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A REGRESSIVE TERTIARY LAKE SYSTEM AND SILICIFIED STRANDLINES, BILLA KALINA AREA, SOUTH AUSTRALIA.

GEOLOGICAL SURVEY

by

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CONTENTS PAGE

FIGURES

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ABSTRACT

A system of parallel arcuate ridges dominates the topography of the Billa Kalina area; facies relationships indicate that they are silicified strandlines of a Miocene lake which have been etched out by later erosion. Clays and dolomites of the Miocene Etadunna Formation were deposited in the distal portion of the lake which at its peak was over 100 km wide.

An initially wet climate was replaced by increased aridity culminating in evaporitic conditions. Climatic deterioration initiated regression of the lake shoreline which is recorded by upward coarsening sequences. In the east, the lake contracted large distances over an essentially flat landsurface in contrast to the north and west, where a higher steeper terrain limited regression. During still-stands shorelines were foci of silica and calcite cementation from laterally moving groundwaters; there is evidence of penecontemporaneous reworking of silica and calcite cemented sediments.

To the north and west of the lake coarse-grained terrestrial sediments of the Mount Sarah Sandstone were deposited. These rocks are strongly silicified to "grey billy" silcrete and correlate with similar silcreted sandstones intertonguing with the Etadunna Formation. The main silcrete of the Billa Kalina area is late Tertiary in age and is unrelated to a deep weathering profile developed in underlying sediments.

INTRODUCTION

This paper describes the Tertiary geology of a 50 000 km^2 area to the west and northwest of Lake Torrens in northern South Australia (Fig. 1). Field data were gathered during mapping BILLA KALINA 1:250 000 map sheet and during brief excursions onto neighbouring CURDIMURKA, ANDAMOOKA and KINGOONYA 1:250 000 map sheets.

The depositional record of the Tertiary in northern South Australia has been previously regarded as comprising two comparatively thin sequences, the earliest being a Palaeocene-Eocene fluviatile sequence of sandstones named the Eyre Formation (Wopfner et. al., 1974). A later depositional phase, during the middle Miocene, resulted in a lacustrine sequence of clays and dolomites, namely the Etadunna Formation (Stirton et. al., 1961) and its equivalents. The ages of these units were estimated palynologically (Wopfner et. al., 1974; Callen and Tedford, 1976; Callen, 1977).

In the course of recent geological investigations Barnes and Pitt (1976a, b and c) have defined a sequence of sandstones, the Mount Sarah Sandstone, which outcrops extensively in northern South Australia. Their interpretation of the age of this unit as late Oligocene to early Pliocene was based mainly on the presence of reworked clasts of silicified Eyre Formation; a Miocene age was preferred because of a suspected intertonguing relationship with the Etadunna Formation. At present, Tertiary stratigraphy in South Australia is in a state of flux, largely as a result of the difficulty in distinguishing the Mount Sarah Sandstone and the Eyre Formation which are of similar lithology.

Inherent in these stratigraphic difficulties is the problem of resolving the age relationships of Tertiary silcretes. Until recently two distinct phases of silcrete were recognised in northern South Australia during the Tertiary: a late Eocene-Oligocene phase which strongly affected the Eyre Formation and was associated with deep weathering, and a later ?Plio-Pleistocene phase (Wopfner, 1974 and 1978). However, the recognition of a late Tertiary silcrete, commonly formed at the top of the Mount Sarah Sandstone, has complicated this picture, especially considering that this silcrete has a typical "grey billy"[1] appearance which is also characteristic of the Eocene-Oligocene silcrete.

1. The term "grey billy" is applied to massive, greyish rocks comprised mainly of host quartz clasts of various sizes, cemented by a matrix of cryptocrystalline quartz or amorphous silica; appearance and texture are variable but conchoidal fracture and a smooth 'pillowed' surface are characteristic.

This paper presents new data from the Billa Kalina area which sheds some light on the general problems surrounding Tertiary stratigraphy and silcretes in northern South Australia. In particular, in the Billa Kalina area there is a series of silcrete capped, arcuate ridges covering an area of 25 000 km^2 (Fig. 1). The stratigraphy, age and origin of these ridges have been variously interpreted by a number of workers (Webb and Wopfner, 1961; Jessup and Norris, 1971; Murrell, 1977). This paper presents a new explanation for the origin of the ridges which has important implications for the stratigraphy and palaeoenvironment of Tertiary sediments in this region.

STRATIGRAPHY

The study area comprises three geomorphic divisions: Millers Creek plateau (informal name), the Stuart Range and a system of arcuate ridges (Fig. 1). The stratigraphy of these areas is discussed separately although they have much in common. Millers Creek plateau occupies an area of approximately 15 km^2 and is bounded on its eastern and southern margins by scarps up to 20 m high. These excellent sections provide a stratigraphic framework for the Tertiary geology of the region as a whole.

Millers Creek plateau

The Tertiary sequence at Millers Creek plateau is flat lying and disconformably overlies Cretaceous and Permian sediments. The thickest exposed Tertiary section, about 13 m, is on the eastern margin of the plateau (Fig. 2, Loc. A; Fig. 3, Section A). Dolomites and dolomitic limestones at the top of the section form a cap to the plateau and are underlain by dolomitic palygorskite clays (at the 18 m level in Section A). The lower part of the section comprises soft, dolomitic green clays containing scattered quartz grains.

The carbonates capping the plateau are mainly dolomite and dolomitic limestone with minor limestone. Secondary coarse-grained calcite fills veins and cracks resulting in fragmental textures (Fig. 4) and in places fine-grained calcite has replaced the sediment forming caliche. The presence of dolomite pebbles in some of the carbonates suggests pene-contemporaneous reworking. Pebbly, sandy limestones exposed on the southwest margin of the plateau contain clasts of earlier cemented calcite and quartz sand, strongly resembling tufa. Relict algal textures occur in some of the carbonates (Whitehead, 1970) and minor silicified wood is present in the underlying green clays but to date no diagnostic fossils have been identified.

On the southern margin of the plateau (Fig. 2, Locs. B and C) the dolomite-green clay sequence grades down into a pebbly conglomeratic sandstone up to 1 m thick (Fig. 3, Sections B and C). This sandstone is coarse-grained and poorly-sorted, containing rounded cobbles and boulders of laminated quartzite, milky quartz granules and pebbles, minor silcrete pebbles and rare black chert granules. The sandstones are variably silicified and silcrete is occasionally exposed in scarps bounding the plateau but occurs more prominently as flat silcrete ramparts abutting the scarps. Silicification of the sandstone has formed a typical "grey billy" silcrete exhibiting "free floating" textures wherein quartz sand and pebbles are suspended in a fine crypto-crystalline silica cement. On the southwestern margin of the plateau the silcrete contains scattered plant fragments.

Lateral transitions from silicified sandstone to non-silicified sandstone are observed on a mesoscopic scale. For example at Moodlampie Hill (Fig. 2, Loc. C), a silicified conglomeratic sandstone passes laterally within a few metres into an unsilicified argillaceous gritty sandstone containing rounded quartzite clasts (Fig. 3, Section C). Transitions from silicified to calcite cemented sandstones also occur on a mesoscopic scale and are best observed on the southeastern margin of the plateau (e.g. Fig. 3, Section B).

Small outcrops of ferruginous silcrete are prominent on the northern and western margins of Millers Creek plateau e.g. 7 km northwest of "Millers Creek". These outcrops comprise silicified and ferruginised quartz sandstone containing numerous polished silcrete pebbles and locally abundant plant material (Fig. 5). One kilometre north-northwest of Moodlampie Hill (Fig. 2, Loc. D) this unit overlies soft green clays identical to those occurring beneath the dolomites in Sections A, B and C. At the same locality ferruginous silcrete pebble conglomerates grade into massive "grey billy" silcretes comprising silicified coarse quartz sandstone containing rounded quartzite clasts and minor silcrete pebbles.

In summary the sequence at Millers Creek plateau comprises mainly green clays and carbonates which grade into variably silicified pebbly sandstones and conglomerates at the base. Ferruginous, silicified, silcrete pebble conglomerates intertongue with this sequence.

<u>Stuart Range</u>

In the Billa Kalina area the Stuart Range consists of dissected tableland country which rises 50-60 m above the level of Millers Creek plateau. A thin blanket of silicified Tertiary sediments cap deeply weathered Cretaceous shales and siltstones. Dissection of the Tertiary landsurface has resulted in silcrete-capped mesas, cuestas and ridges rising 30-40 m above the surrounding gibber plains (e.g. Danae Hill and Serrated Range). Silcrete outcrop is most prominent along the upper edges of escarpments.

The Tertiary sequence is less than 2 m thick and comprises medium to coarse-grained gritty sandstones containing rounded milky quartz granules, silcrete pebbles and cobbles, bleached shale fragments and more rarely cobbles and boulders of laminated quartzite, the latter reworked from the underlying boulder-bearing Cretaceous shales. The sandstones often contain very fine, angular interstitial quartz (0.05-0.1 mm). Silcrete clasts are common and pebbles, which predominate, are usually polished whilst larger sizes are generally dull (Fig. 6). Silicification of clays on some of the mesas has produce porcellanites while quartzose "grey billy" silcretes typify coarse-grained sandstones.

A weathering profile, developed in Cretaceous shales beneath the silcrete, varies in thickness up to a maximum of 30 m. The upper few metres of this profile usually comprises porcellanitic shales which grade down in bleached, kaolinitic shales up to 15 m thick. In places a multicoloured zone incorporating pale yellow, pink and maroon shales veined by alunite and gypsum underlies the upper bleached zone. Below this weathered profile, usually exposed in the lower parts of escarpments, are fresh, dark-grey Cretaceous shales.

<u>Arcuate Ridges</u>

A conspicuous system of concentric, silcrete-capped ridges developed west and northwest of Lake Torrens trend northwards for 130 km across CURDIMURKA, KINGOONYA and ANDAMOOKA 1:250 000 map sheet areas onto the southeast corner of BILLA KALINA (Fig. 1). The ridges have a distinctive arcuate form with the centre of curvature to the west, and this is readily observed on LANDSAT imagery of the area (Fig. 7). A Pleistocene-Holocene aeolian dune system is superimposed on the ridges, approximately at right angles (Fig. 7).

Although the ridges are shown as regular trends on ANDAMOOKA (Johns et. al., 1966) they demonstrate considerable variation in width, height and separation. At Emu Bluff (Fig. 1) active erosion has resulted in clear definition of flat-topped ridges which rise 30-40 m above adjacent water courses; the ridges have a width of 100-1000 m and separation of 200-300 m. Further south, less vigorous erosion has formed a more subdued topography; small playa lakes and claypans occupy shallow depressions between low ridges which are less than 300 m apart. On a partly dissected plateau northwest of Ferguson Hill (Figs 1 and 7, Loc. F) the ridges are not well defined except around the eastern margin. On this margin parallel, modern watercourses are eroding the plateau forming elongate, tongue shaped valleys bounded by complimentary, parallel silcrete capped ridges. The surface of the plateau is slightly undulating and inter-ridge depressions are infilled by younger sediment which may record an earlier period of erosion. Certainly the evolution of the ridges by differential erosion has a complex history and is continuing now.

Capping the ridges are flat-lying sediments which vary in thickness from 5 m in the west to 5-10 m farther east. In the vicinity of Stuart Creek Opal Field, Vnuk (1978) estimates that their pre-erosion thickness exceeded 30 m. The caprocks disconformably overlie flat lying Cretaceous Bulldog Shale in the north, but contiguous ridge lines are superimposed on Cambrian rocks to the south (Johns et. al.,1966).

The caprocks are lithologically variable, poorly-sorted conglomeratic sandstones predominate, containing silcrete cobbles, pebbles and grains, quartz granules and pebbles and more rarely cobbles and boulders of quartzite (Fig. 8). All of the clasts are well-rounded and granule to pebble size silcrete and quartz clasts are polished. The host rock is usually rounded to sub-rounded coarse quartz sandstone often containing an abundance of fine (0.02-0.05 mm), angular interstitial quartz. Thin siltstone laminae, displaying graded bedding and small tubular structures of probable pedogenic origin, are interlayered with these coarse-grained sediments. Irregular masses of silty and sandy limestone containing reworked silcrete clasts intertongue with the sandstones although the two lithologies are sometimes interlayed (Fig. 9).

The fossil record of the ridge caprocks has not been fully evaluated although scattered plant fragments have been observed. A well preserved flora occurs in silicified, well-sorted and cross-bedded sandstones which crop out in a zone along the banks of Stuart Creek, hereafter referred to as the Stuart Creek fossil locality (Fig. 1, Loc. E). Some details of the flora and lithologies are in Ambrose et. al., (1979). It was concluded the sediments belong to the same sedimentary cycle as the sequence on adjacent arcuate ridges (e.g. Fig. 3, Section F) despite the fact that these sediments are topographically higher.

With the exception of some easternmost ridges the sequences on the ridges generally coarsen upwards. Capping a ridge 3 km west of Saddle Hill (Fig. 1) is a sequence comprising 3 m of fine to medium-grained, cross-bedded sandstone which passes upwards into 3.5 m of pebbly grit. A similar upward coarsening silt-sand-conglomerate sequence, 5.7 m thick, caps arcuate ridges 6 km west-northwest of Ferguson Hill (Fig. 3, Section F). Vnuk (1978) describes a section 5.8 m thick, 5 km west of Stuart Creek Opal Field, where basal brown clays and minor silts pass up into silts and sands with coarse pebbly sands near the top. Sequences on the easternmost ridges sometimes contain a basal conglomerate. For example at Stuart Creek Opal Field, the ridge caprocks comprise 5-10 m of uniform coarse-grained, cross-bedded quartz sands with a basal quartz granule and silcrete pebble conglomerate (Barnes and Scott, 1979). Near Charlie Swamp the sequence laps onto Proterozoic quartzites and comprises mainly sands and a basal conglomerate containing quartzite and silcrete clasts (Nichol, 1979).

The ridge caprocks are variably altered by silicification, calcification and ferruginisation. Silcretes predominate and these vary widely in texture, composition and general appearance (Fig. 11). Hard, massive "grey billy" silcretes are most common and a number of phases of cementation are recognised (Whitehead, 1978a and b), the earliest and most dominant of which is a microcrystalline-cryptocrystalline silica cement often stained by brown titanium oxide (?anatase). A later chalcedonic cement, frequently fibrous, infills voids and cavities. At Stuart Creek Opal Field sandstone caprocks are cemented by opaline silica and patches of potch opal have been observed within this sandstone (Barnes and Scott, 1979). Quartz overgrowth and chalcedonic silcretes are widespread on the ridges but sub-dominant. A sample of silcrete from a ridge near Charlie Swamp is silicified by quartz grain overgrowths, but in the same sample many of the interstices are filled by fine-grained, fibrous chalcedonic quartz (Whitehead, 1978a). Wopfner (1978) recognises three major periods of silcrete formation in northern South Australia and attemps to correlate these with broad categories of silcrete based in part on different mineralogic forms of silica. As described above a number of mineralogic forms of silica are recognised in silcretes capping the arcuate ridges and these forms show rapid lateral variations. It is apparent Wopfner's categorisation is not valid in this area and its applicability elsewhere in northern South Australia is doubtful.

The ridge caprocks are ferruginised in part, particularly friable sandstones occurring on the eastern portion of the ridge system. The silcretes are occasionally ferruginous, and evidence presented by Whitehead (1978a) suggests the earliest ferruginisation occurred prior to silicification in some localities.

Sediments cemented by calcium carbonate are widespread on the ridges but are less prominent than silcrete. Rocks cemented by multiphase calcite resemble caliche and tufa; both rock types incorporate reworked silcrete clasts. The complex relationship between calcite and silica cements is demonstrated in a sample from a ridge near Charlie Swamp. The rock, described by Whitehead (1978b), is a fine-grained sandstone with zones of calcite and silica cementation. The boundary between the calcareous and siliceous zones is irregular and gradational over 2-3 mm. In this transition zone there are small isolated patches of calcite in optical continuity with larger masses of calcite but separated by zones of fibrous chalcedony up to 0.1 mm wide. This evidence suggests silica has replaced calcite.

A similar sandstone, also from Charlie Swamp, is variably cemented by chalcedonic to microcrystalline quartz and very fine-grained calcite (Whitehead, 1978a). The fine-grained calcite merges with turbid layers of calcite, characteristic of caliche, which encrust the surface of the sandstone. Some interstices are lined with a colloform layer of chalcedonic quartz while the interior of the interstices contain calcite which appears to have crystallised after the quartz. Alternatively some interstices are lined by calcite overlain by chalcedonic or microcrystalline quartz with another layer of calcite formed in the interior of the interstice. Whitehead (1978a) concluded there was alternation in crystallisation of calcite and quartz with no great age difference between them.

Many of the sediments record several phases of calcite cementation and contain clasts of earlier cemented calcite. One example from a ridge on northern ANDAMOOKA contains a clast of fine-grained carbonate (?dolomite) which has been fractured and then recemented by coarse-grained calcite; an earlier and later phase of calcite cementation are recognised in the same sample (Steveson, 1978).

CORRELATION AND REGIONAL RELATIONSHIPS

The clays and dolomites at Millers Creek plateau were first described by Jessup and Norris (1971). On the basis of strong lithologic similarity they correlated the sequence with the Etadunna Formation from Lake Palankarinna 250 km to the northeast (Fig. 13). Pebbly sandstones and conglomerates, which intertongue with the sequence at Millers Creek plateau, have not been previously described. These coarse-grained sediments are lithologically similar to the Mount Sarah Sandstone which in its type section at Mount Sarah (Fig. 13) comprises 25 m of fine to very coarse quartz sandstones containing polished silcrete pebbles. The upper part is usually strongly silicified to a "grey billy" silcrete. Intertonguing between the Mount Sarah Sandstone and Etadunna Formation was suggested by Barnes and Pitt (1976a and 1977) but evidence was limited. Our observations at Millers Creek plateau provide data supporting intertonguing between the two units. A medial Miocene age has been determined palynologically for the basal Etadunna Formation and its equivalents (Wopfner et. al., 1974; Callen and Tedford, 1976) and a similar age is adopted for the Mount Sarah Sandstone.

Unnamed ferruginised silicified, silcrete pebble conglomerates which outcrop sporadically at Millers Creek plateau correlate with the Mirackina Conglomerate (Barnes and Pitt, 1976). This unit is a channel facies of the Mount Sarah Sandstone which occurs within the Mirackina Palaeochannel (Fig. 13).

Jessup and Norris (1971) considered silcreted sandstones capping the Stuart Range to be of early Tertiary age and they suggested later warping and erosion gave rise to shallow basins in which lacustrine sediments of the Etadunna Formation accumulated. Similarly Wopfner et al. (1974a) considered the silcretes to be upwarped equivalents of the Palaeocene-Eocene Eyre Formation which were silicified in the late Eocene-Oligocene. Despite some lithological affinities with the Eyre Formation we consider the sequence on the Stuart Range correlates more readily on a lithological basis with the Mount Sarah Sandstone equivalents at Millers Creek plateau. Silcrete clasts are common in both areas and these probably denote reworking of silicified Eyre Formation although remnants of this older silcrete horizon have not been identified in the study area.

The sequence capping the arcuate ridges includes pebbly sandstones of very similar lithology to the Mount Sarah Sandstone including the presence of reworked silcrete pebbles. Caliche and tufa which also form part of the sequence on the ridges and are lithologically similar to sediments in the Etadunna Formation equivalent at Millers Creek plateau. The sequences in these areas show common alteration and are variably cemented by silica, calcite and iron.

Thus a Miocene sequence equivalent to the Etadunna Formation and Mount Sarah Sandstone occurs at Millers Creek plateau and equivalent sediments occur to the north on the Stuart Range, and to the east on the system of arcuate ridges. These sequences have been variably silicified and "grey billy" silcrete is a feature of the three areas; the silcrete varies from a nodular "pseudo pebbly" appearance to a smooth, bulbous, whorled form with characteristic pillow structures (Fig. 11).

The Etadunna Formation correlates with several other units occurring in separated basins in northern South Australia. South-east of the Billa Kalina area in the Pirie-Torrens Basin (Fig. 13) over 100 m of Miocene clays and dolomites overlie early Tertiary sediments (Callen and Tedford, 1976). This relatively thick accumulation of Miocene sediments was probably facilitated by penecontemporaneous faulting associated with the Torrens Hinge Zone which separated this basin from the Billa Kalina area. The Namba Formation (Callen and Tedford, 1976) of the Tarkarooloo Basin in the Lake Frome area and the Garford Formation (Benbow and Pitt, 1978) which occurs in the Garford Palaeochannel (Fig. 13) are also correlatives of the Etadunna Formation. A palygorskite-sepiolite clay mineral assemblage is a useful criterion for correlating these units.

Silcrete is often associated with these sequences. Several boreholes in the Tarkarooloo Basin have intersected opaline "puddingstone" developed in clays at the top of the Namba Formation and brown silcrete is sometimes developed on sandy facies of this unit (Callen and Tedford, 1976). Locally in the Garford Palaeochannel there is a lateral gradation from palygorskite-dolomite clays into poorly sorted sandstones silicified to "grey billy" silcrete (Barnes and Pitt, 1977). The Alberga Limestone, which occurs several hundred kilometres north of the Billa Kalina area comprises chalcedonic limestone, dolomite, green clay and minor brown arenaceous limestone containing reworked silcrete pebbles (Freytag et al., 1967). Locally at Mount Alice (Fig. 13) the Mount Alice Conglomerate Member, a ferruginous, silicified silcrete pebble conglomerate, interfingers with the limestone (Freytag et al., 1967). Overall these lithologies and their interrelationships are similar to those described for the Billa Kalina area.

Thus, in the past extensive "grey billy" silcretes capping highlands such as the Stuart Range have generally been regarded as silicified, upwarped equivalents of the Palaeocene-Eocene Eyre Formation. However as described above, in widely separated areas of northern South Australia, different workers have noted an association between lacustrine sediments equivalent to the Etadunna Formation and silicified sandstones and conglomerates. Barnes and Pitt (1976a and 1977) consider equivalents of these sandstones may occur in highland areas in the absence of the Etadunna Formation. Our observations in the Billa Kalina area support this view and further promote the possibility of a late Tertiary age for at least part of similar extensive sandstone sheets elsewhere in the State, at present regarded as Eyre Formation.

PALAEOENVIRONMENT

The Mount Sarah Sandstone on the Stuart Range is interpreted to be largely colluvial-talus slope deposits with some fluviatile contribution. The sediments are characterised by coarse grain-size and poor-sorting, but there are minor well-sorted silt-clay facies containing rootlet moulds and small tubular structures of probable pedogenic origin. Close packed, silcrete clast-bearing sediments may have formed during in situ reworking of an earlier (?Eocene-Oligocene) silcrete. This thin blanket of terrestrial sediments formed in an area of moderately high topography to the north and west of Millers Creek plateau where, in a shallow depression, clays and dolomites of the Etadunna Formation were deposited contemporaneously. A lacustrine origin is well established for the clay-carbonate component of the Etadunna Formation and its equivalents elsewhere in South Australia (e.g. Stirton et al., 1961; Callen and Tedford, 1976; Callen, 1977) and the lithology and distribution of this unit at Millers Creek plateau are consistent with this view. Sandstones and conglomerates intertonguing with the clays and dolomites denote influxes of fluviatile sediments and stream channels are indicated by linearly arranged outcrops of silcrete pebble conglomerate.

Intertonguing between coarse terrestrial sediments, typical of the Stuart Range, and the lacustrine sequence occurs 9 km north-north-west of "Millers Creek". Here flat-lying dolomites abut a low rise of Cretaceous shales capped by coarse-grained, silicified conglomerate; on the down slope of this low rise conglomerates intertongue with the carbonates.

The nature of the sediments capping the arcuate ridges has been discussed by a number of workers who were mainly concerned with the reason for their arcuate distribution. Webb and Wopfner (1961) interpreted the ridges as lake shoreline dunes developed along former shorelines of a chain of small lakes lying to the west, now represented by Devil's Playground, Bamboo Swamp and Curdlawidny Lagoon (Fig. 2). A Plio-Pleistocene age was allocated following their observation that "low ridges defining the lineations ..... are perched on top of some of the duricrust ridges". On ANDAMOOKA (Johns et al., 1966) the ridges are interpreted as an old silicified and kunkarised dune system overlying duricrusted Tertiary sediments. Sprigg (1978) tentatively adopts this interpretation in a discussion of prevailing wind directions and their control of Australia's principle dune deserts and lunette systems. The present study shows that the ridges are composed of, rather than overlie, Tertiary duricrust and that the lithologies on the ridges are inconsistent with aeolian sediments. A further interpretation was presented by Jessup and Norris (1971). They concluded that differential erosion of dipping, lithologically variable units of the Bulldog Shale (Cretaceous) resulted in accumulation of thicker Tertiary fluviatile deposits in shallow valleys between ridges. These deposits were massively silcreted compared with the adjacent thinner fluvial sediments which were only weakly silicified. Subsequent erosion stripped the latter effectively inverting the original topography as only the thicker, more massively silicified strips remained. This interpretation is unlikely considering the Bulldog Shale is essentially flat-lying and lacks any evidence of regular lithological variations. Also the fact that the ridges are developed on Cambrian sediments on southern ANDAMOOKA detracts from this hypothesis. Murrell (1977) believes the ridges reflect lineaments formed by differential erosion of folded,steeply dipping lower Proterozoic quartzites. He reports a steeply dipping weathered sequence from a locality 20 km southwest of Saddle Hill and suggests thin quartzites within this sequence have controlled the erosion of weathered material. Although this locality has not been visited, numerous observations to the north and west show that sediments on and below the ridges are flat-lying. Furthermore, if these are strike ridges, they reflect an extraordinarily large and uniform structure quite out of character with fold patterns of lower Proterozoic rocks elsewhere in the State. It is concluded Murrell's suggestion has little supportive evidence. Barnes and Scott (1979) suggest the ridge caprocks are of fluviatile origin and both they and Forbes (1977) suspected a relationship with sediments at Millers Creek plateau but did not elaborate.

We have already established that the ridges have evolved by erosion of caprocks which correlate with a Miocene sequence at Millers Creek plateau. The main questions to be answered are (1) how were the ridge caprocks deposited, and (2) what factors have caused them to be differentially eroded in such a regular manner?

In the following discussion we will demonstrate that the caprocks are silicified strandline deposits related to regression of a shallow lake which at its peak extended at least as far east as Charlie Swamp. In this locality the lake lapped out onto upfaulted, folded late Proterozoic Adelaidean rocks. Lacustrine sedimentation focussed at Millers Creek plateau where deposition of the Etadunna Formation dominated. Westerly migration of the lake's eastern shoreline resulted from a period of increased aridity which initiated regressive sedimentation patterns. Successive shorelines during pauses in this regression were major foci of silicification with silica transported laterally by groundwaters, possibly as a gel. Thus there developed continuous linear variations in hardness parallel to the shoreline and later, differential erosion etched out the ridges.

A number of macroscopic features support a strandline origin. The circumferential occurrence of the ridges around Millers Creek plateau suggests a genetic connection. This is well demonstrated on LANDSAT Imagery of the area (Fig. 7) as is the convergence of ridge trendlines (Fig. 7, Loc. G) in a manner similar to Pleistocene shoreline dunes of southeastern South Australia (Sprigg, 1959). The latter feature results from shorelines truncating slightly older, curved strandlines formed in embayments.

The lithologies of the ridge caprocks are also consistent with a regressive lacustrine sequence. The presence of minor limestones suggests a lacustrine and/or spring influence and the preponderance of upward coarsening sequences is consistent with a regressing shoreline. A typical sequence is exposed on a ridge 6 km west-northwest of Ferguson Hill. Basal siltstones, which disconformably overlie bleached Cretaceous shales, pass up into well-sorted, cross-bedded sandstones, some of the current directions parallelling the strike of the ridges. These sandstones probably represent beach deposits or off-shore bars deposited by longshore currents. Uppermost poorly-sorted, pebbly sandstones denote the final regressive phase of sedimentation; these sediments may be lags formed on beaches or behind lunettes (subsequently eroded) where there was some fluvial contribution. Many of the sandstones and interbedded siltstones possess pedogenic features suggesting phases of soil development during periods of non-deposition. The ridge sediments have similarities with abandoned shoreline sediments around Lake George in New South Wales described by Coventry (1976). These form curved ridges comprising poorly to well-sorted, rounded gravel interbedded with varying amounts of well-sorted medium to very coarse sand and finer sediments.

As the lake contracted westwards shallow lagoons probably existed for a period of time behind the actual shoreline and as these dried up gypsum precipitated. On Emu Bluff and several adjacent arcuate ridges, silcreted clayey siltstones contain moulds of tabular gypsum crystals which are partly infilled by later calcite (Fig. 10). The habit and shape of the crystals suggest they grew within the sediment under saline conditions (Cody, 1976) probably by syngenetic evaporative precipitation from groundwaters. The Mg/Ca ratios of these groundwaters would be increased due to the loss of Ca via the precipitation of gypsum. Mg-enriched groundwaters percolating down gradient towards Millers Creek plateau and mixing with lake waters could have facilitated either direct precipitation of dolomite or early diagenetic replacement of calcite. Later phases of calcite cementation may have occurred in the lagoons as the watertable fluctuated. Springs may have been periodically active on the lake's margins; some of the limestones contain calcite intraclasts and resemble tufa. Certainly the sediments record a complex hydrologic history.

On the eastern margin of the ridge system some of the capping sequences fine upwards and show a greater thickness variation than occurs to the west. Barnes and Scott (1979) and Nichol (1979) consider these sequences are mainly fluviatile and this interpretation is consistent with increased stream activity on the margins of the basin closer to source areas. In the vicinity of Stuart

Creek Opal Field, the bleached profile at the top of the Cretaceous sequence (approximately 30 m thick) has been completely removed by fluviatile activity associated with deposition of sandstones containing bleached and silicified shale fragments (Barnes and Scott, 1979).

At the Stuart Creek fossil locality cross-bedded, fossiliferous sandstones are interpreted as fluviatile sediments deposited by a low energy meandering river, the course of which was perhaps controlled by the same linear structure which today defines the course of Stuart Creek. The sandstones are topographically lower than sediments on adjacent arcuate ridges which may reflect lowering of base level and incision of earlier formed shorelines. Similar cross-bedded sandstones have been observed some distance to the west but have not been traced continuously to Millers Creek plateau. It is uncertain whether the ancestral stream reached the lake centre or ponded behind an older lake shoreline.

Overall the ridge sediments record a number of facies: lacustrine, shoreline, lagoonal, and fluviatile. Figure 14 is a generalised diagram demonstrating facies inter-relationships. The regression of the shallow lake produced a thin sedimentary record with subtle facies changes, probably complicated by minor shoreline oscillations, and these are not depicted in Fig. 14.

The trend of the easternmost arcuate ridges sub-parallels that of the Torrens Hinge Zone, a regional fracture zone which played an important role in determining the eastern shoreline configuration in addition to controlling regional drainage gradients. Westerly gradients were low and the vast distances over which the lake contracted together with the uniform, parallel development of its strandlines, imply a relatively flat and stable pre-Miocene topography. The uniform thinness of the Miocene sequence also reflects basinal stability. However a northerly trending lineament, immediately west of Emu Bluff, may have been active during sedimentation, facilitating a slightly thicker accumulation of lacustrine sediments at Millers Creek plateau.

Arcuate ridges are notably absent to the north and west of Millers Creek plateau. This is attributed to a high, irregular palaeotopography in this area. Because of the steep gradients, the lake's extent was limited hence during regression the western shoreline did not contract the large distances that it did to the east. Channel conglomerates and sandstones most commonly intertongue with lake sediments on the northern and western margins of Millers Creek plateau, suggesting source areas occurred to the north and west. Further evidence of the palaeotopography is supplied by the present day relief of the Stuart Range-Millers Creek plateau-arcuate ridge system (Fig. 15). Taking the surface of Millers Creek plateau as base level Figure 15 demonstrates that the flat tops of the arcuate ridges and that of the plateau form a concordant surface (with a gentle westerly dip of less than one degree) which mimics the Miocene depositional surface. The silcrete-capped surface of the Stuart Range is 50-70 m higher than Millers Creek plateau and this elevation difference may approximate that which existed during Miocene deposition (cf. Fig. 14).

Climate

Studies of faunal assemblages in the Etadunna Formation near Lake Eyre indicate subtropical conditions prevailed during deposition (Stirton et al., 1961, 1967 and 1968). Callen (1977), combining evidence from mineralogy, palynology and vertebrate palaeontology, suggests a warm high rainfall climate for the lower part of the Miocene sequence (Namba Formation) in the Tarkarooloo Basin at Lake Frome; palygorskite-dolomite rocks near the top of the sequence accumulated during dry intervals superposed on this climate. The palygorskite-dolomite assemblage also occurs in the upper part of the Etadunna Formation at Millers Creek plateau. This suggests that increasingly arid conditions prevailed during the latter stages of sedimentation. In addition there is evidence of evaporitic precipitation of gypsum in Miocene sediments on the arcuate ridges which is further indication of climatic deterioration instigating regression.

The dominant influences on climate during the Miocene were the continued northward "drift" of Australia and the continued development of the Antarctic ice cap (Kemp, 1978) although more rapid climatic fluctuations were probably superimposed on these broad trends. The flora in fossiliferous sandstones from the Stuart Creek fossil locality (Fig. 1, Loc. E) is briefly described by Lange in Ambrose et al., (1979). There are some xeromorphic forms in this flora but the most important discovery was that of Eucalyptus fruits. It was concluded this flora reflects greater floral diversification than has previously been documented in the Australian Palaeogene. During this period Australia was dominated by a wet tropical climate with zonation and vegetation diversification minimal (Kemp, 1978 and Kennett, 1978). Kemp (1978) also shows that in the Australian flora there is no evidence of pronounced cooling until the Oligocene, coinciding with the first sudden cooling in Antarctica which had just separated from Australia; vegetation during this period was of low diversity. The Miocene saw the development of a major Antarctic ice-cap and continued northward drift of Australia meant increasingly arid conditions to the north and northwest and vegetation became more diverse (Kemp, 1978). However, it is uncertain whether the climatic shift reflected in the Miocene sequence in the Billa Kalina area may be attributed to gradual change in palaeolatitude due to continental drift and/or build up of Antarctic ice, in preference to more rapid local climatic fluctuations.

There is evidence that the climatic shift affected adjacent centres of Miocene lacustrine deposition. In eastern South Australia strings of claypans, mesoplayas and watercourses parallel the eastern margins of Lakes Eyre, Callabonna and Frome. These lakes are underlain by Miocene sediments. Loffler and Sullivan (1979) suggest that the strings of claypans are depressions formed behind littoral shoreline dunes of a gradually diminishing lake of ?late Tertiary-Pleistocene age. Callen (pers. comm.) suggests that the same features are controlled by the presence of underlying ridge systems similar to those in the Billa Kalina area and of Late Miocene to Early Pleistocene age. Wopfner (1978) refers to the circumferential occurrence of silcrete around the southern margin of Lake Eyre; he suspected some genetic connection but did not elaborate. Wopfner considered these silcretes to be lower Tertiary but his description suggests they are similar to those on the Billa Kalina arcuate ridges. It is possible they have a similar age and origin.

SILICA AND CALCITE CEMENTATION

During the retreat of the Miocene lake in the Billa Kalina area, silicification focussed at shorelines during stillstands but was also prominent in channel-confined sediments. Silica was transported by lakeward percolating groundwaters until trapped by permeability barriers within lenticular beds or in channel fills. This permeability control is demonstrated at Millers Creek plateau where silicified conglomerates channel into unsilicified clays and dolomites. Silica may have precipitated from a gel where intermixing of lakewater and groundwater occurred; the thick 'custard-like' appearance of some silcretes (Fig. 11) is suggestive of formation from a gel. The Coorong in southern

South Australia is an example of a modern sedimentary environment in which silica is being deposited from a gel in association with Mg-rich minerals (Peterson and von der Borch, 1965). Changes in pH, largely seasonal, facilitated precipitation of gelatinous opal-cristobalite chert in addition to high Mg calcite, magnesite and dolomite.

On the ridges, silcretes are formed most commonly in coarse-grained pebbly sandstones at the top of the sequence. However, silcrete may occur irregularly through the sequence at different levels. For example at Stuart Creek Opal Field, Nichol (1979) records lenticular, semi-planar bodies of silcrete, several metres across, and formed at several levels in friable sandstones near the base of the Miocene section. The reason for this irregular silcrete development in a uniform lithology is uncertain but may result from precipitation of silica at centres of lowered pH. There are similarities with lenticular, multiple silcrete beds formed in the early Tertiary Glendower Formation in southwest Queensland (Senior and Senior, 1972) but these formed from silica-bearing groundwaters trapped by permeability barriers.

Fossiliferous quartz overgrowth silcretes from Stuart Creek fossil locality provide evidence of the onset of silicification. These silcretes contain excellently preserved plant material and have many similarities with fossiliferous silcretes from near Woomera described by Lange (1978). Lange describes preservation of very fine detail in the fossil plant material from Woomera (e.g. turgid epidermal cells and stomata) and suggests prompt development of a surface-contact film of silica. By analogy with these silcretes it is suggested the earliest phase of silicification of sediments at Stuart Creek and on the ridges was essentially synchronous with deposition. The time span of this silicification and possibility of later phases are uncertain although some features of the silcrete (e.g. columnar structures) suggest prolonged pedogenic activity.

Successive silicifications during still-stands would allow penecontemporaneous reworking of silcrete on shorelines and this could explain, to an extent, the abundance of reworked silcrete clasts. The rounded nature of the silcrete clasts need not imply long periods of reworking since the rounding may be in part inherited from nodular "pseudo pebbly" textures commonly developed in the silcrete. This could also explain the dominance of pebbles over other clast sizes. It is significant that Barnes and Pitt (1977) conclude that during deposition of the Mount Sarah Sandstone there were "many erosional breaks, periods of reworking, silicification and renewed deposition". In addition to penecontemporaneous reworking of Miocene silcrete, it is highly likely clasts of older silcrete (late Eocene-early Oligocene) are included in the Miocene sediments. However the proportion of older silcrete clasts to Miocene silcrete clasts is uncertain since there is no lithological distinction.

The source of silica is problematic. Paucity of quartz overgrowths suggests that silcrete was not, in general, derived through enlargement of original quartz grains. A small proportion of the quartz clasts display dissolution embayments, but it is unlikely the framework was a major source of silica. From a study of similar silcretes in New South Wales and Queensland, Watts (1978) concluded that dissolution within the main silcrete horizon accounted for less than 25 per cent of the total cryptocrystalline silica. Dissolution of quartz in ferruginous sandstones which cap many of the ridges may have provided a source of silica (Barnes and Scott, 1979) but confirmatory evidence is lacking. Silcrete formation, as originally suggested by Jessup and Norris (1971), is not related to the deep weathering profile developed in underlying Cretaceous sediments as indicated by the following considerations:

a) The Stuart Range - Millers Creek plateau area demonstrates differential erosion of the weathered profile prior to Miocene sedimentation; the profile is up to 30 m thick on the Stuart Range but is absent under Millers Creek plateau. At Stuart Creek Opal Field silcreted Mount Sarah Sandstone rests on unbleached Cretaceous shales (Barnes and Scott, 1979).

b) The presence of bleached Cretaceous shale clasts in the Mount Sarah Sandstone indicates weathering was substantially complete prior to Miocene sedimentation and silicification.

The lack of a causal association between silicification and deep weathering does not exclude the possibility of a superimposed, less intense Miocene weathering event. Although the deep weathering profile is largely absent under Millers Creek plateau some ?Permian sediments on the southern margin of the plateau are bleached; whether these are remnants of the eroded deep weathering profile or product of a younger event is unknown.

It is pertinent, at this stage, to point out that the term 'duricrust' in the sense of Woolnough's (1927) definition implying silicification of a pre-existing peneplain surface in close association with deep weathering is incompatible with the origin of silcrete proposed for the Billa Kalina area; thus use of the term 'duricrust' is avoided in this paper.

The close association of silica and calcite cements is a feature of sediments at Millers Creek plateau and on the arcuate ridges as opposed to the Stuart Range where calcite cements are absent. In some cases there is evidence of alternation in crystallisation of calcite and quartz suggesting no great age difference between the two cements (Whitehead, 1978b); varying pH conditions may have been responsible for this alternation. Some calcite cements were probably spring deposited while others take the form of caliche. Calcite intraclasts in some of the sediments are probably reworked tufa fragments recemented during slightly later phases of spring activity.

SUMMARY

Study of a Miocene sequence at Millers Creek plateau has shown an intertonguing relationship between the terrestrial Mount Sarah Sandstone and the lacustrine Etadunna Formation. Dolomites and clays of the Etadunna Formation were deposited in a shallow lake in the vicinity of Millers Creek plateau. On higher areas to the west and north, silcrete pebble-bearing terrestrial sediments of the Mount Sarah Sandstone were deposited. A silcrete pebble conglomerate facies of this unit channelled into the lake from the north and west.

A warm high rainfall climate characterised the first stages of deposition, and the Miocene lake extended eastwards from Millers Creek plateau for over 100 km. During the latter stages of deposition increased aridity culminated in evaporative conditions. The lake contracted westwards over an essentially flat land-surface and regressive sedimentation is recorded by upward coarsening sequences. Successive shorelines during pauses in the regression were major foci of silicification with silica transported by laterally migrating groundwaters, probably as a gel. The earliest silicification was syndepositional and there is evidence of penecontemporaneous reworking of silcrete on lake shorelines although there were also contributions from older silcrete horizons (viz. Eocene-Oligocene silcrete). Closely associated with the silcretes are sediments cemented by calcite and there is petrological evidence indicating altern-

ation of calcite and silica cementation, possibly in response to varying pH conditions. Post-Miocene erosion has etched out the massively indurated strandlines, the remnants of which today occur as an extensive system of arcuate, flat topped ridges.

By demonstrating intertonguing between the Etadunna Formation and silcretes capping areas such as the Stuart Range we have repudiated the concept that "grey billy" silcretes capping highland areas of this region represent silcreted equivalents of the lower Tertiary Eyre Formation. Also the concept of a genetic association between silcrete formation and deep weathering is not substantiated in the Billa Kalina area where Miocene silcrete truncates the deep weathering profile developed in the underlying Bulldog Shale.

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GJA:RBF:ZV

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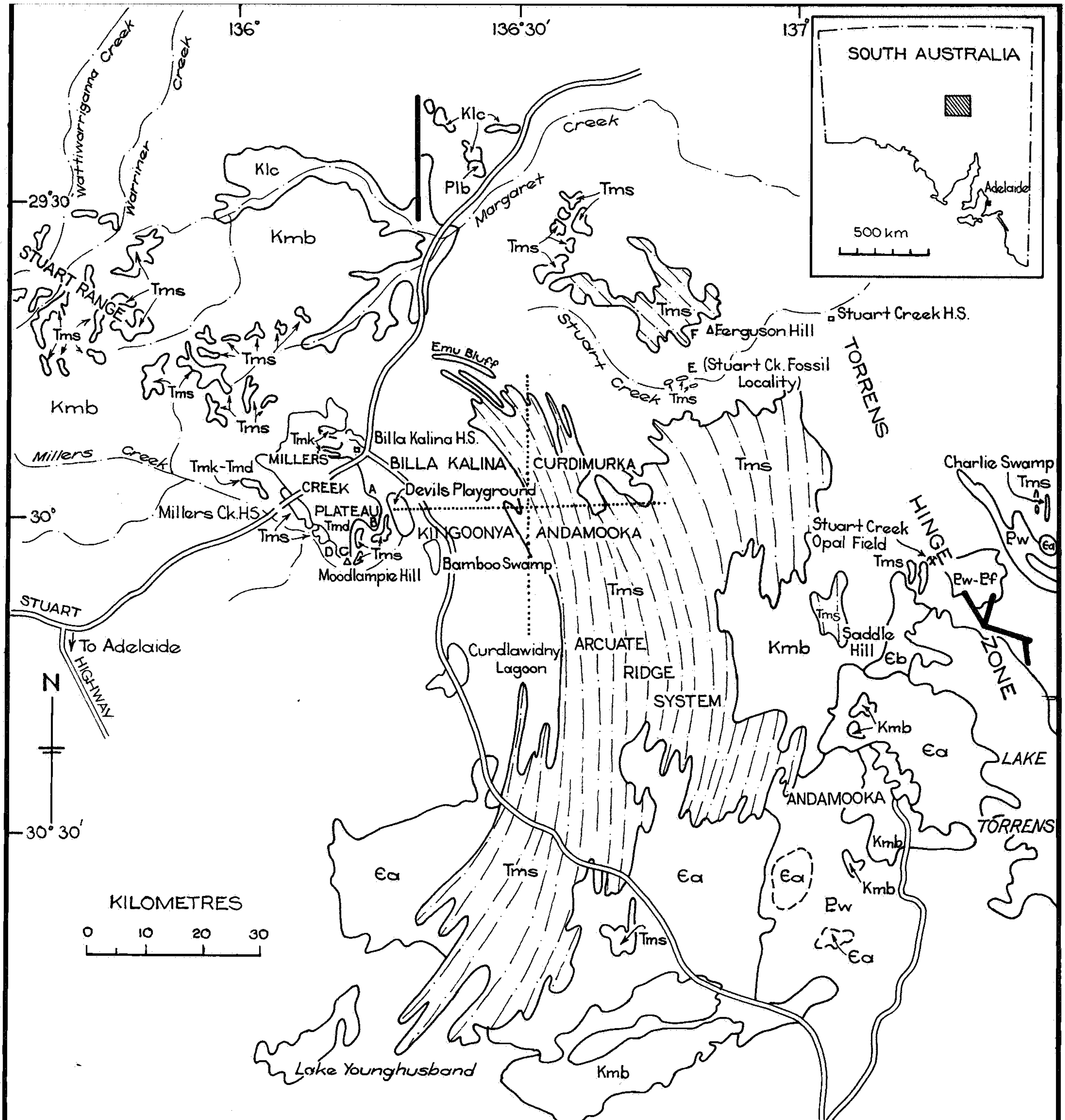


LEGEND

Tmk / Tmd / Tms	TERTIARY (MIOCENE) Etadunna Formation (Tmd). Unnamed conglomerate (Tmk). Mount Sarah Sandstone (Tms).
Kmb / Klc	CRETACEOUS Bulldog Shale Cadna-owie Formation.
Plb	PERMIAN Boorthanna Formation.
Ɛa-Ɛb	CAMBRIAN Andamooka Limestone and Yarra-wurta Shale.
Ɛw-Ɛf	ADELAIDEAN Wilpena Group and Farina Subgroup.
....	1:250,000 map sheet boundary.

FIG I

REGIONAL SURVEYS SECTION	DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	SCALE: 1:1,000,000.
COMPILED: G. AMBROSE	REGIONAL GEOLOGY OF THE BILLA KALINA AREA	DATE: April '79
DRN: J.W. / CKD:		PLAN NUMBER S14054

1323

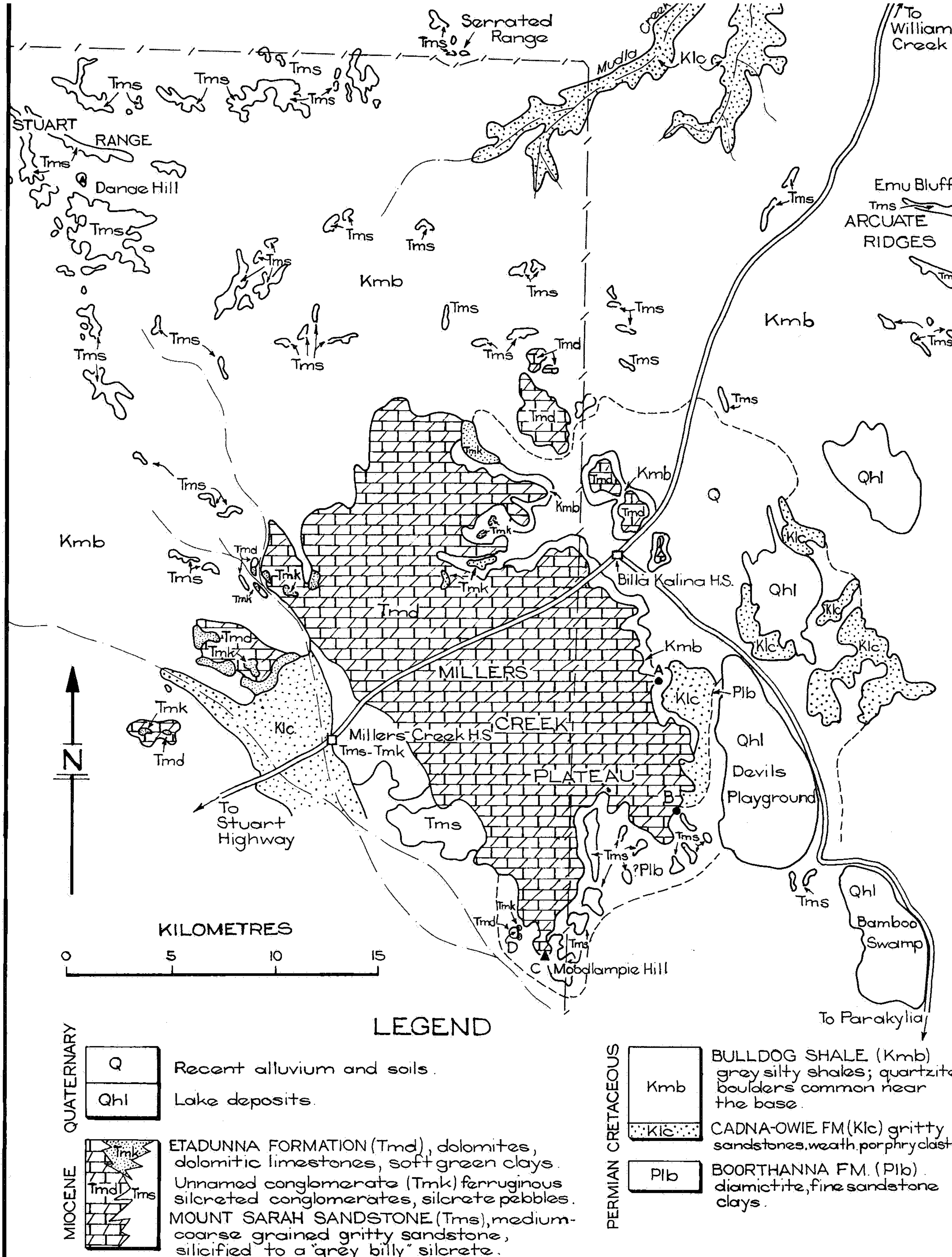


FIG. 2

REGIONAL SURVEY SECTION	DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	SCALE: 1:250,000
COMPILED: G. AMBROSE	GEOLOGY OF THE STUART RANGE & MILLERS CREEK PLATEAU	DATE: MAY '79
DRN: J.W · CKD:		PLAN NUMBER S14055

1323

1323

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

REGIONAL SURVEY SECTION

COMPILED: G. AMBROSE

DRN: J.W. CKD:

GEOLOGICAL SECTIONS
MILLERS CREEK PLATEAU (SEC.A,B&C) AND ARCUATE RIDGE (SEC.F)

SCALE:

DATE: May '79

PLAN NUMBER S14056

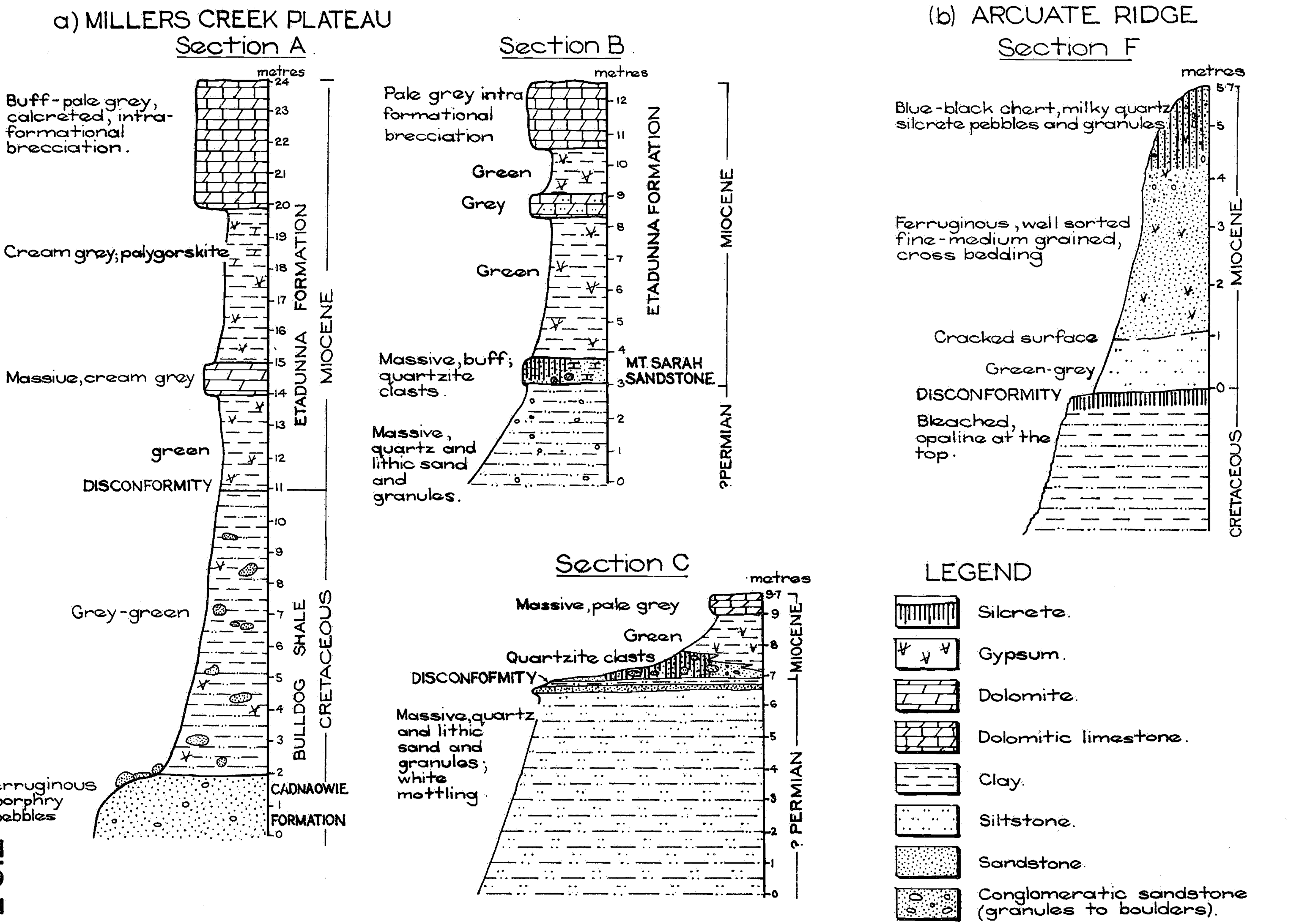


FIG.3

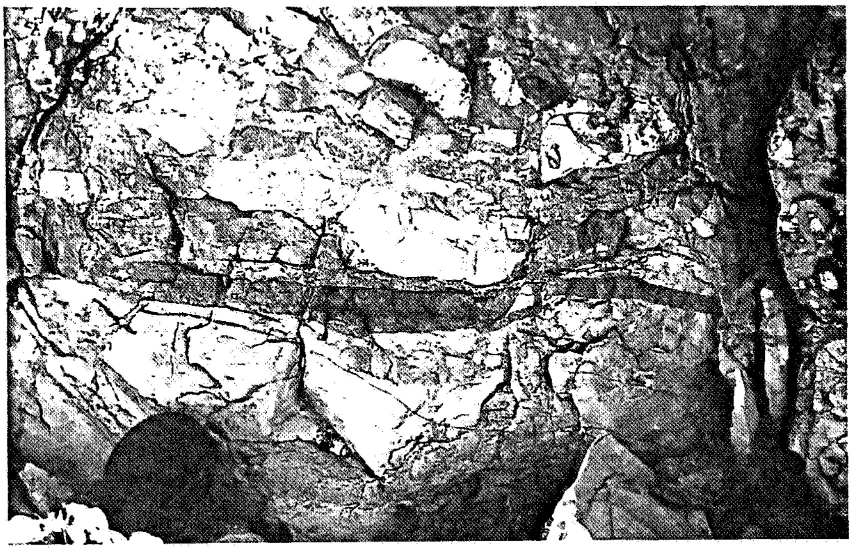
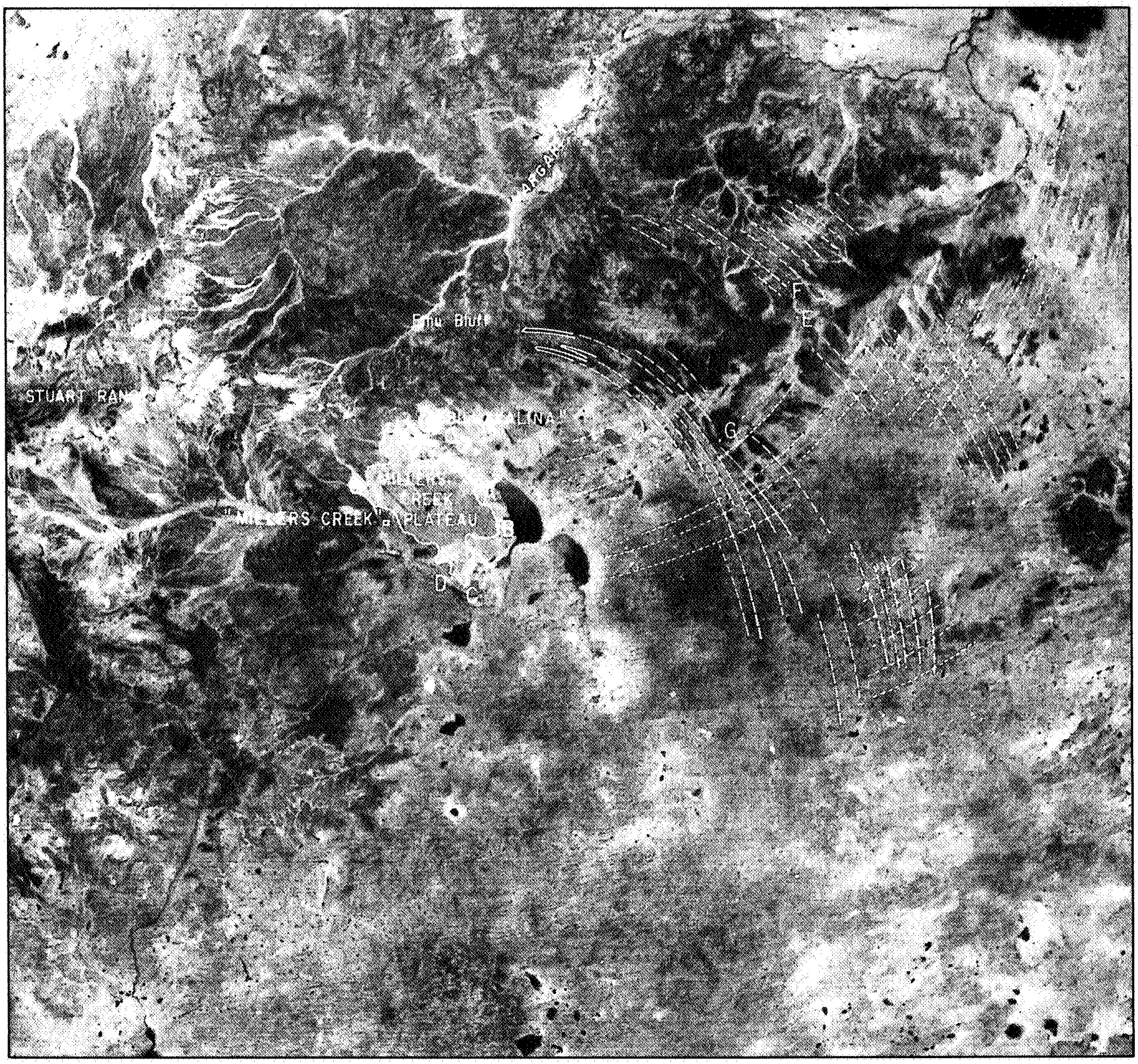


Fig. 4. Calcite veining a cream-grey dolomite capping Millers Creek plateau.
P30093

Fig. 5. Ferruginous silici ied conglomerate containing polished silcrete pebbles; this unit intertongues with Etadunna Formation clays an dolomites at Millers Creek plateau.
P30702

Fig. 6. Silcrete on the Stuart Range; comprises silicified Mount Sarah Sand stone containing reworked silcrete clasts.
P30697

FIG. 7



S.A. DEPT. OF MINES AND ENERGY

BILLAKALINA AREA

LANDSAT IMAGE 1207-00162-7

SCALE 1 : 1000 000

Miocene Arcuate ridges ....

Pleistocene - recent dunes ....

S 13948

GR.

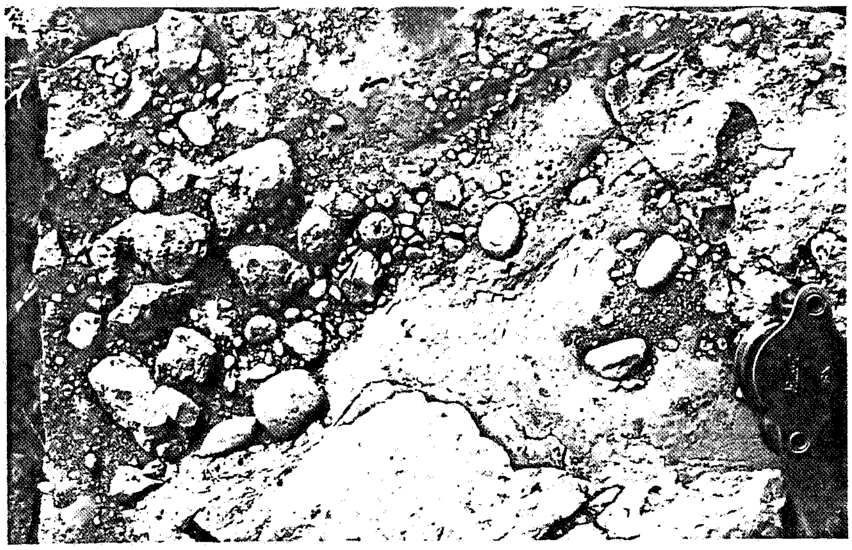


Fig. 8. Silicified pebbly sandstone from Emu Bluff containing reworked pebbles and cobbles of silcrete.
P30096

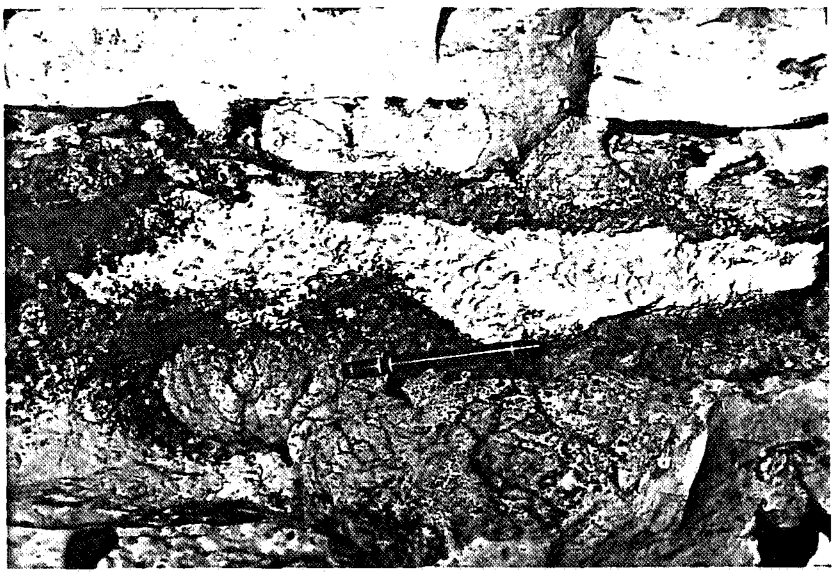


Fig. 9. Interlayered calci cemented (centre) and silic cemented sandy siltstones (bottom) at Emu Bluff.
P30700

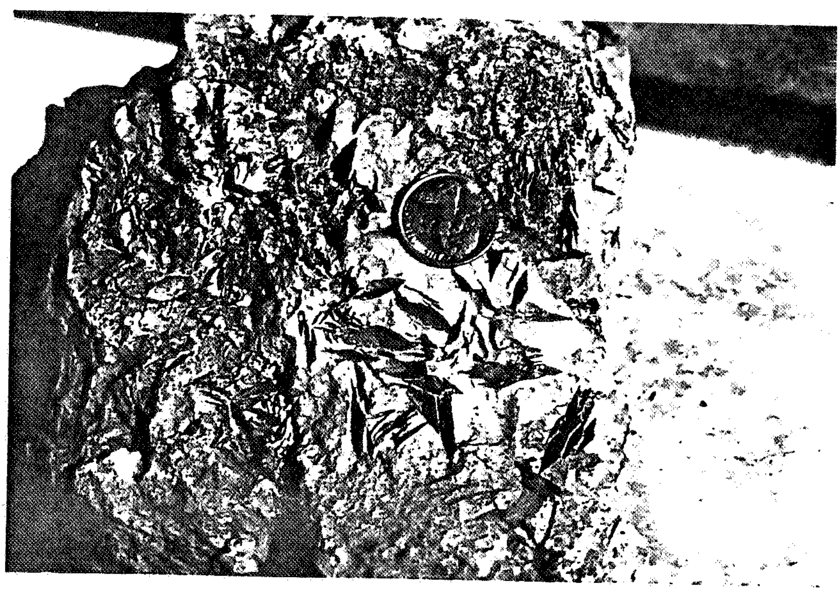


Fig. 10. Silcrete from Emu Bluff incorporating moulds of tabular gypsum crystals partly infilled by later calcite.
P30698

Fig. 11. Bulbous, whorled form of a silcrete capping Emu Bluff.
P30701

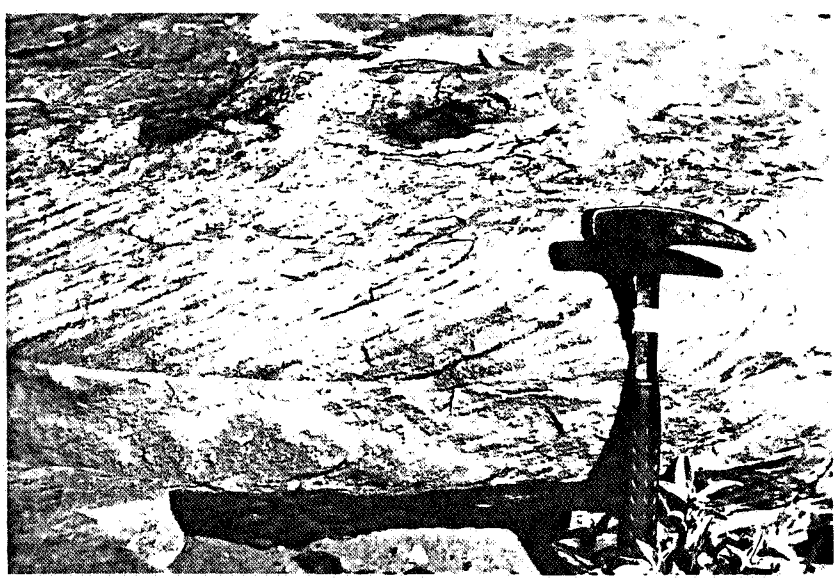


Fig. 12. Cross-bedded, silicified sandstone from the Stuart Creek fossil locality (Fig. I, Loc. E).
P30695

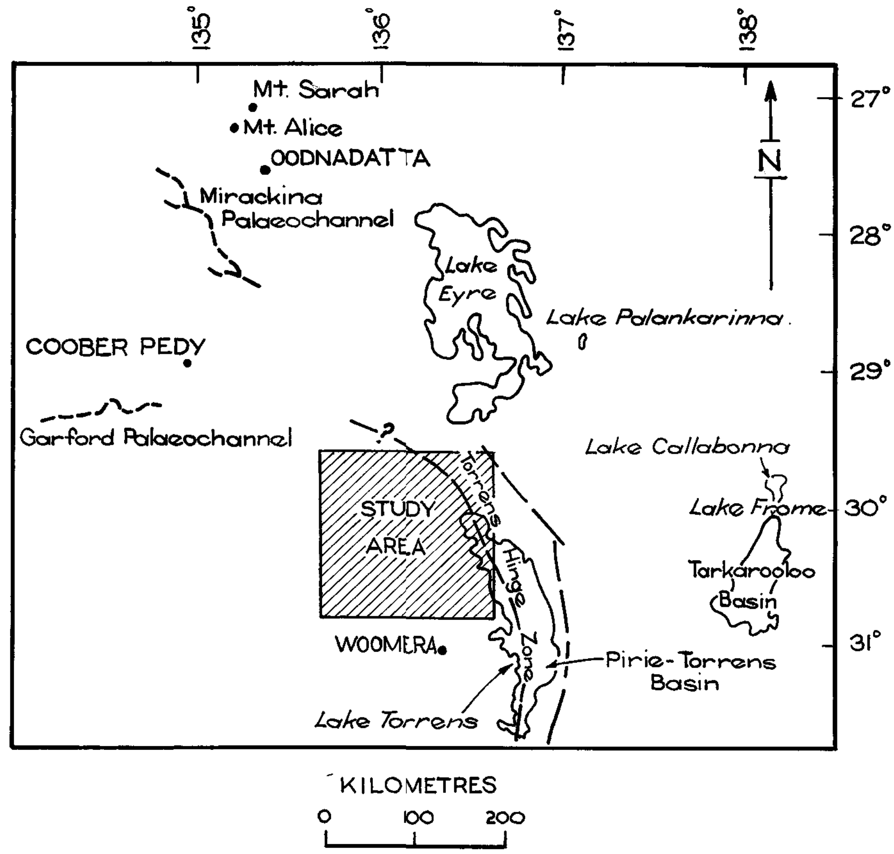
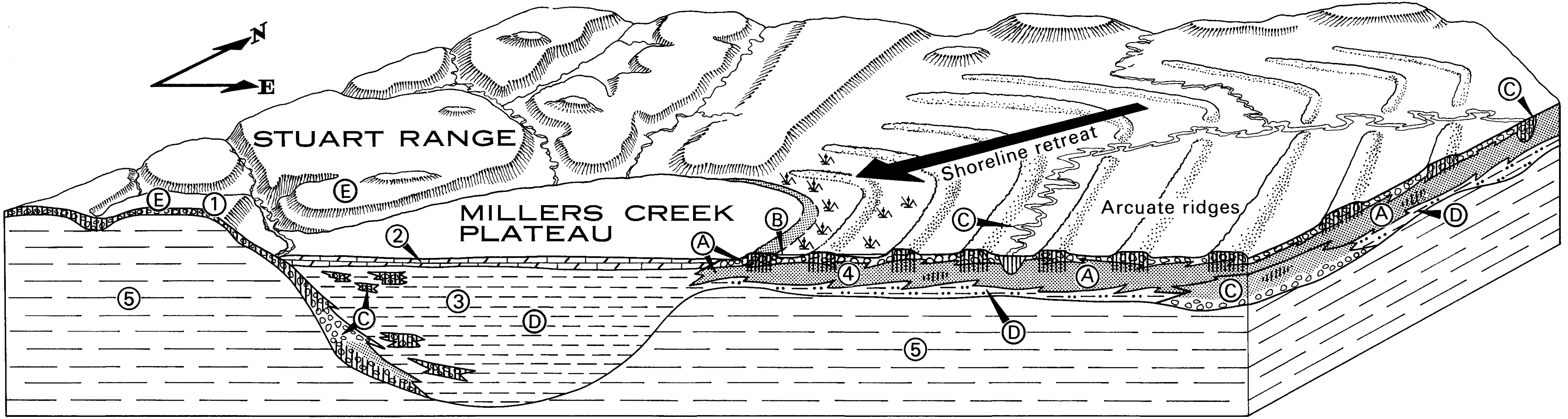


FIG. 13

	DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	SCALE: 1:10,000,000
COMPILED: G. AMBROSE	TERTIARY GEOLOGY OF THE BILLA KALINA AREA	DATE: JUNE '79
DRN: J.W. CKD:	LOCALITY PLAN	PLAN NUMBER S14136

1343



REFERENCE

- Silcrete
- Clay
- Silt, Sand
- Pebbly sandstone

STRATIGRAPHY

MIRIKATA FORMATION:

1. Danae Conglomerate Member
2. Millers Creek Dolomite Member
3. Billa Kalina Clay Member
4. Watchie Sandstone Member

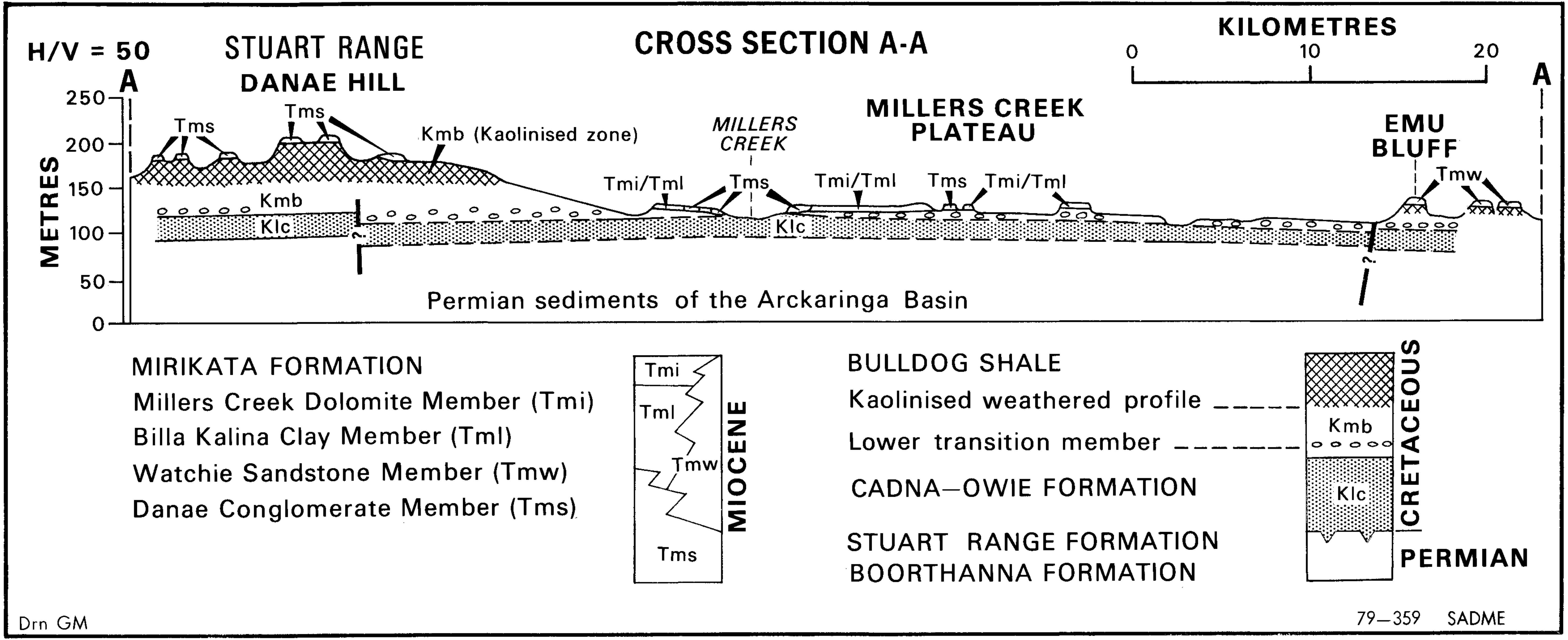
5. Cretaceous sediments

DEPOSITIONAL ENVIRONMENTS

- (A) Shoreline and near shoreline
- (B) Shallow lagoonal, some spring activity
- (C) Fluviatile; Lacustrine fan—delta
- (D) Lacustrine
- (E) Colluvial—alluvial

Drn GM

79—358 SADME


CROSS SECTION A-A
H/V = 50
STUART RANGE
DANAE HILL
KILOMETRES
0
10
20
A
A
250
200
150
100
50
0
METRES
Tms
Tms
Kmb (Kaolinised zone)
MILLERS CREEK
MILLERS CREEK PLATEAU
EMU BLUFF
Tmi/Tml
Tms
Tmi/Tml
Tms
Tmi/Tml
Tmw
Kmb
Klc
Klc
Permian sediments of the Arckaringa Basin
MIRIKATA FORMATION
Millers Creek Dolomite Member (Tmi)
Billa Kalina Clay Member (Tml)
Watchie Sandstone Member (Tmw)
Danae Conglomerate Member (Tms)
Tmi
Tml
Tmw
Tms
MIOCENE
BULLDOG SHALE
Kaolinised weathered profile
Kmb
Lower transition member
CADNA—OWIE FORMATION
Klc
CRETACEOUS
STUART RANGE FORMATION
BOORTHANNA FORMATION
PERMIAN
Drn GM
79—359 SADME