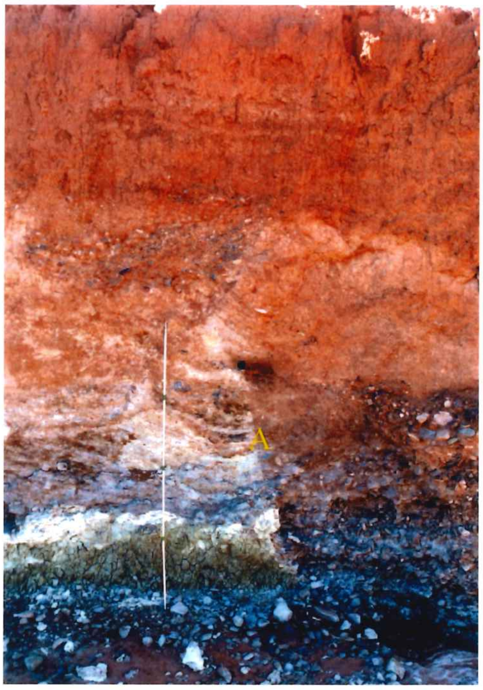
(**d**) Gypsum horizon on top of high level outwash remnants and lake-deposit mesa. Locality 4 (M 2.8). Hammer for scale.

Plate 2

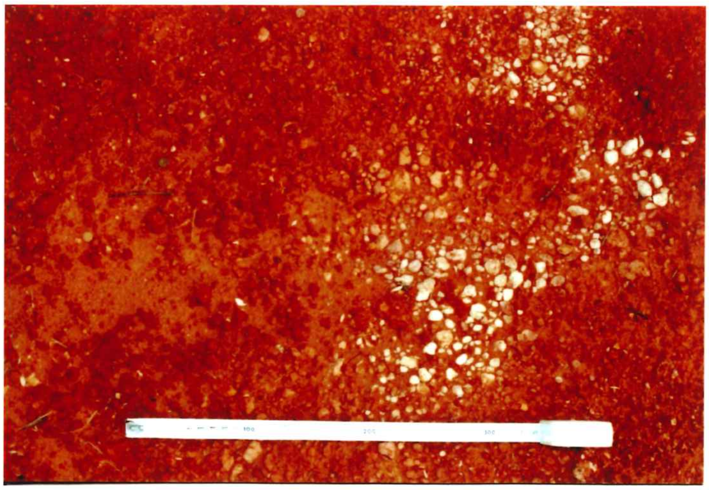
(a) Laterite outcrop found in Northern Dune zone (B 1.8). Hammer for scale



(b) Creek Cut near station (Q 4.2). Erosion surface cut into lacustrine clays. Lens cap below X for scale.



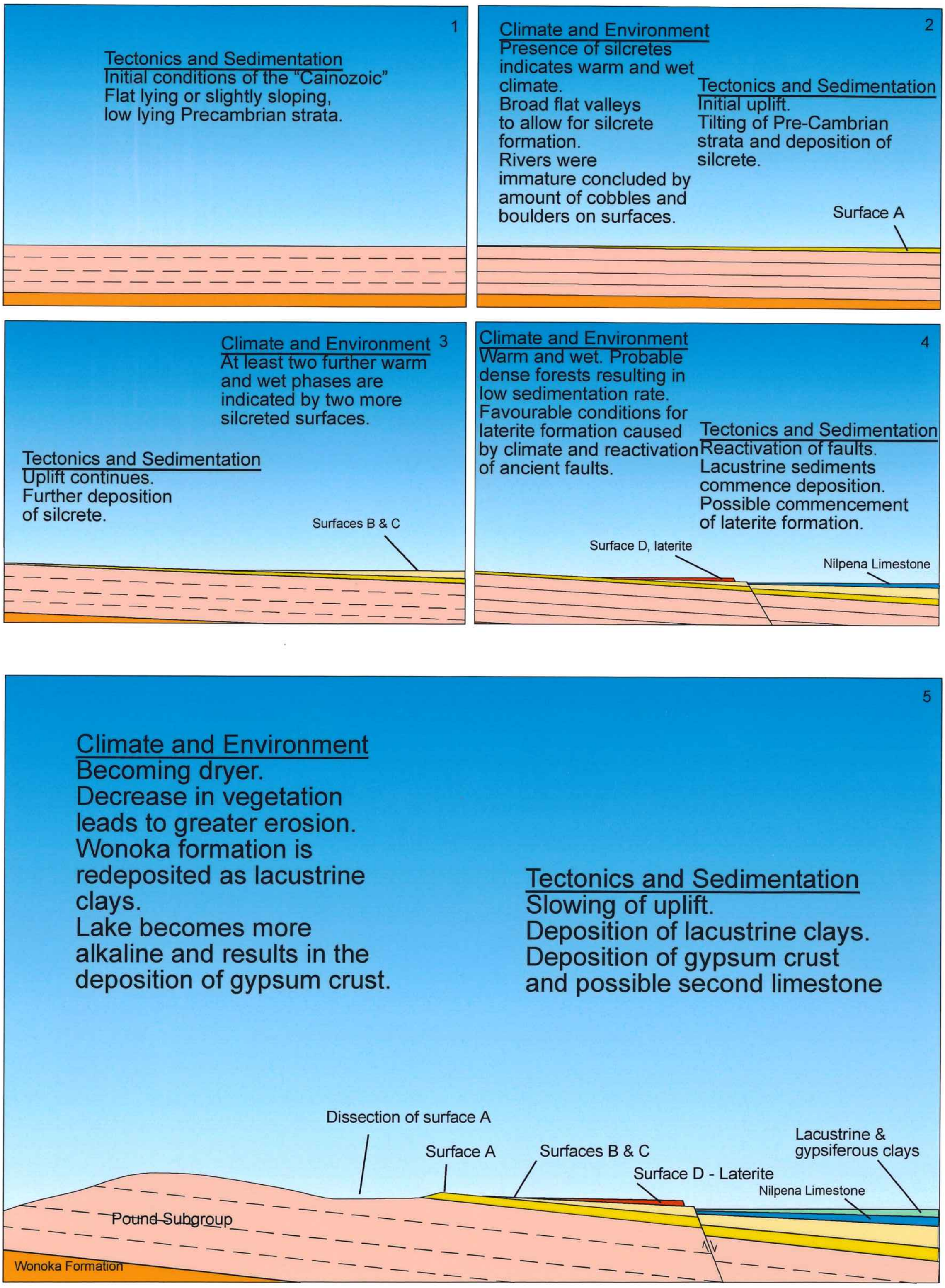
(c) Fault in creek cut near station. Fault shows offset of 1 metre. The fault is part of the graben complex faults (fault A on figure 3.1). 2-metre pole for scale.



(d) Close-up of laterite seen in (a). White blotches are bleached and kaolinised nodules. Length of tape shown is approximately 30cm.

Plate 3

Cainozoic Palaeoenvironmental Reconstructions



LEGEND

Water courses

Fault (normal)

Surface extent

Locality Number .4

Surfaces

Surface A

Surface B

Surface C

Surface D

Surface E

Surface F

Surface G

Surface H

Surface I

Surface J East

Surface J West

Other sediments and strata

Pre-Cambrian (Pound Subgroup)

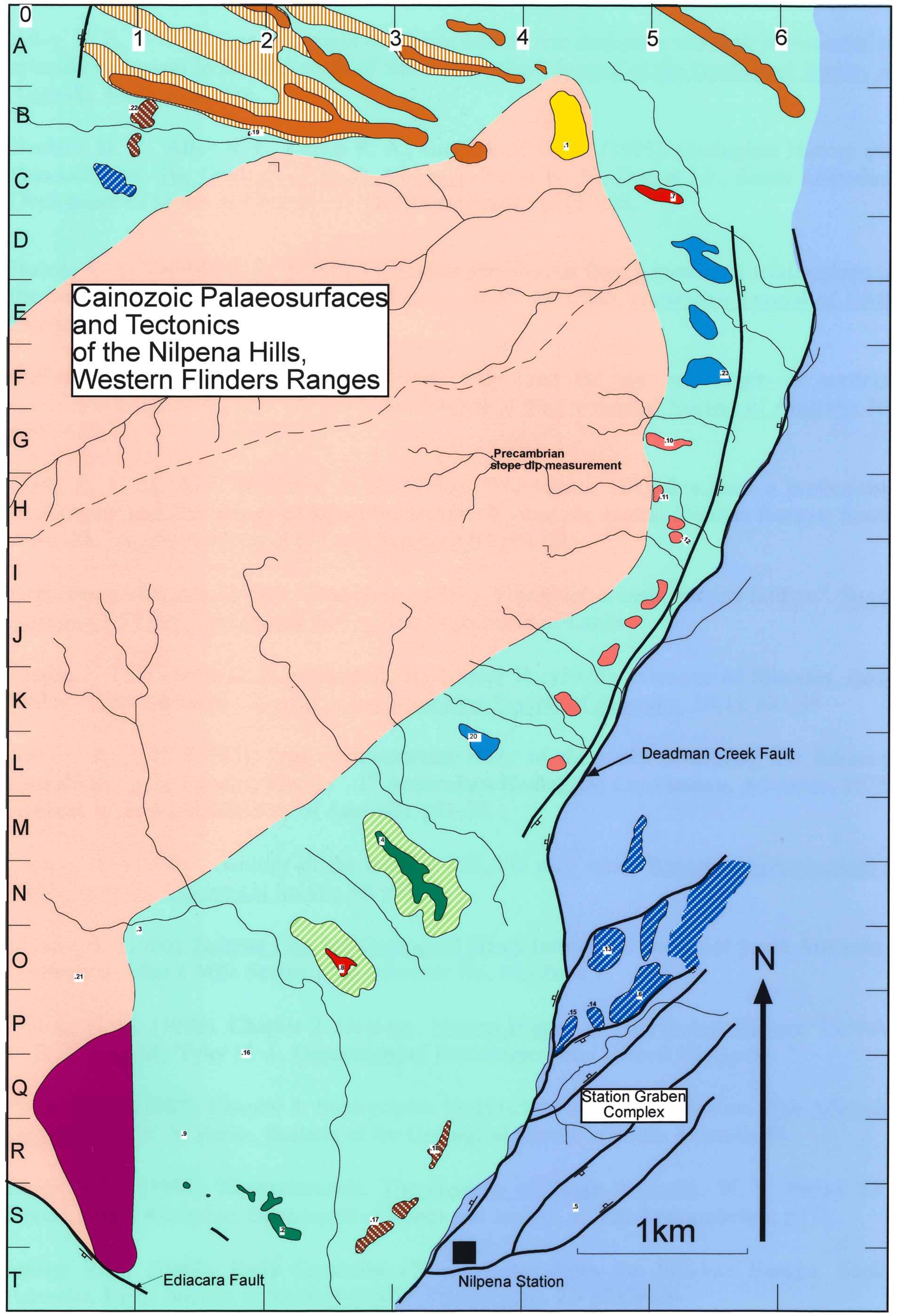
Cambrian (Parachilna Formation)

Sand dunes

Weathered lake sediments

Note: Surface J East and Surface J West are separated by Deadman Creek Fault and an elevation difference of about two metres with the eastern surface being the higher surface. This difference decreases northwards along Deadman Creek Fault.

Plate 4



References

Alley, N. F., (1977). "Age and origin of laterite and silcrete duricrusts and their relationship to episodic tectonism in the mid-north of South Australia." Journal of the Geological Society of Australia **24**(2): p107-116.

Benbow M. C., Alley N. F., Callen R. A., Greenwood D. R., (1995). Geological History and Palaeoclimate. The Geology of South Australia. Preiss W. V., Drexel J.F., South Australian Department of Mines and Energy. **2: The Phanerozoic:** p208-218.

Bourne J. A., Twidale C. R., (1998). Pediments and alluvial fans: genesis and relationships in the western piedmont of the Flinders Ranges, South Australia. Australian Journal of Earth Sciences. **45**, p123-135

Callen R. A., (1983). Late Tertiary 'grey billy' and the age and origin of surficial silicifications (silcrete) in South Australia. Journal of the Geological Society of Australia **30**: p393-410.

Cock, B. J., M. A. J. Williams, et al., (1999). "Pleistocene Lake Brachina: a preliminary stratigraphy and chronology of lacustrine sediments from the central Flinders Ranges, South Australia." Australian Journal of Earth Sciences **46**: p61-69.

Department of Lands, (1990). "Warrioota, 6536-3, Topographic Map, Second Edition". South Australia 1:50 000 Topographic Series. The Department of Lands.

Hutton J. T., Twidale C. R., Milnes A. R., Rosser H., (1972). "Genesis of Silcretes, Beda Valley, South Australia". Journal of the Geological Society of Australia. **19**(1): p31-39

Jenkins R. J. F., (1975). "An environmental study of the rocks containing the Ediacara assemblage in the Flinders Ranges". **1st Australian Geological Convention, Adelaide, 1975. Abstracts**. Geological Society of Australia, p21-22.

Leeson, B., (1970). "Geology of the Beltana 1:63,360 map area." Report of Investigations - South Australia, Geological Survey **35**: p92.

Leeson, B., (1966). Beltana 1:63,360 Geological Sheet. Geological Survey of South Australia. **Geological Atlas 1 Mile Series**. Map reference No. 696 Zone 5.

Lemon, N. M. (1996). Chapter 2: Geology. Natural History of the Flinders Ranges. Twidale C. R., Davies M., Tyler M. J., Department of Environment and Natural Resources. **7**.

Preiss W.V., (1987). Chapter 3: Stratigraphic Nomenclature and Classification. The Adelaide Geosyncline. W. V. Preiss, Bulletin of the Geological Survey of South Australia **54**.

Preiss W.V., (1993). Neoproterozoic. The Geology of South Australia. W. V. Preiss. J.F. Drexel, South Australian Department of Mines and Energy. **1: The Precambrian:** p171.

Sprigg R.C., (1947). Early Cambrian (?) jellyfishes from the Flinders Ranges. South Australia. Royal Society of South Australia. Transactions. **71**: p212-224

Twidale C. R., Bourne J. A. (1996). Chapter 5: The Development of the Land Surface. Natural History of the Flinders Ranges. Twidale C. R., Davies M., Tyler M. J., Department of Environment and Natural Resources. **7**.

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Appendix 1

X-ray Diffraction Analysis Results

The results for the XRD analysis are contained in the following table.

SAMPLE NO.	LOCATION DESCRIPTION	MAJOR MINERALS	MINOR MINERALS
1	Sugar Loaf sample 1	Quartz, Glauconite	Feldspar
2a	Sugar Loaf sample 2a – Fine material	Quartz, Glauconite, Montmorillonite	Calcite
2b	Sugar Loaf sample 2b – Nodular material	Calcite, Quartz	Feldspar, Smectite
3	Sugar Loaf sample 3	Quartz	Goethite, Illite
4a	Sugar Loaf sample 4a – Fine material	Quartz, Gypsum	Glauconite, Illite
4b	Sugar Loaf sample 4b – Nodular material	Calcite, Quartz	Glauconite, Illite, Montmorillonite, Smectite
5	Sugar Loaf sample 5	Gypsum	Calcite, Quartz, Smectite
7	White nodules found with laterite, Northern dunes	Kaolinite, Quartz	Smectite?
8	500m west of East bore	Gypsum, Kaolinite	Quartz
9	Gully cut near camp	Glauconite, Quartz	Feldspar
12	‘Calcrete’ high creek cut	Calcite	Glauconite, Illite, Quartz
13	Strange black ‘calcrete’, surficial layer found in many areas	Calcite	Glauconite, Quartz
21	Crust near top of white Bluff	Gypsum	None discernible

Figure. Appdx 1.1

Appendix 2

Surface lithologies – clasts and matrix

Surface 1.

This surface can be broadly described as a silcreted surface. It consists of angular to sub-rounded, quartzite or sandstone clasts with a silcrete coating on some clasts. The clasts are fifty percent pebbles, thirty five percent cobbles, ten percent boulders and less than ten percent granules. The silcrete coating is white to light grey but yellow-brown examples can be found. The quartzite clasts are derived from the Precambrian Rawnsley Quartzite. The pebbles and cobbles are matrix supported. The matrix is a red-brown sandy clay matrix and is calcareous.

Surface 2.

The clasts on this surface consisted of calcrete particles to calcrete cobbles. There were occasional ironstone pebbles. There was a small amount of Aboriginal stone tools. Most of the calcrete clasts were less than two centimetres in diameter. The matrix was a deep pink calcareous clay sand. The surface was matrix supported with patches of small (<2cm) calcrete clasts. The calcrete was white to pale pink-brown which was probably a reflection of the matrix. The calcrete clasts were angular while the ironstones were rounded.

Surface 3, Surface 4 and Surface 20

These surfaces consist of sandstone or quartzite cobbles, pebbles and boulders. There is no significant indication of silcrete. The proportion of sizes of clasts is similar to that of surface 1. The matrix is a red-brown sandy clay and is calcareous. These surface sit on top of a mottled ‘large honey comb’ calcrete. There is no calcrete on the surfaces.

Surface 5 and Surface 9

These surfaces are very similar to surfaces 3 and 4 but also contains ferruginised sandstone and quartzite as well as some ironstones. The clasts are angular to sub-rounded.

Surface 6, Surface 17 and Surface 18

These surfaces are strongly armoured surfaces. They have ferruginised cobbles, pebbles and boulders on a tile-work of small pebbles and boulders. The clasts are ferruginised sandstone and quartzite. The clasts are rounded to sub-angular. The matrix is a red-brown sandy clay.

Surface 7

This surface has sandstone and quartzite clasts of cobble to pebble size with some evidence of silcrete. There is an even mix of clast and matrix with the matrix being a red-brown clay sand. The clasts are angular to sub-rounded. This surface also sits on top of a mottled 'large honey comb' calcrete similar to surfaces 3 and 4.

Surface 8

The surface consists of sandstone and quartzite cobbles, pebbles and boulders and has evidence of silcrete. There is a balance between matrix and clasts with the matrix being a red-brown sandy clay. The matrix is calcareous.

Surface 10 and Surface 11

These are silcreted surfaces with silcreted cobbles, pebbles and boulders of quartzite and sandstone. They are matrix supported and the matrix is a red-brown sandy clay. These surfaces also sit above mottled 'large honey comb' calcrete.

Surface 12

Surface 12 is a ferruginised equivalent of surfaces 10 and 11. There is a lesser extent of silcrete and there are smaller and more numerous clasts.

Surface 13, Surface 14 and Surface 15

These surfaces have ferruginised cobbles and pebbles of sandstone, quartzite and siltstone. They are clast supported with a red-brown sandy clay.

Surface 16

This surface has ferruginised cobbles and pebbles, with rare boulders, of sandstone and quartzite. It is clast supported in a matrix of red-brown clay sand. There are some silcreted pebbles and calcrete cobbles.

Surface 19

This surface has ferruginised ironstone granules and cobbles in a matrix of red-brown clay sand. It is clast supported. This surface may not have been properly preserved or may be an outwash fan.

Surface 21 and Surface 23

These surfaces have cobbles, pebbles and boulders of slightly silcreted quartzite and sandstone. They are matrix supported and have a red brown clay matrix, which has significantly less sand.

Surface 22

This is a highly ferruginised surface with ironstone granules, pebbles and cobbles in a matrix of red-brown clay sand. The surface is clast supported and forms a smooth pavement.