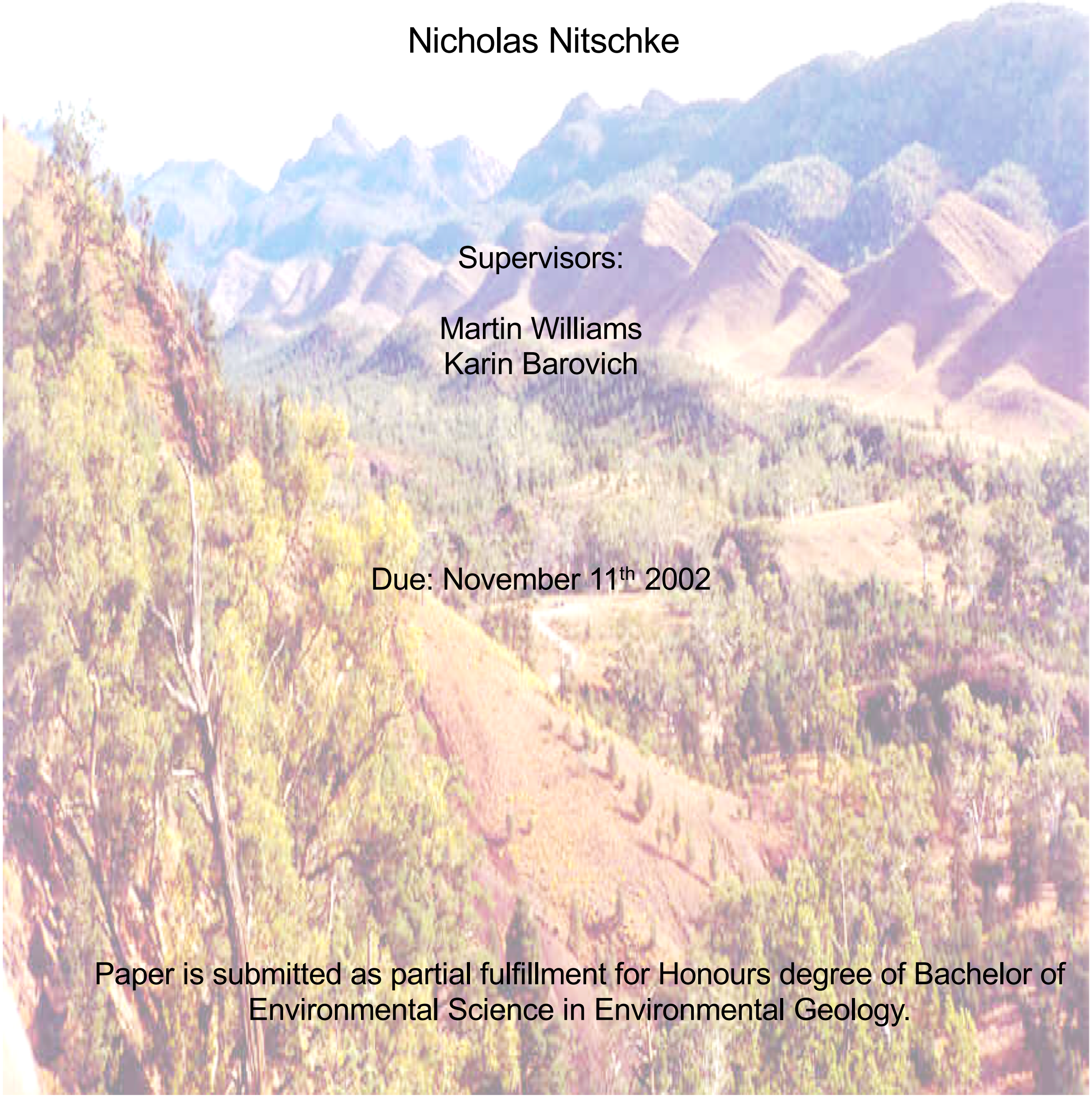
The University of Adelaide
Department of Geology and Geophysics

Identification of aeolian dust mantles in the semi-arid Flinders Ranges, South Australia.

Nicholas Nitschke



Supervisors:

Martin Williams
Karin Barovich

Due: November 11th 2002

Paper is submitted as partial fulfillment for Honours degree of Bachelor of Environmental Science in Environmental Geology.

The University of Adelaide
Department of Geology and Geophysics

Identification of aeolian dust mantles in the semi-arid Flinders Ranges, South Australia.

Nicholas Nitschke

Supervisors:

Martin Williams
Karin Barovich

Due: November 11th 2002

Paper is submitted as partial fulfillment for Honours degree of Bachelor of Environmental Science in Environmental Geology

Contents Page

List of Figures

List of Tables

Abstract

Sediment samples have been analyzed from ridge-top and valley-fill profiles and Lake Torrens in the central Flinders Ranges, South Australia. Ridge-top samples show evidence of addition of silty clay rich aeolian dust. The aeolian dust is characterized by its uniform texture (silty clay to fine sandy clay) and colour (dark red brown) over a range of topography and lithology. On the ridge-tops this material ranges in depth from 5 - 30 cm, and is distinguished by a well-sorted particle size distribution and significant particle population in the 2 – 63μm size fraction. Kaolinite and illite dominate the clay mineral suite in the ridge-top samples. Trace elements Zr, Ti, Th, La, Ce, Y, Cr and Nd are enriched in the ridge-top profiles compared to the underlying bedrock. $^{143}Nd/^{144}Nd$ ratios of the ridge-top, valley-fill and Lake Torrens samples show clear correlation with the Bunyeroo and Brachina Formations. $^{87}Sr/^{86}Sr$ residue ratios show a similar pattern with ridge-top, valley-fill and Lake Torrens samples similar to the Bunyeroo and Brachina Formations. $^{87}Sr/^{86}Sr$ leachate ratios are notably lower, ranging from (0.710- 0.715), showing the influence of the carbonate rock units of the Flinders Ranges and marine derived windblown carbonate. Excluding sample LT-6 the Lake Torrens samples have the same clay mineral suite, similar major and trace element geochemistry patterns and similar $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios as the ridge-top and valley-fill samples along with the Bunyeroo and Brachina Formations.

The particle size, geochemical and isotopic data all imply a significant recycling of sediment between the Flinders Ranges and Lake Torrens. During drier intervals fine sediment is blown eastwards from the Lake Torrens playa to form the ridge-top and hillslope aeolian dust mantles, later reworked by slopewash and incorporated into the fine-grained valley-fill deposits. During the more humid phases fine sediment is transported westwards by streams from the Flinders Ranges out to the Lake Torrens playa.

KEYWORDS: aeolian dust, Flinders Ranges, Lake Torrens, ridge-top profiles, valley-fill deposits.

Introduction

Windblown aeolian dust has made significant contributions to soil formation in many regions throughout the world (Simonson 1995). An excellent example is the classic loess (silt sized quartz) deposits of northwest China. These deposits vary in thickness from 100m up to 300m in some areas (Liu Tungsheng 1991). Aeolian dust has been widely deposited in south-eastern Australia and has had a major influence in many regions on both soil landscape and soil properties (Greene et al. 2001). Butler and Hutton (1956) identified numerous dust mantles, later described as *parna* deposits (clay-sized material) in the southeastern parts of Australia. Butler (1982) described aeolian dust or parna deposits as uniform deposits in terms of texture and content, extending across a range of substrates and a diversity of topography. For simplicity, the term aeolian dust will be used in this paper to describe such deposits.

The Quaternary Period encompasses the past 1.8 Ma; it saw consistent cyclic shifts in climate and environment at a magnitude and frequency that was unprecedented in the last 65 Ma (Williams et al. 1998). Glacial / interglacial cycles persisted throughout this period, with rapid and intense cyclic shifts causing significant change in climate and environment. The legacy of the glacial / interglacial cycles has been well preserved throughout inland Australia with extensive alluvial, lacustrine and aeolian deposits (Magee et al. 1995). During times of glacial maximum, aridity was at its peak with much expanded arid areas. Sea levels were up to 140m lower than present, lake levels were low with increased salinity assisting in the activation and construction of clay rich dunes (lunette deposits) around such lakes (Bowler 1976). Hence the dunefields, playa lakes, lunette deposits, and other desert landforms, along with the exposed continental shelf represented a major source of potential dust material during times of glacial maximum (Greene et al. 2001). The strong winds that prevailed during these times would have readily blown calcareous dust off the exposed continental shelf and clay rich material off dry lakes and lunette deposits, transporting and later depositing the clay and carbonate dust as mantles where it was incorporated into the landscape (Williams 2000; Williams et al. 1991). Aeolian activity and wind blown dust were most recently evident during the last two glacial maxima, which peaked at 150 ka and 16 -18 ka (Bowler 1976; Williams 2000).

Aeolian dust deposits rarely form discrete mantles, but generally become mixed into existing soil profiles and sediments, so the accurate identification of aeolian dust can be a difficult task (Chartres et al. 1988). In the past authors have inferred an aeolian origin from particle size distribution, presence of soil carbonate, soil sub-plasticity and above all from the presence of a uniform mantle overlying a range of substrates and a diversity of topography (Chen 2001). Quade et al. (1995) used $^{87}Sr/^{86}Sr$ ratios to trace the origins of carbonate in soils in South Australia and Victoria. They concluded that in most soils sampled the calcium carbonate originated from the ocean and was transported as dust and sea spray. In recent years the importance of aeolian dust deposits and their effect on soil formation has been increasingly recognised by earth scientists in Australia (Greene et al. 2001; Quade et al. 1995).

There has been much work on aeolian dust deposits in south-eastern Australia, but very little detailed work has been undertaken in South Australia, in particular across the Olary Ranges and west through to the Flinders Ranges. The aeolian influence on the landscape in these areas has not been studied in detail although the aeolian influence is readily observed in the field (Williams et al. 2001; Williams et al. 1991). This paper aims to identify, describe and characterize aeolian dust deposits in the central Flinders Ranges and to distinguish their possible sources. Field observations and particle size analysis along with geochemistry based on detailed XRD analysis, XRF major and trace element analysis and isotope data including $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios were used to characterize the aeolian silty clays. These deposits provide an opportunity to examine in detail the influence of aeolian dust in the central Flinders Ranges and its effects on the present landscape.

Study area: geology, climate and geomorphology

The Flinders Ranges consist of uplifted and deformed Proterozoic and Cambrian sedimentary rocks that form a series of north-south trending ridges extending for approximately 400km (Lemon 1996). The Ranges are located to the east of the Torrens Hinge Zone (Preiss 1999), they run in a north-south direction from latitudes 30^{o} to 33^{o}S, and encompass the area between longitude 138^{o} to 140 ^{o}E (Figure 1). The present day climate of the central Flinders region is classed as semi-arid, with mean annual rainfall between 250 and 350 mm and annual evaporation exceeding 2000 mm (Figure 1). The basement geology includes a variety of steeply dipping Proterozoic and Cambrian units that include resistant quartzite and mature sandstone, fine grained shale and siltstone plus a number of dolomitic and calcareous units (Preiss 1999) (Figure 2). There are also a number of Tertiary and Quaternary alluvial, fluvial and lacustrine deposits throughout the ranges. Alluvial fans flank the western edge of the ranges with a number of creeks dissecting them on their way towards Lake Torrens to the west. Modern fluvial sediment of Brachina Creek and other fluvial deposits in the Flinders Ranges is made up of cobbles, gravels and coarse sands, but the present day Brachina Creek channel cuts through silty clay wetland deposits of late Pleistocene age (Williams et al. 2001). There is a vast difference between the modern sediments (cobbles, gravels and coarse sands) and the silty clay deposited in the late Pleistocene. The latter indicates that a very different climate and environment persisted in the central Flinders Ranges during the late Pleistocene from $\approx$ 33 ka to $\approx$ 15 ka (Williams et al. 2001).

Geomorphologically, the Flinders Ranges are structurally controlled; the high quartzite and sandstone ridges follow large-scale anticlines and synclines (Williams et al. 2001). Smaller rolling hills and valleys, which consist of the more readily weathered shale, siltstone and limestone units generally separate the high ridges. Evident in the field is the presence of a thin mantle of silty clay material that occurs on ridge-tops and down slope to the valley bottom (Williams et al. 2001). The study area is centred on the ridges, hills and valley-fill deposits in and around Brachina Gorge in the Central Flinders Ranges, with sampling focusing on the silty clay material (Figure 2). Brachina Creek flows in a westerly direction through Brachina Gorge, and then cuts through the alluvial fan deposits and flows west towards Lake Torrens.

Lake Torrens is a structurally controlled playa located to the west of the Flinders Ranges. Lake Torrens has been the site of accumulation of over 300 metres of sediments since Eocene times (Schmid 1985). The top 75 metres of sediment is classed as Quaternary, and consists dominantly of chocolate brown, red and grey clays inter-bedded with fine sand layers and white seed gypsum (Johns 1968). The rapid and intense changes in climate during the Quaternary did not significantly affect Lake Torrens, which remained in a dry to ephemeral depositional environment throughout this period (Schmid 1985). The Flinders Ranges that lie to the east of the Lake are the major sediment source for the thick sequence that exists in Lake Torrens.

Methods

Sediment and soil samples were collected from various ridge-top and valley-fill deposits in and around Brachina Gorge in the central Flinders Ranges (Figure 2 and Table 1). These samples were described using field texturing and Munsell colours. For comparison whole rock samples were also taken from each geological formation through Brachina Gorge. Samples were also collected from Lake Torrens Bore no.3, from the Moonta Drill Core Library, Primary Industries and Resources, South Australia.

Particle size was determined for the Flinders Ranges samples using the Pipette Particle Size Analysis (PSA) equipment at CSIRO Land and Water. Moisture content for all the samples was determined. Pre-treatment P1, for removal of organic matter, was used on all samples. Pre-treatment P3, for the removal of carbonate, was used on those samples which had significant amounts of carbonate present (>1%). Dispersion of the samples took place in the end over end shaker for 20 hours. Details of the methods for Pre-treatment P1 & P2 and the dispersion are given in McKenzie et al. (2002). Determination of the silt and clay fraction (<31μm) and fine to coarse sand fraction (31-2000μm) was done using the standard methods of settling and pipetting as detailed in McKenzie et al. (2002). Ten size fractions were measured giving a detailed analysis of the particle size distribution. All residues (<31μm) were weighed to 4 decimal places while sand fractions (31-2000μm) were weighed to 3 decimals. The advantage of the pipette PSA method is that it allows the collection of different size fractions for individual analysis. Size fractions <2μm, 2-31μm, 31-63μm, 63-125μm and 125-1000μm were collected for XRD analysis, along with whole rock and Lake Torrens drill core samples. Samples were prepared as smears on glass slides using DI water or ethanol. Analyses were carried out on a Philips PW 1050 goniometer at the University of Adelaide. The source of radiation was a Co-anode X-ray tube, operating at 50kV, 30 mA. A general scan of the diffracted X-rays from the samples was taken over the angular range 3 to 75 degrees 2-theta, at a step size of 0.05 degrees. Clay samples (<2um) were run over an angular range 3 to 40 degrees 2-theta, at a step size of 0.02 degrees. Mineralogy of the samples was determined by matching the series of peaks for a given mineral with the peaks extracted from the scan data, using identifying programs XPLOT and TRACE.

Bulk samples for geochemical analysis were dried in an oven at 60^oC overnight, after which the samples were milled to a fine powder. Whole rock samples were crushed then milled to a fine powder. Preparation for trace element analysis involved 5-10gm of sample powder mixed with 1ml of binder solution (Poly Vinyl Alcohol) and pressed to form a pellet. Preparation for major element analysis involved the drying of the samples at 110^oC in an oven for over two hours to remove any absorbed moisture. Samples were then weighed into alumina crucibles and ignited overnight in a furnace at 960^oC, to yield the Loss on Ignition (LOI) values. 1gm of the ignited sample was accurately weighed with 4gm of flux, this mixture was then fused into a disk using a propane-oxygen flame at approximately 1150^oC, in Pt-Au crucibles. Both major and trace element analyses were carried out on a Philips PW 1480 X-ray Fluorescence Spectrometer at the University of Adelaide, where a variety of programs were used for each analysis. Details of the methods for XRF major and minor element analysis are given in Stanley (2002).

Strontium (Sr) and Neodymium (Nd) ratios were determined on selected Flinders Ranges and Lake Torrens samples. The size fraction <2-100μm can be readily transported long distances in suspension by wind (Gatehouse et al. 2001). Therefore all Flinders Ranges samples were sieved to <125μm, to reduce the isotopic signature of the parent material, particularly in the ridge-top samples. To separate the labile Sr from the residual Sr, 200mg of sample were accurately weighed into centrifuge tubes, where 3ml of ultra-pure 1M acetic acid were added to each sample and placed in an ultrasonic bath for 30 minutes. After this the acid was pipetted off, and the residue was washed three times with DI water. Each time the leachate was pipetted off and kept for its own analysis. The residue material was digested in an HF-HNO_3 mixture. After complete dissolution, samples were brought to dryness, and then redissolved in 2M HCl. Sr and Nd were separated using standard ion exchange techniques (Bruce 2002). Sr and Nd were loaded on to Ta filaments with a mixture of $TaCl_5$ and HNO_3 and 1M HNO_3 respectively. The Sr was measured using the single filament assembly while Nd was measured using the Ta-Re double filament assembly. The analyses were carried out at Adelaide University on the Finnigan-MAT Mass Spectrometer 262. Typically, 130 ratios were collected for Sr analysis and 100 ratios for Nd analysis. The increased number of ratios collected for the Sr analysis was to ensure adequate precision. Over the course of the study the average for the NBS987 Sr Standard is .710266± 8 (2S.E.). The average for the in house Nd Standard (J&M specpure Nd_2O_3) is .511601± 8 (2S.E., n=19), and long term average of the BCR-1 standard gives .512593± 6 (n=12). Typical blanks are 1 ng for Sr and 100-200 pg for Nd.

Observations and Results

Profile Morphology

A thin mantle of silty clay material occurs on ridge-tops, down slope to the valley bottom and is evident in the field throughout the central Flinders Ranges (Williams et al. 2001). The material is a brown to dark brown silty to fine sandy clay, uniform from ridge-top downslope (Table 1). On the ridge-tops this material ranges in depth from 5 cm up to 30 cm in some places, and overlies the quartzite and sandstone bedrock. The silty clay material is not a likely weathering product of quartz-dominated quartzite and sandstone bedrock. The late Pleistocene wetland valley-fill deposits identified and dated by Williams et al. (2001) consist of red brown medium to fine sandy clay with a clay content ranging from 35 – 50 %. The Lake Torrens samples are a mixed variety of orange brown / grey brown / brown clay layers inter-bedded with occasional gypsum layers (Table 1).

Particle size analysis

Research in eastern Australia has used particle size characteristics of soil profiles to indicate the presence of aeolian dust (Blackburn 1981). The size fraction <2-100μm can be readily transported long distances in suspension by wind (Gatehouse et al. 2001). Figures 3 and 4 show the particle size distribution of the 2 – 2000μm fraction of the ridge-top and valley-fill samples. The three ridge top samples 5BF, 6AF and 6DF have smooth cumulative mass percent curves

(Figure 3), indicating a well-sorted particle population. This well sorted feature is not typical of the underlying rock, which one would expect to weather to a bi-modal particle size population. Sample 3AF does not exhibit quite as well sorted an appearance as the other ridge-top samples. It does, however, show a distinct influence from the underlying parent material, the Brachina Formation, with similar percentages in each increasing size fraction, which was evident under the microscope. Ridge-top samples have a distinct population of particles from 2 – 63μm size fraction (Table 2). The well-sorted particle population and the distinct population of particles from 2 – 63μm in the ridge top samples, suggest that they have had some aeolian dust additions. The valley-fill samples 2AF, 2BF and 2GF represent three different horizons (Figure 4). Sample 2AF (the pedal unit) shows a vast increase in clay content compared to the other two samples, and has 28% clay material <2μm (Table 2). The valley-fill samples have 66% to 78% of particles <63μm, indicating that the valley-fill deposits are made up dominantly of clay, silt and fine sand. Cumulative totals for the valley fill samples are lower than the ridge-top samples due to the significant accumulation of carbonate material.

Mineral suites

The mineral suites of the ridge-top samples 5BF, 6AF and 6DF from size fraction 31-1000μm dominantly reflect their quartzite and sandstone parent material. With quartz dominating the size fraction 31-1000μm with micas also present in minor amounts. But there are some notable anomalies in the <2-31μm size fraction, which can be attributed to dust accession. Kaolinite and illite dominate the clay size fraction (<2μm) with trace amounts of vermiculite also identified. The clay fraction (<2μm) XRD spectra for ridge-top samples 5BF, 6AF and 6DF are very similar (Figure 5). Ridge-top sample 3AF has a variety of clay minerals including illite, smectite, and kaolinite (Figure 5). The underlying Brachina Formation has clay minerals, including kaolinite and illite with trace amounts of vermiculite; the Bunyeroo Formation also has the clay minerals kaolinite and illite present. The clay mineral suite of the valley-fill samples is more diverse than that of the ridge-top samples, for it includes illite, kaolinite, vermiculite, montmorillonite and smectite. The size fraction 31-1000μm is dominated by quartz with minor micas and feldspars evident from rock fragments present in the samples.

The Lake Torrens samples are dominated by quartz along with minor gypsum, calcite and halite with illite and kaolinite dominating the clay mineral suite (Table 3). The respective proportion of each mineral varies with different layers, some layers having increased gypsum or clay material, while in some calcite is absent. Samples LT-5 and LT-7 are layers with increased clay material. The clay minerals identified are the same as those in the clay fraction in the ridge top samples, with kaolinite and illite dominant. The Lake Torrens Bore samples analysed cover a depth range of 1.2 – 47 m. Johns (1968), looked at Bore 3 and 3A down to a depth of 287 m. He found similar patterns with kaolinite and illite dominating the clay mineral suite of the upper 48m. But from 48m – 80m (to the Quaternary-Tertiary boundary), he found the clay mineral suite was dominated by dehydrated halloysite with minor palygorskite.

Major and trace element composition

Reflecting the character of the parent material, the Si concentrations of the ridge-top samples are high ranging from 70 to 80 % (Table 4). In contrast, Ti and Zr concentrations are significantly higher than in the underlying quartzite bedrock (Figures 6, 7), indicating enrichment of Ti and Zr in the ridge-top profiles. The trace element geochemistry also shows enrichment of trace elements in these profiles. Th, La, Ce, Y, Cr and Nd are all in greater concentration in the ridge-top samples than in the underlying bedrock (Figure 8). The Brachina and Bunyeroo formations have greater concentrations of trace elements than the quartzite and sandstone units (Figure 8). Except for sample LT-6 (a layer dominated by gypsum) the Lake Torrens samples are all geochemically similar (Tables 4, 6). The trace element geochemistry also shows similar patterns with all samples (except LT-6) having very similar Th, La, Ce, Y, Cr and Nd concentrations (Table 6).

Isotope analysis

The leachate $^{87}Sr/^{86}Sr$ ratios for the ridge-top samples range from 0.713 to 0.715, while the leachate valley-fill $^{87}Sr/^{86}Sr$ ratios have values of 0.710 (Figure 9). The lower ratio in the valley-fill samples reflect the high carbonate concentration in these samples compared to the ridge-tops, indicating a bigger influence from the carbonate whole rocks and/or the influx of carbonate from the ocean (Faure 1986). The ridge-top and valley-fill ratios are slightly higher than local carbonate whole rock and modern ocean, with $^{87}Sr/^{86}Sr$ ratios of 0.709 and 0.709, respectively (Figure 9). Lake Torrens leachate samples are similar to the ridge-top samples with values of 0.714 - 0.715.

Residue $^{87}Sr/^{86}Sr$ ratios show a wider range than the leachate samples, with ridge-top samples ranging from 0.742 to 0.771, while valley-fill samples range from 0.736 - 0.751 (Figure 10). Lake Torrens samples have slightly lower values ranging from 0.727 - 0.732. The minor input of airborne sea derived salts and the occurrence of evaporitic minerals in the Lake Torrens sediment (Schmid 1989; Johns 1968) can account for the lower $^{87}Sr/^{86}Sr$ ratios. $^{87}Sr/^{86}Sr$ ratios of the Bunyeroo and Brachina Formations taken from various sources range from 0.733 - 0.786 and 0.743 - 0.769 respectively (Table 7). The $^{143}Nd/^{144}Nd$ ratios for the ridge-top, valley-fill and Lake Torrens samples are 0.511977 (3AF), 0.511958 (5BF), 0.511947 (6AF), 0.511994 (2AF), 0.512096 (LT-5), and 0.511990 (LT-7) respectively (Table 8). $^{143}Nd/^{144}Nd$ ratios for the two Bunyeroo and one Brachina Formation samples are 0.511803, 0.511818 and 0.512092, respectively (Table 7).

Discussion

Evidence for windblown dust

Primary evidence for wind blown dust material is the ridge-top particle size data, which shows a well-sorted particle population and distinct population of particles from 2 – 63μm size fraction. Both these characteristics indicate an influx of silty clay windblown dust. The mineral composition of the ridge-top samples also indicates an aeolian dust addition. Kaolinite and illite are present in relatively large amounts with trace amounts of vermiculite. The presence of kaolinite and illite in such amounts would not be expected from the in situ weathering of quartzite and sandstone. Zircon and titanium are remarkably resistant to weathering due to their low solubility in aqueous solutions, so these elements would not be added to or removed from weathering profiles in significant amounts (Nesbitt 1979). However, the 5BF, 6AF and 6DF ridge-top samples show a significant enrichment of both Zr and Ti compared to the underlying parent material (Figures 6, 7). Ridge-top sample 3AF and the Brachina Formation show only a small difference between the Zr and Ti concentrations (Figure 6 and 7), the relationship showing the strong influence of the underlying parent material on ridge-top sample 3AF. Trace element patterns in sediments are indicative of parent material when all fractions of weathering products are present in the sample (Nesbitt 1979). Trace element concentrations of Th, La, Ce, Y, Cr and Nd show a notable increase in the ridge-top profile samples compared to the underlying bedrock (Figure 8). Crichton and Condie (1993) found that a positive correlation between trace elements and Al_2O_3, suggests but does not prove (due to the inverse relationship of SiO_2 and Al_2O_3), that trace elements are contained predominantly in the clay minerals. Trace elements Th, La, Ce, Y, Cr and Nd plotted against Al_2O_3 show a distinctive positive correlation (Figure 11), suggesting that most of the trace elements maybe contained in the clay minerals of the sediments, shales and quartzite units. Considering the other results along with the positive correlation between Al_2O_3 and the trace elements, there is significant evidence to indicate that the ridge top samples show significant enrichment of trace elements (Zr, Ti, Th, La, Ce, Y, Cr and Nd) through the accession of silty clay rich, aeolian dust.

Valley-fill deposits: How much is aeolian dust?

Williams et al. (2001) estimated the rate of sedimentation of the late Pleistocene valley-fill deposit (wetland unit) to be ≈ 0.7m ka^{-1}. This value is significantly higher than long-term rates of erosion in the catchment, which have been determined by in situ cosmogenic ^{10}Be to range from 6 to 14 mm ka^{-1} (Williams et al. 2001). The proportion of fine sand, silt and clay (<63µm) ranges from 66 % to 78 % in the wetland unit (Table 2), values which are significantly higher than the sediment carried in the creeks from the Flinders Ranges today. Williams et al. (2001) concluded that much of the wetland sediment is composed of windblown dust that was reworked by slope wash and incorporated into the wetland unit. There are close similarities between the ridge-top samples and the wetland unit. The clay minerals kaolinite and illite are present in large amounts in the ridge-top samples and are also present in the clay rich wetland samples. The trace elements Th, La, Ce, Y, Cr and Nd of the ridge-top and wetland unit samples have similar concentrations (Table 6). Considering sedimentation and erosion rates and the mineralogical and geochemical composition of the ridge-top and valley-fill samples, there is strong evidence that a significant amount of the valley-fill (wetland) unit is composed of reworked aeolian dust.

Lake Torrens: a potential dust source

The clay mineral suite of the ridge-top samples and the upper 47 m of Lake Torrens samples are identical, with kaolinite and illite dominant. Taking into account the effect of the parent quartzite and sandstone bedrock in the ridge-top samples and excluding LT-6 from the Lake Torrens samples, the geochemistry of the ridge-top and Lake Torrens samples is very similar (Figure 12). The presence of gypsum in the valley-fill samples in notable amounts compared to the bedrock units (Table 4), also provides evidence that dust containing gypsum was blown in from Lake Torrens where gypsum is abundant. $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios for ridge-top, Lake Torrens and whole rock samples show notable similarities (Figure 9, 10). $^{87}Sr/^{86}Sr$ leachate ridge-top ratios range from 0.712- 0.715 and 0.714- 0.715 for the Lake Torrens samples (Figure 9), with $^{143}Nd/^{144}Nd$ ratios for ridge-top and Lake Torrens samples both within the range 0.511900 – 0.512100 (Table 8). The slightly increased $^{87}Sr/^{86}Sr$ residue ratios in the ridge-top samples compared to the Lake Torrens samples can be attributed to the influence of marine derived salts and the occurrence of evaporitic minerals in the Lake Torrens sediment (Johns 1968; Schmid 1989).

There is thus evidence that material from Lake Torrens was a major source of windblown dust to the ridge-tops and in turn the valley-fill deposits in the Flinders Ranges. The uplifted Flinders Ranges lie in a North –South orientation perpendicular to the major southeast dust path identified by McTainsh and Lynch (1996). Therefore the Flinders Ranges would have acted as a dust trap for the dust travelling the southeast dust path from the outwash plains and playas of Lake Torrens and beyond during times of peak aridity (Williams et al. 2001).

The Flinders Ranges: sediment source for Lake Torrens

Schmid (1989) identified the ephemeral streams draining the Flinders Ranges as the dominant sediment supply to Lake Torrens along with a minor input of airborne sea derived salt. Droste (1961) and Grim (1968) determined that the clay mineral composition of desert saline lake sediments is controlled almost entirely by the composition of the source area. As discussed, kaolinite and illite dominate the clay mineral suite of Lake Torrens sediments; kaolinite and illite are also present in the Bunyeroo and Brachina Formation, which make up the valleys in the central Flinders Ranges. Förstner (1977) in his study of various arid Australian lakes determined that the mineralogy and chemical composition of fine grained lake sediments is primarily influenced by its detrital heritage, the lithology of the sediment source. Excluding LT-6, the Lake Torrens samples have a very similar major and trace element geochemistry to the Bunyeroo and Brachina Formation (Tables 4, 5, 6). Figure 13 shows the close relationship between the Lake Torrens sediment and the Bunyeroo and Brachina Formation.

In most isotopic studies of aeolian dust input vs in situ weathering there is a sharp contrast between the aeolian dust and the underlying parent material (Chiquet et al. 1999). However, the $^{87}Sr/^{86}Sr$ leachate and residue ratios along with $^{143}Nd/^{144}Nd$ ratios of the ridge top, Lake Torrens, valley fill and Flinders Ranges whole rock samples show similar patterns. Figure 14, a plot of $^{87}Sr/^{86}Sr$ vs $^{143}Nd/^{144}Nd$, shows the close relationship between the samples. The $^{143}Nd/^{144}Nd$ ratios lie between the Bunyeroo and Brachina Formation ratios, while the $^{87}Sr/^{86}Sr$ residue ratios of Lake Torrens show good correlation with the Bunyeroo and Brachina Formations (Figure 10). The leachate samples also have a close relationship, plotting in a distinct cluster (Figure 14). Their $^{87}Sr/^{86}Sr$ ratios are similar to the Wonoka, Nuccaleena and Trezona Formations and slightly higher than the modern and Cainozoic ocean values (Figure 9).

The results indicate that the major sources of residual Sr and Nd in the Lake Torrens, ridge-top and valley-fill sediments come from the Flinders Ranges rock units, particularly the Bunyeroo and Brachina Formations. The source of labile Sr in the Lake Torrens, ridge-top and valley-fill sediment reflects the influence of carbonate units within the Flinders Ranges and windblown marine derived carbonate. The clay mineralogy and geochemistry (especially the isotope geochemistry) of Lake Torrens samples and the units in the Flinders Ranges, indicate that the Flinders Ranges units, in particular the Bunyeroo and Brachina Formations, are the major source of sediment for Lake Torrens. Therefore there is an effective sediment recycling transport system between the ridge-top dust mantles, the valley-fill deposits, Lake Torrens and the Flinders Ranges rock units.

Conclusions

Field observations, particle size analysis, mineralogy, geochemistry and $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic ratios of ridge-top, valley-fill, Lake Torrens and Flinders Ranges whole rock samples, indicate that dust deposition has played a vital role in landscape evolution in the central Flinders Ranges. The Flinders Ranges acted as a dust trap collecting kaolinite and illite rich dust blown from Lake Torrens along the major southeast dust path during times of peak aridity. Dust mantles developed on the ridge-tops and clay rich material was worked down slope and incorporated into the valley-fill deposits. Lake Torrens sediment is predominantly derived from the Flinders Ranges, in particular the Bunyeroo and Brachina Formations. These data are consistent with a continuous sediment transport cycle between the Flinders Ranges, Lake Torrens and the ridge-top profiles during drier phases in the late Quaternary.

Acknowledgments

I thank the National Parks and Wildlife Service of South Australia for the opportunity to work in such a spectacular and inspiring environment, PIRSA and CRC LEME for financial support. Adrian Beech and his team at CSIRO Land and Water for the use of particle size analysis equipment and assistance throughout the process. I also thank the University of Adelaide for technical and logistical support, Vic Gostin and Liz Campbell for their valuable thoughts in respect to Lake Torrens. Carly Chor, Dennis Rice and Martin Williams for field assistance during April and May 2002, and Amy Jericho, for help in perfect conditions throughout August 2002.

References

BLACKBURN G. 1981. Particle-size analysis of Widgelli parna in southeast Australia. *Australian Journal of Soil Research* **19**, 355-360

BOWLER J.M. 1976. Aridity in Australia: age, origins and expression in aeolian landforms and sediments. *Earth-Science Reviews* **12**, 279-310.

BRUCE D. 2002. Official written safe work procedure: Ion exchange columns. Department of Geology and Geophysics, Adelaide University (unpubl).

BUTLER B.E. 1982. The location of aeolian dust mantles in southeastern Australia. Quaternary dust mantles of China, New Zealand and Australia. Proceedings of a workshop, pp. 141-144. Australian National University, Canberra.

BUTLER B.E. & HUTTON J.T. 1956. Parna in the riverine plain of South Eastern Australia and the soils thereon. *Australian Journal of Agricultural Research* **7**, 536-553.

CALVER C. R. 2000. Isotope stratigraphy of the Ediacarian (Neoproterozoic III) of the Adelaide Rift Complex, Australia, and the overprint of water column stratification. *Precambrian Research* **100**, 121-150.

CHARTRES C.J., CHIVAS A.R. & Walker P.H. 1988. The effect of aeolian accessions on soil development on granitic rocks in southeastern Australia. II. Oxygen-isotope, mineralogical and geochemical evidence for aeolian deposition. *Australian Journal of Soil Research* **26**, 17-31.

CHEN X.Y. 2001. The red clay mantle in the Wagga Wagga region, New South Wales: evaluation of an aeolian dust deposit (Yarabee Parna) using methods of soil landscape mapping. *Australian Journal of Soil Research* **39**, 61-80

CHIQUET A., MICHARD A., NAHON D. & HAMELIN B. 1999. Atmospheric input vs in situ weathering in the genesis of calcretes: an Sr isotope study at Galvez (Central Spain). *Geochimica et Cosmochimica Acta* **63**, 311- 323.

COCK B., WILLIAMS M. & ADAMSON D. 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**, 61-69.

CRICHTON J.G. & CONDIE K.C. 1993. Trace elements as source indicators in cratonic sediments: A case study from the early Proterozoic Libby Creek Group, Southeastern Wyoming. *The Journal of Geology* **101**, 319-332.

Department of Mines and Energy South Australia, (undated). *Brachina George Geological Trail*. Printed by Kitchener Press, Adelaide.

DROSTE J.B. 1961. Clay minerals in sediments of Owens, China, Searles, Panamint, Bristol, Cadiz, and Danby Lake Basins, California. *Bulletin Geology Society America* **72**, 1713-1722, Washington.

FAURE G. 1986. Principles of Isotope Geology. 2nd ed. John Wiley and Sons, New York.

FODEN J., BAROVICH K., JANE M. & O'HALLORAN G. 2001. Sr-isotopic evidence for Late Neoproterozoic rifting in the Adelaide Geosyncline at 586 Ma: implications for a Cu ore forming fluid flux. *Precambrian Research* **106**, 291-308.

FÖRSTNER U. 1977. Mineralogy and geochemistry of sediments in arid lakes of Australia. *Geologische Rundschau* **66**, 146-156.

GATEHOUSE R.D., WILLIAMS I.S. & PILLANS B.J. 2001. Fingerprinting windblown dust in southeastern Australian soils by uranium-lead dating of detrital zircon. *Australian Journal of Soil Research* **39**, 7-12.

GREENE R., GATEHOUSE R., SCOTT K. & CHEN X.Y. 2001. Aeolian dust-implications for Australian mineral exploration and environmental management. *Australian Journal of Soil Research* **39**, 1-6.

GRIM R.E. 1968. Clay Mineralogy. 2nd ed. 596pp, McGraw Hill, New York.

JOHNS R.K. 1968. Report of Investigations No 31, Part 1, *Investigation of Lake Torrens*. Department of Mines South Australia, Adelaide.

LEMON N.M. 1996. Geology. In: Davies M., Twidale C.R & Tyler M.J. eds. *Natural History of the Flinders Ranges*, pp.14-29. Royal Society of South Australia, Adelaide.

LIU TUNGSHENG. ed. 1991. Loess, Environment and Global Change. Science Press, Beijing.

MAGEE J.W., BOWLER J.M., MILLER G.H. & WILLIAMS D.L.G. 1995. Stratigraphy, sedimentology, chronology and palaeohydrology of Quaternary lacustrine deposits at Madigan Gulf, Lake Eyre, South Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology* **113**, 3-42.

MCKENZIE N.J., COUGHLAN K.J. & CRESSWELL H.P. 2002. Australian Soil and Land Survey Handbook Series vol. 5, Soil physical measurement and interpretation for land evaluation, Particle size analysis. CSIRO Publishing.

MCTAINSH G.H. & LYNCH A.W. 1996. Quantitative estimates of the effect of climate change on dust storm activity in Australia during the Last Glacial Maximum. *Geomorphology* **17**, 263-271.

NESBITT H.W. 1979. Mobility and fractionation of rare earth elements during weathering of a granodiorite. *Nature* **279**, 206-210.

PREISS W.V. 1999. Parachilna, South Australia 1:250 000 map sheet and explanatory notes. Primary Industries and Resources South Australia, Openbook Publishers, Adelaide.

QUADE J., CHIVAS A.R. & MCCULLOCH M.T. 1995. Strontium and carbon isotope tracers and the origins of soil carbonate in South Australia and Victoria. *Palaeogeography, Paleoclimatology, Palaeoecology* **113**, 103-117.

SCHMID R.M. 1985. Lake Torrens, South Australia: sedimentation and hydrology. Ph.D. Thesis in the School of Earth Sciences, Flinders University of South Australia (unpubl).

SCHMID R.M. 1989. The exploration potential of Lake Torrens, South Australia. *Quarterly Geological Notes* **10**, 9-11. Issued by the Geological Survey of South Australia, Adelaide.

SIMONSON R.W. 1995. Airborne dust and its significance to soils. *Geoderma* **65**, 1-43.

STANLEY J. 2002. X-Ray Fluorescence: sample preparation, instrumentation and results. Department of Geology and Geophysics, Adelaide University (unpubl).

TURNER S., FODEN J., SANDIFORD M. & BRUCE D. 1993. Sm-Nd isotopic evidence for the provenance of sediments from the Adelaide fold belt and southeastern Australia with implications for episodic crustal addition. *Geochimica et Cosmochimica Acta* **57**, 1837-1856.

WILLIAMS M. 2000. Quaternary Australia: Extremes in the last glacial-interglacial cycle. In: Veevers J.J. ed. Billion-year earth history of Australia and neighbours in Gondwanaland. GEMDC Press, Sydney. pp. 55-59.

WILLIAMS M., DE DECKKER P., ADAMSON D. & TALBOT M.R. 1991. Episodic fluviatile, lacustrine and aeolian sedimentation in a late Quaternary desert margin system, central western New South Wales. In: WILLIAMS M., DE DECKKER P., KERSHAW A. P. eds. *The Cainozoic in Australia: a re-appraisal of the evidence*. Special Publication No. **18**, 258 –287. Geological Society of Australia, Sydney.

WILLIAMS M., DUNKERLEY D., DE DECKKER P., KERSHAW P. & CHAPPELL J. 1998. Quaternary Environments, second edition. Arnold, London, pp. 329.

WILLIAMS M., PRESCOTT J.R., CHAPPELL J., ADAMSON D., COCK B., WALKER K. & GELL P. 2001. The enigma of a late Pleistocene wetland in the Flinders Ranges, South Australia. *Quaternary International* **83-85**, 129-144.

Figure Captions

Figure 1 - Location of Brachina Gorge study site in the central Flinders Ranges and Lake Torrens that lies to the west of the Flinders Ranges South Australia. The elevation of the Flinders Ranges and mean annual rainfall isohyets are also shown (Figure 1 taken from Cock et al. 1999).

Figure 2 - Detailed cross section of the study site, Brachina Gorge, showing steeply dipping Proterozoic and Cambrian units that decrease in age (young) to the west. The section shows the resistant quartzite and sandstone units that form the ranges and the more readily eroded shale, siltstone and limestone units that make up the valleys (Preiss 1999). Brachina Creek and its tributaries are seen to cut through the ABC and Heysen Range and flow west towards Lake Torrens. Sampling locations are, ▪ ridge top samples ● valley fill samples, (Figure 2 is adapted from Department of Mines and Energy South Australia undated; Williams et al. 2001).

Figure 3 - Particle size distribution of the 2 – 2000μm fraction of the ridge-top samples, as determined by pipette analysis and dry sieving.

Figure 4 - Particle size distribution of the 2 – 2000μm fraction of the valley-fill samples, as determined by pipette analysis and dry sieving.

Figure 5 – X-ray diffraction spectra obtained from clay fraction (<2μm) of the ridge top samples a) ABC - 5BF, b) Rawnsley - 6AF, c) Bonney - 6DF, d) Brachina - 3AF. The clay minerals identified from the peaks are, I= illite, K= kaolinite, Q=quartz, S= smectite.

Figure 6 – Zr concentrations of ridge top samples compared to the underlying bedrock.

Figure 7 – Ti concentrations of ridge top samples compared to the underlying bedrock.

Figure 8 – Trace element plot of ridge top samples, underlying bedrock and average Bunyeroo (n=5) and average Brachina (n=2) Formations.

Figure 9 - The $^{87}Sr/^{86}Sr$ - isotopic composition and range of specific leachate samples, whole rock data taken from Turner et al. (1993), Foden et al. (2001), Calver (2000) and ocean values taken from Faure (1986). The number of samples used in each unit is indicated.

Figure 10 - The $^{87}Sr/^{86}Sr$ - isotopic composition and range of specific residue samples and whole rock data taken from Turner et al. (1993), Foden et al. (2001), Calver (2000). The number of samples used in each unit is indicated.

Figure 11 – Correlation plots of trace elements Th, Y, La, Cr, Ce and Nd vs Al_2O_3, includes line of best fit and regression R^2 values. Sample identification ♦- ridge top samples, ●- quartzites, X- Bunyeroo Formation, o- Brachina Formation, ■- Lake Torrens.

Figure 12- Trace element plot of ridge top and Lake Torrens samples, ж- 5BF, + - 6AF, X - 6DF and ▪ - LT samples.

Figure 13- Al_2O_3 vs TiO_2, plot of Lake Torrens and Flinders shale units (Bunyeroo and Brachina Formations).

Figure 14- Isotope graph- $^{87}Sr/^{86}Sr$ vs $^{143}Nd/^{144}Nd$.

Table Captions

Table 1 – Colour and texture of Lake Torrens samples.

Table 2 – Particle size analysis data.

Table 3 – Lake Torrens XRD data.

Table 4 – Major element data.

Table 5 – Trace and Major element data of Bunyeroo and Brachina Formations.

Table 6 – Trace element data.

Table 7 – Sr and Nd whole rock isotope data.

Table 8 – Sr and Nd isotope data, Flinders Ranges and Lake Torrens.

Figure 1

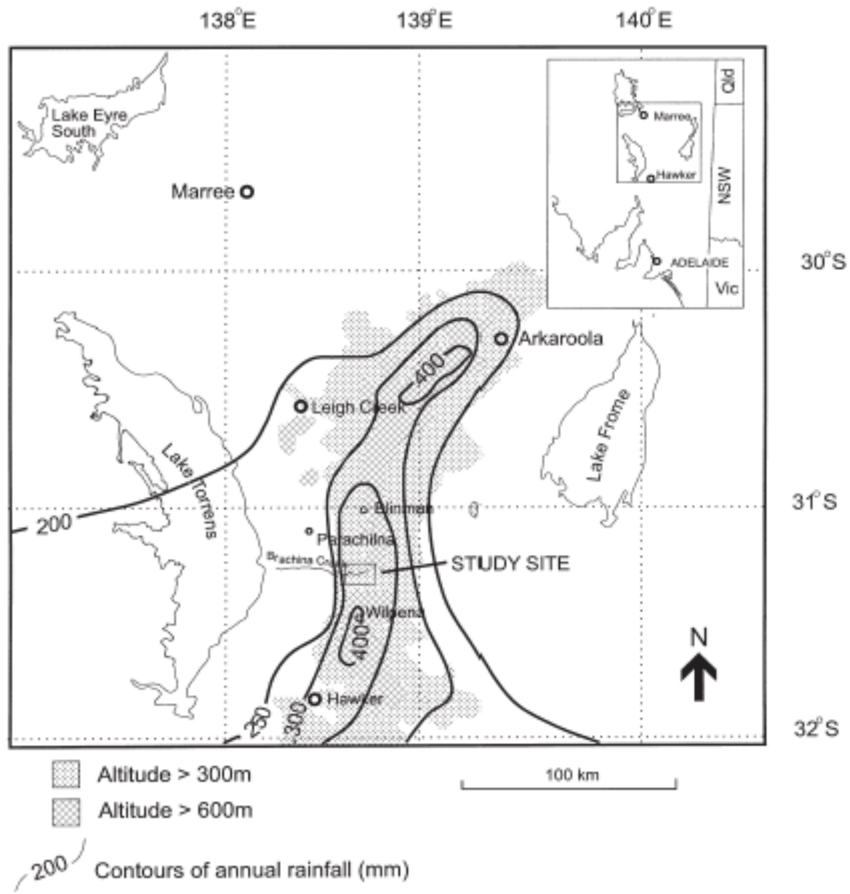
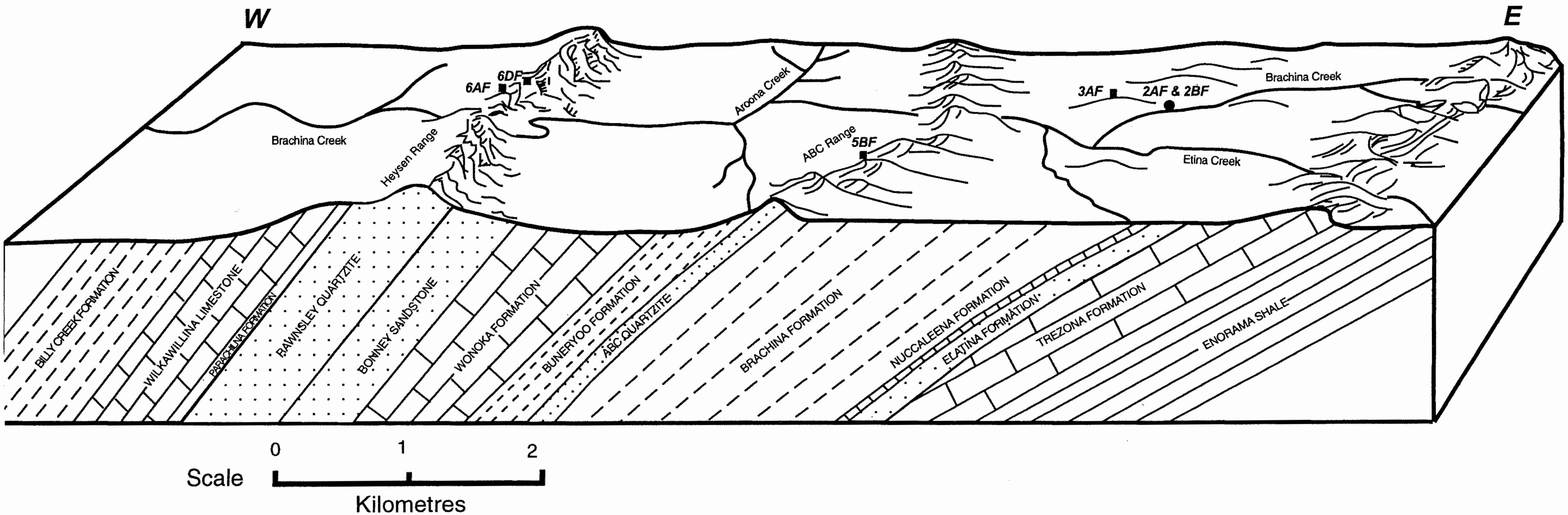

138°E
139°E
140°E
30°S
31°S
32°S
Lake Eyre South
Marree
Qld
NSW
Vic
Hawker
ADELAIDE
Arkaroola
Leigh Creek
Lake Torrens
Lake Frome
Blinman
Parachilna
Brachina Creek
STUDY SITE
Wilpena
Hawker
200
250
300
400
N
100 km
Altitude > 300m
Altitude > 600m
200
Contours of annual rainfall (mm)

Figure 2



Sample Locations and sample number

▪ - Ridge top sample

● - Valley fill sample

Figure 3

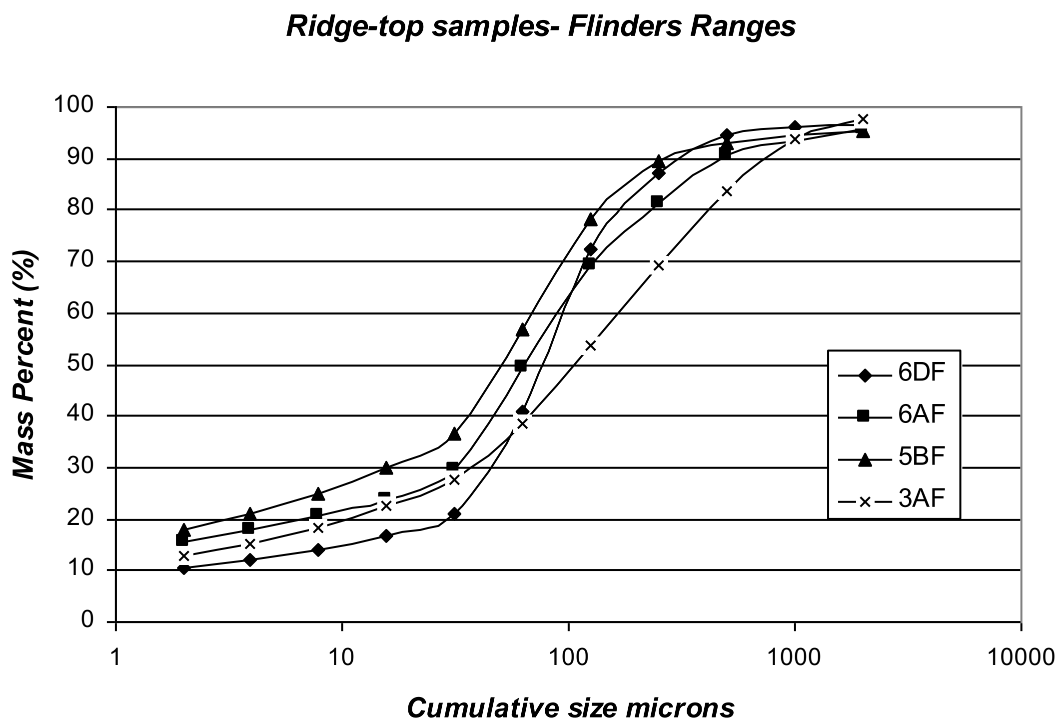

Ridge-top samples- Flinders Ranges
Mass Percent (%)
100
90
80
70
60
50
40
30
20
10
0
1
10
100
1000
10000
Cumulative size microns
6DF
6AF
5BF
3AF

Figure 4

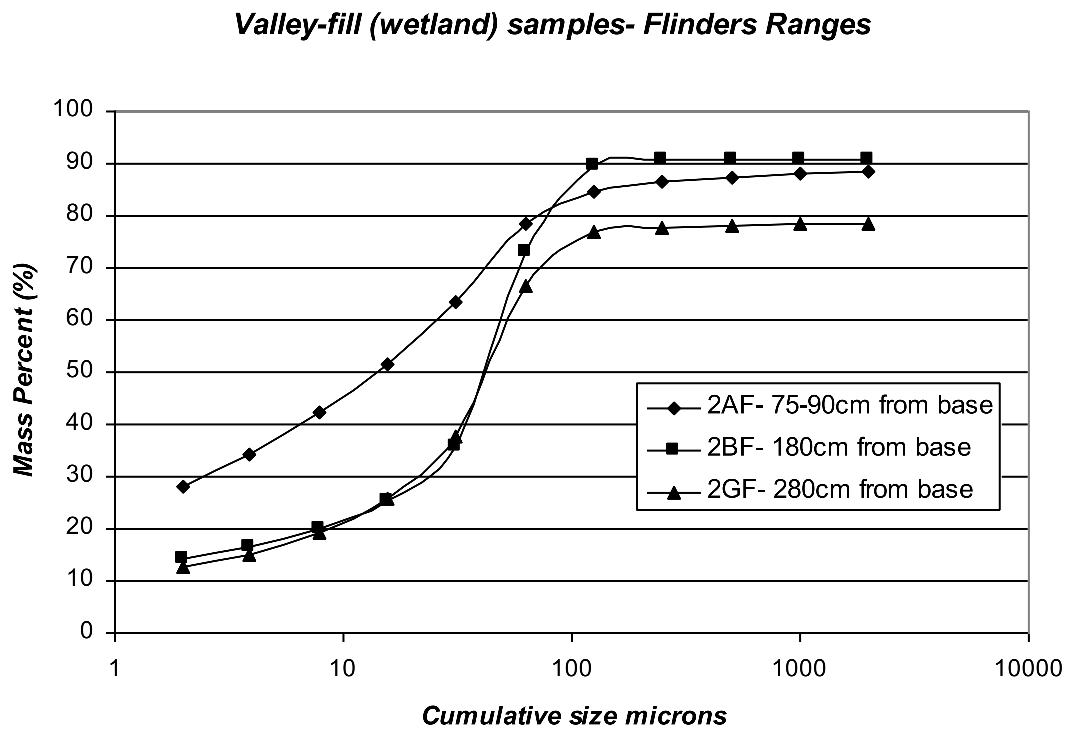

Valley-fill (wetland) samples- Flinders Ranges
Mass Percent (%)
100
90
80
70
60
50
40
30
20
10
0
1
10
100
1000
10000
Cumulative size microns
2AF- 75-90cm from base
2BF- 180cm from base
2GF- 280cm from base

Figure 5

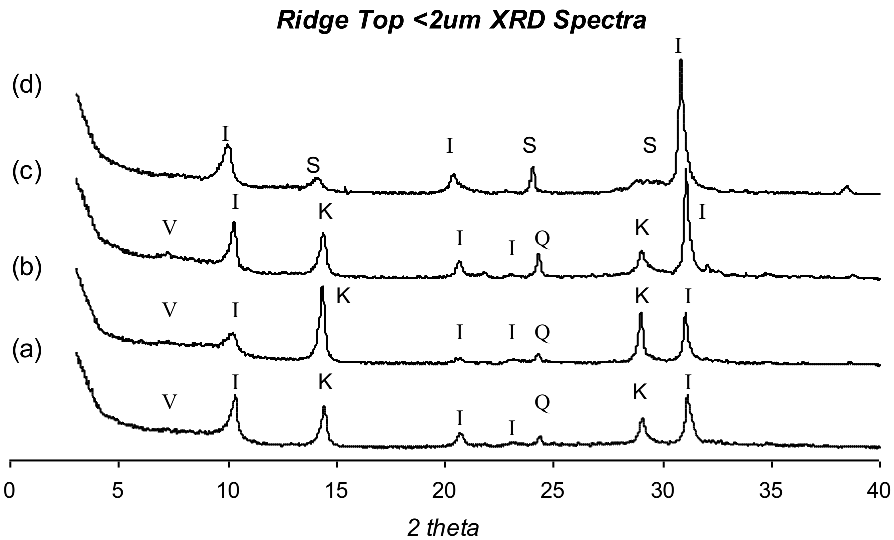

Ridge Top <2um XRD Spectra
(d)
(c)
(b)
(a)
I
S
I
S
S
I
V
I
K
I
I
Q
K
I
V
I
K
I
I
Q
K
I
V
I
K
I
I
Q
K
I
0
5
10
15
20
25
30
35
40
2 theta

Figure 6

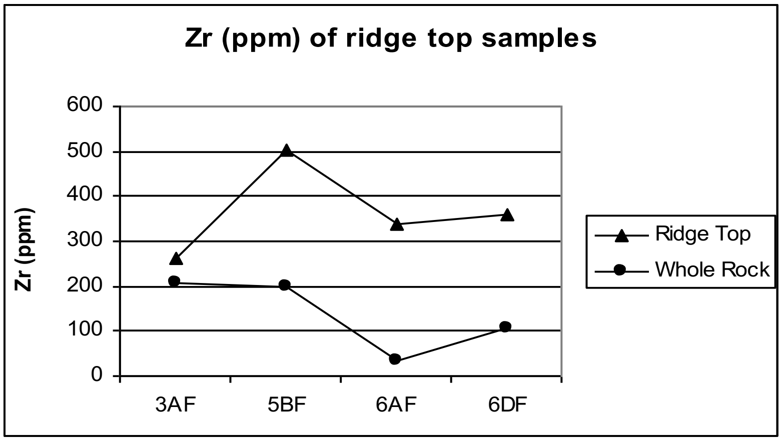


Figure 7

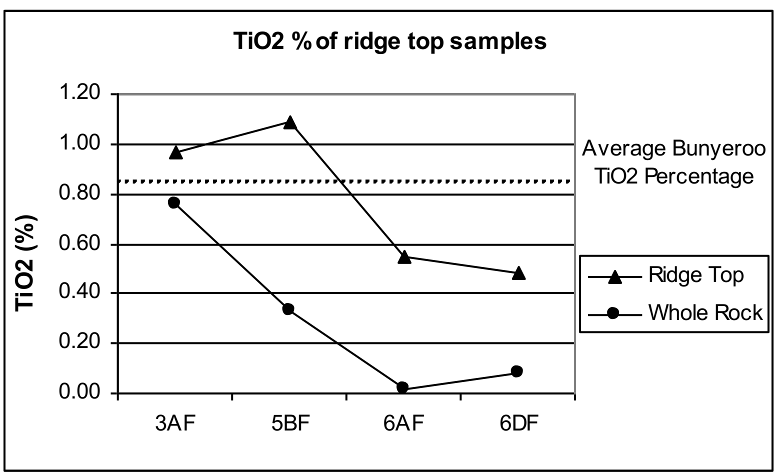


Figure 8

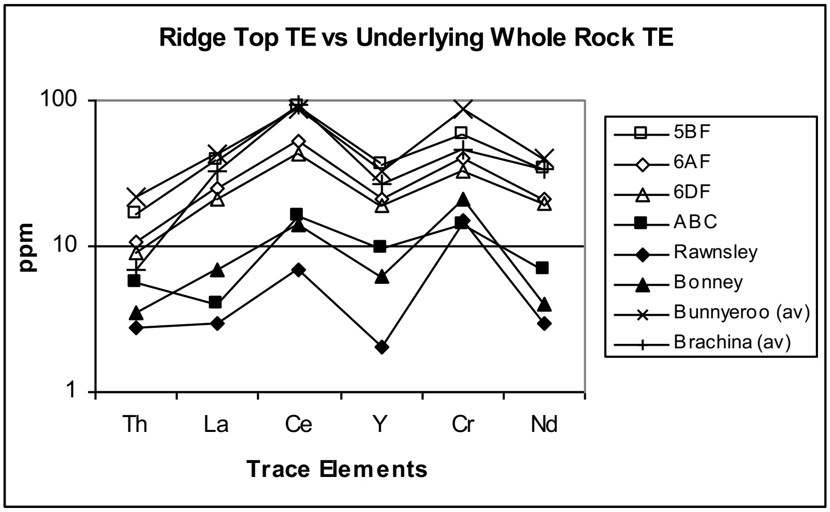

Ridge Top TE vs Underlying Whole Rock TE
100
10
1
ppm
Th
La
Ce
Y
Cr
Nd
Trace Elements
5BF
6AF
6DF
ABC
Rawnsley
Bonney
Bunnyeroo (av)
Brachina (av)

Figure 9

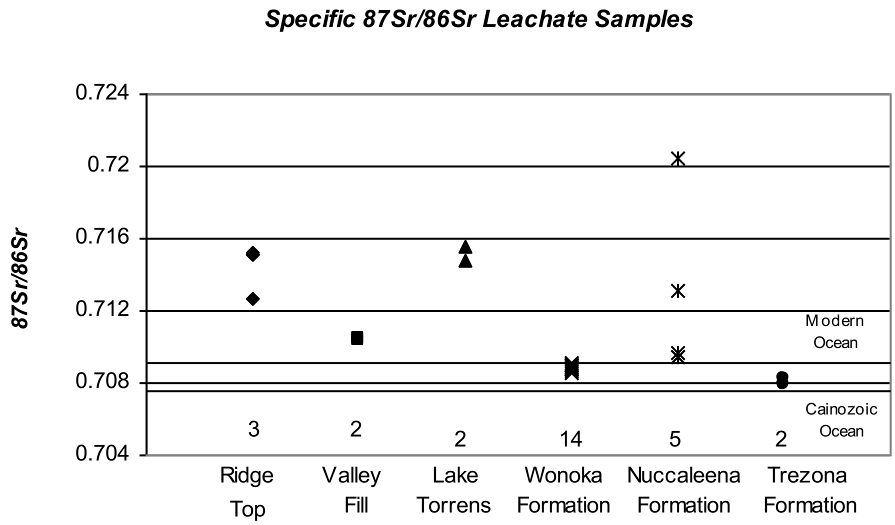


Figure 10

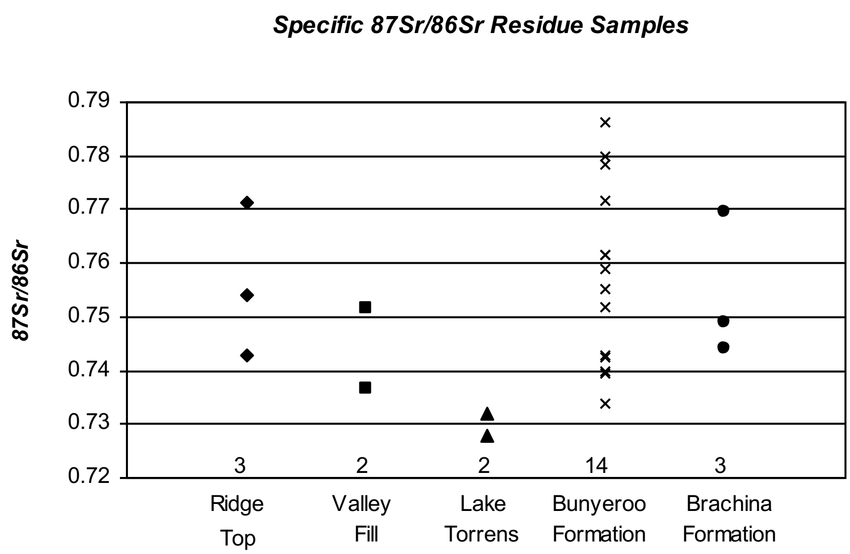


Figure 11

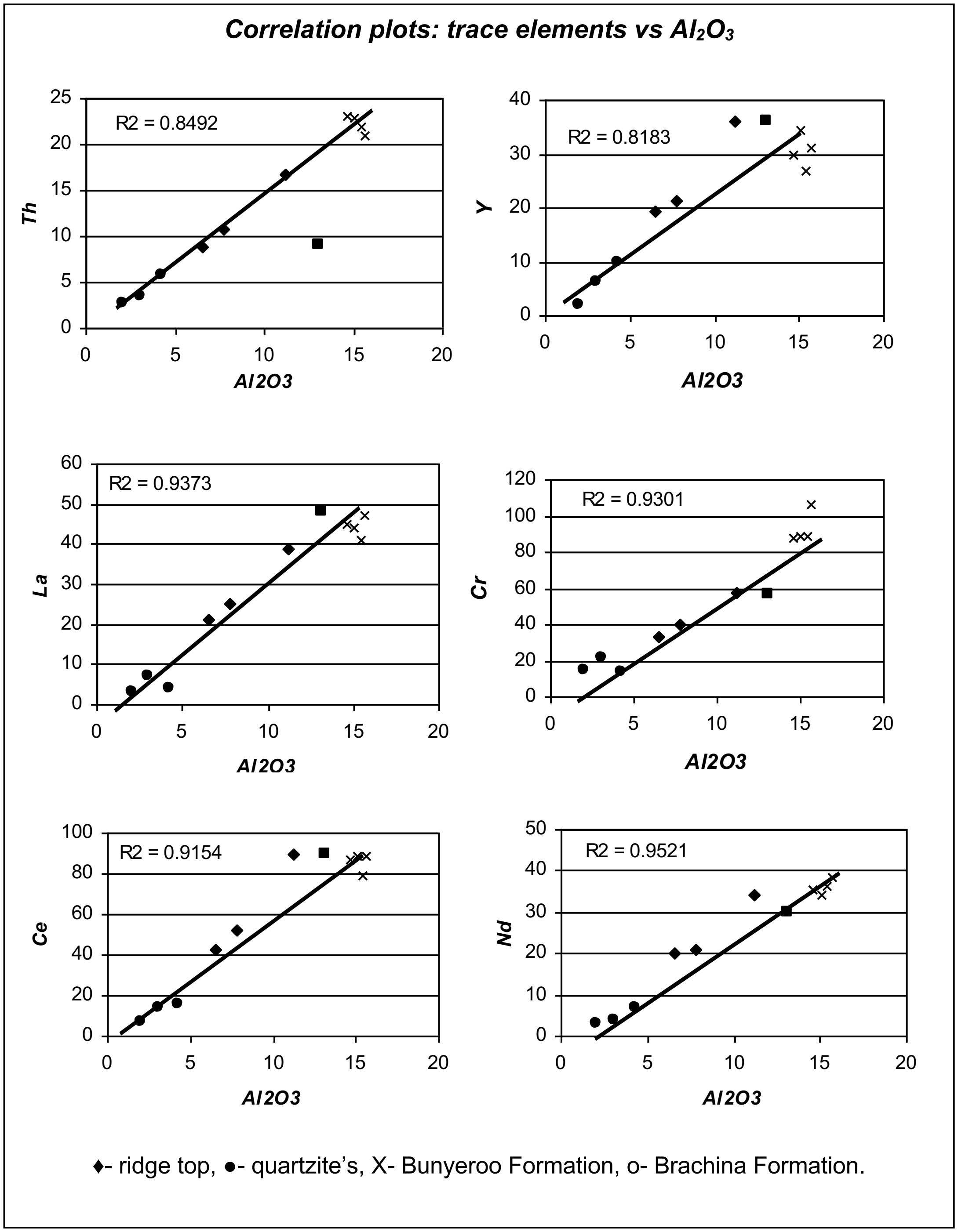

Correlation plots: trace elements vs Al₂O₃
R2 = 0.8492
Th
Al2O3
R2 = 0.8183
Y
Al2O3
R2 = 0.9373
La
Al2O3
R2 = 0.9301
Cr
Al2O3
R2 = 0.9154
Ce
Al2O3
R2 = 0.9521
Nd
Al2O3
♦- ridge top, ●- quartzite's, X- Bunyeroo Formation, o- Brachina Formation.

Figure 12

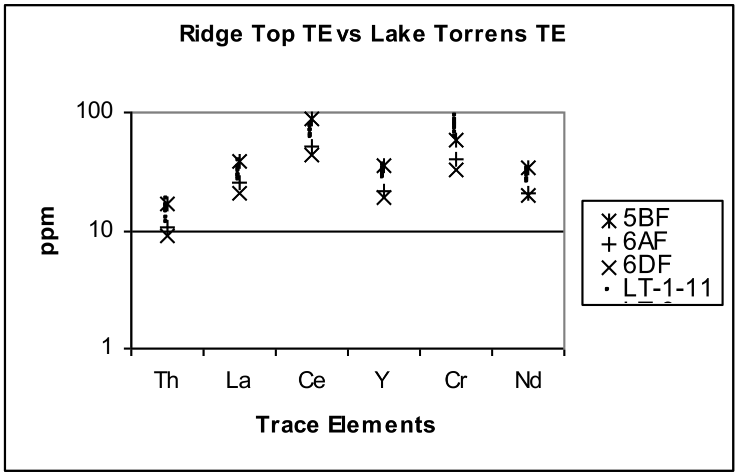


Figure 13

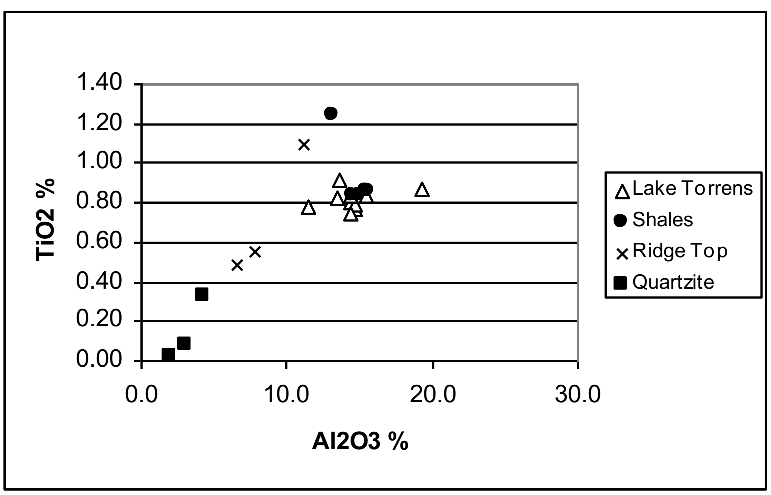


Figure 14

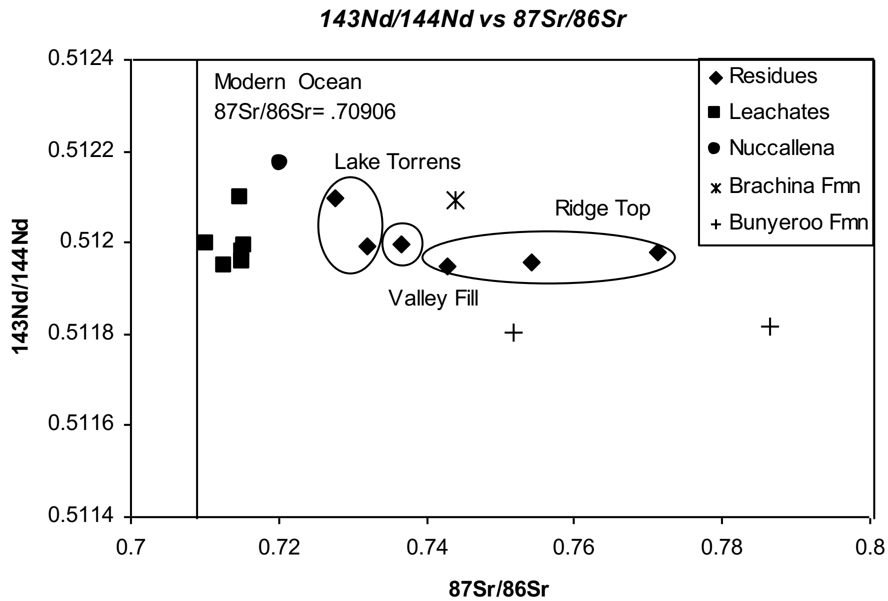

143Nd/144Nd vs 87Sr/86Sr
Modern Ocean
87Sr/86Sr= .70906
Lake Torrens
Ridge Top
Valley Fill
Residues
Leachates
Nuccallena
Brachina Fmn
Bunyeroo Fmn
143Nd/144Nd
87Sr/86Sr
0.5124
0.5122
0.512
0.5118
0.5116
0.5114
0.7
0.72
0.74
0.76
0.78
0.8

Table 1
Flinders Ranges Samples.

Sample	GPS locations	Colour- dry	Colour- wet	*Field Description and Texture, by N. Nitschke 2002*
2AF	273498- 6530623	7.5YR 5/4	7.5YR 4/6	medium to fine sandy clay -50% clay
2BF	273498- 6530623	7.5YR 5/6	7.5YR 4/6	medium to fine sandy clay -35% clay
2GF	273498- 6530623	7.5YR 4/6	7.5YR 4/7	silty clay loam some stones present
*3AF**	272391- 6530819	7.5YR 4/4	7.5YR 2/3	medium to coarse loamy sand
*5BF**	268162- 6522355	7.5YR 4/6	7.5YR 3/4	very fine to medium sandy clay
*6AF**	267902 -6531080	7.5YR 4/6	5YR 2/4	medium sandy loam
*6DF**	268084- 6531142	7.5YR 4/4	7.5YR 2/3	medium sandy loam slightly less clay

* whole rock samples of the underlying bedrock at the ridge top locations were also taken.

Lake Torrens Bore 3.

Sample	Depth	Colour- dry	Colour- wet	*Bore No. 3 Log Description, by R.K. Johns 1968*
LT- 1	4-5ft	-	7.5YR 4/6	chocolate brown clay, sandy in part
LT- 2	20-21ft	-	10YR 3/1	blue-grey clay with some gypsum
LT- 3	21-26ft	-	5YR 3/6	dark brown clay with occasional selenite crystals
LT- 4	37-44ft	-	5YR 4/6	brown Clay
LT- 5	44-50ft	-	5YR 4/6	brown Clay
LT- 6	79-85ft	-	7.5YR 8/3 [+]	off-white fine seed gypsum
LT- 7	99-105ft	-	5YR 4/8	orange brown, dark brown clay, silty in parts
LT- 8	105-115ft	-	7.5YR 4/4	orange brown, dark brown clay, silty in parts
LT- 9	118-121ft	-	7.5YR 4/6	orange brown silty clay
LT- 10	138-151ft	-	5YR 4/6	brown silty clay
LT- 11	153-154ft	-	7.5YR 4/6	brown silty clay

[+] mottled with some 2.5YR 7/2

Table 2
Particle size analysis data of the ridge top and valley fill profiles, as determined by pipette analysis and dry sieving.

	Cumulative total percentage (%) less than a given apparent spherical diameter										
Sample	<2µm	<3.9µm	<7.8µm	<15.6µm	<31.2µm	<63µm	<125µm	<250µm	<500µm	<1000µm	<2000µm
*2AF**	28.01	34.2	42.2	51.4	63.5	78.3	84.7	86.5	87.5	88	88.3
*2BF**	14.4	16.4	20	25.4	36	72.9	89.6	90.7	90.9	90.9	90.9
*2GF**	12.7	15.1	19.2	25.7	37.8	66.3	76.8	77.8	78.2	78.5	78.6
3AF	12.7	15.1	18.2	22.4	27.5	38.5	53.8	69.4	83.5	93.9	97.7
5BF	17.9	21.1	25.1	29.9	36.7	56.8	78.3	89.4	92.8	94.5	95.4
6AF	15.5	17.8	20.4	23.6	29.4	49.3	69.3	81.2	90.6	93.5	95.8
6DF	10.6	12	13.9	16.6	21.2	40.8	72.6	87.1	94.7	96.2	96.5

*- carbonate present in sample Pretreatment P-3 used, % is made up with CaCO3

Table 3
XRD analysis of Lake Torrens Bore 3. samples.

Sample	Depth (m)	Minerals Present
LT-1	1.2 - 1.5	quartz major with minor halite and calcite Clay minerals- illite and kaolinite (1MD)
LT-2	6.1 - 6.4	quartz major with minor halite, calcite and gypsum Clay minerals- illite and kaolinite (1T)
LT-3	6.4 - 7.9	quartz major with minor gypsum and calcite Clay minerals- illite and kaolinite (1T)
LT-4	11.3 - 13.4	quartz major with minor halite and calcite Clay minerals- illite and kaolinite (1MD)
LT-5	13.4 - 15.3	quartz major with minor gypsum and calcite Clay minerals- illite and kaolinite (1T)
LT-6	24.1 - 25.9	gypsum and quartz major
LT-7	30.2 - 32	quartz and clay mineral major Clay minerals- illite and kaolinite (1T) increase in %
LT-8	32 - 35.1	quartz and clay mineral major with minor halite Clay minerals- illite and kaolinite (1T)
LT-9	36 - 36.9	quartz major with minor halite Clay minerals- illite and kaolinite (1T)
LT-10	42.1 - 46.1	quartz dominant Clay minerals- illite and kaolinite (1T)
LT-11	46.7 - 47	quartz dominant Clay minerals- illite and kaolinite (1T)

Table 4
Elemental composition of the Flinders Ranges soil samples, Lake Torrens Bore 3 samples and Flinders Ranges whole rock units, as determined by X-ray fluorescence spectroscopy.

	Element concentration (%)												
SAMPLE	*SiO2*	*Al2O3*	*Fe2O3*	*MnO*	*MgO*	*CaO*	*Na2O*	*K2O*	*TiO2*	*P2O5*	*SO3*	*LOI*	*Total*
1BF	78.38	9.19	3.72	0.05	1.07	1.13	0.30	1.41	0.58	0.08	0.03	3.86	99.79
1CF	68.23	8.59	3.50	0.04	1.30	7.51	0.42	1.36	0.56	0.12	0.12	8.53	100.29
2AF	57.92	13.15	5.68	0.08	2.89	5.33	1.63	2.35	0.82	0.12	0.11	9.39	99.48
2BF	70.36	10.33	3.84	0.02	1.86	3.03	1.67	2.31	0.76	0.10	0.10	5.48	99.86
3AF	66.21	12.74	9.89	0.13	1.56	0.27	0.61	3.07	0.97	0.14	0.01	3.80	99.39
5BF	71.25	11.18	4.22	0.06	0.92	0.33	0.38	2.87	1.09	0.18	0.02	6.68	99.19
6AF	79.00	7.77	2.87	0.04	0.70	0.34	0.37	1.51	0.55	0.09	0.01	5.85	99.10
6DF	81.10	6.52	2.14	0.03	0.56	0.29	0.34	2.27	0.48	0.07	0.01	4.83	98.63
LT1	62.81	11.44	5.02	0.13	3.38	1.84	3.52	2.20	0.78	0.12	0.44	7.76	99.45
LT2	55.69	14.76	5.67	0.05	4.21	2.93	2.70	2.55	0.77	0.12	0.96	9.48	99.91
LT3	59.31	14.43	6.33	0.07	4.68	1.85	1.72	2.58	0.80	0.14	0.15	7.41	99.46
LT4	60.16	14.66	6.31	0.09	4.30	1.12	2.13	2.39	0.79	0.14	0.10	7.35	99.54
LT5	56.54	14.37	6.16	0.09	4.31	1.21	3.58	2.23	0.75	0.11	0.14	9.26	98.76
LT6	27.39	3.39	1.34	0.01	0.96	26.84	0.41	0.56	0.22	0.09	36.23	4.41	101.86
LT7	54.51	19.25	8.22	0.09	3.11	0.52	1.42	3.48	0.87	0.19	0.08	7.98	99.72
LT8	60.15	15.52	6.84	0.09	2.85	0.67	2.45	2.87	0.83	0.15	0.12	7.23	99.76
LT9	63.89	13.64	6.14	0.08	2.33	0.70	2.62	2.89	0.92	0.11	0.06	6.20	99.57
LT10	62.73	14.46	6.54	0.09	2.41	0.39	2.56	2.82	0.83	0.11	0.08	6.32	99.35
LT11	65.72	13.49	6.05	0.21	1.88	0.19	2.43	2.72	0.82	0.10	0.09	5.78	99.48
WILKAWILLINA	1.38	0.43	0.77	0.17	19.69	30.37	0.21	0.05	0.06	0.05	0.10	45.75	99.02
PARACHILNA	73.60	10.47	5.36	0.05	1.52	0.57	3.36	1.26	0.99	0.17	0.03	1.75	99.12
RAWNSLY	95.15	2.04	0.07	0.00	0.03	0.03	0.00	0.20	0.02	0.01	0.01	0.67	98.23
BONNEY	89.07	3.05	0.35	0.00	0.14	0.03	0.00	1.64	0.08	0.01	0.01	0.51	94.89
WONOKA	2.23	0.43	1.57	0.68	18.94	29.64	0.20	0.08	0.05	0.05	0.09	45.04	99.01
BUNYEROO	58.59	15.05	8.23	0.11	3.67	1.06	1.69	4.06	0.84	0.12	0.04	4.15	97.62
ABC	88.74	4.28	0.88	0.00	0.16	0.07	0.00	1.38	0.33	0.09	0.01	1.15	97.08
BRACHINA	62.75	4.23	27.72	0.54	1.86	0.16	0.04	0.25	0.17	0.06	0.01	2.19	99.97
NUCCALEENA	8.00	1.93	1.39	0.17	17.99	27.44	0.49	0.41	0.15	0.08	0.08	41.34	99.49
ELATINA	74.80	5.15	1.53	0.04	0.99	5.06	1.11	1.15	0.22	0.06	0.06	4.90	95.06
TREZONA	5.88	0.92	1.29	0.02	1.58	47.01	0.21	0.10	0.09	0.12	0.13	40.01	97.35

Table 5
Combined elemental data* of the Flinders Ranges Brachina and Bunyeroo Formations.

	Element concentration (%)											
SAMPLE	*SiO2*	*Al2O3*	*Fe2O3*	*MnO*	*MgO*	*CaO*	*Na2O*	*K2O*	*TiO2*	*P2O5*	*LOI*	Total
Brachina[1] 819-84	68.42	13.11	6.95	0.05	2.22	0.43	3.05	1.23	1.24	0.24	2.63	99.57
Brachina[1] 474-K	59.51	15.55	6.93	0.16	5.14	2.86	1.68	5.30	0.76	0.19	1.02	99.10
Bunyeroo[1] 939-90-13	60.08	15.66	8.25	0.08	3.43	0.63	1.83	4.97	0.86	0.15	4.00	99.94
Bunyeroo[1] 939-90-15	57.07	14.61	7.81	0.20	3.93	2.91	1.71	4.15	0.83	0.13	6.62	99.97
Bunyeroo[1] 939-90-16	59.61	15.40	11.48	0.47	2.50	0.35	0.41	4.84	0.86	0.15	3.76	99.83

	Element concentration (ppm)																
SAMPLE	Zr	Nb	Y	Sr	Rb	U	Th	Pb	Ga	Ni	Ba	V	Ce	Nd	La	Cr	Sc
Brachina[1] 819-84	205	15	36	55	56	3.	9	48	14	31	236	110	90	29	48	57	11
Bunyeroo[1] 939-90-13	164	15	31	90	192	2	21	19	23	48	445	132	89	38	47	106	18
Bunyeroo[1] 939-90-14	303	15	44	80	77	3	21	8	12	22	515	132	86	54	35	63	8
Bunyeroo[1] 939-90-15	175	16	30	78	186	3	23	53	20	46	416	112	87	35	45	88	18
Bunyeroo[1] 939-90-16	171	17	27	53	220	3	22	11	21	54	408	108	79	36	41	89	17

* Data sources (1) Turner et al. (1993)

Table 6
Elemental composition of the Flinders Ranges sediment samples, Lake Torrens Bore 3 samples (LT 1 – LT 11) and Flinders Ranges whole rock samples.

	Trace element concentration (ppm)																			
SAMPLE	*Zr*	*Nb*	*Y*	*Sr*	*Rb*	*U*	*Th*	*Pb*	*Ga*	*Cu*	*Zn*	*Ni*	*Ba*	*Sc*	*Co*	*V*	*Ce*	*Nd*	*La*	*Cr*
1BF	218	9	23	98	57	2	12	13	12	18	50	19	277	11	25	82	52	24	24	50
1CF	237	9	21	136	56	1	10	16	11	17	48	18	284	11	23	81	46	20	21	45
2AF	231	13	31	239	103	3	13	16	17	28	74	29	313	16	18	113	62	28	27	69
2BF	285	12	23	144	94	3	13	16	13	17	45	20	345	11	12	92	48	20	20	54
3AF	261	16	34	40	150	4	18	17	19	18	96	40	335	18	27	136	77	27	32	99
5BF	503	17	36	68	124	3	17	21	15	20	52	16	668	12	17	106	90	34	39	58
6AF	336	10	21	50	62	2	11	17	11	27	42	12	288	9	21	68	52	21	25	40
6DF	361	8	19	48	87	3	9	15	8	12	29	11	407	7	21	51	43	20	21	33
LT1	275	12	29	145	92	4	13	14	16	24	69	25	417	13	16	111	62	26	27	60
LT2	195	11	30	235	101	8	12	60	19	45	129	36	400	17	31	150	65	26	28	72
LT3	221	12	31	145	105	3	14	14	21	27	188	31	422	16	20	129	69	29	29	74
LT4	207	11	30	104	95	6	12	17	20	31	490	29	370	14	19	128	70	26	28	66
LT5	189	10	28	98	93	6	14	20	20	31	748	28	356	15	19	131	63	25	29	71
LT6	70	5	6	627	20	1	5	6	6	8	50	8	120	6	12	33	17	2	6	16
LT7	186	13	35	99	142	4	18	23	27	42	119	38	302	20	20	150	79	32	38	93
LT8	214	13	33	99	122	2	16	22	22	35	247	34	409	16	20	139	74	31	34	84
LT9	245	15	36	79	124	4	15	22	19	31	89	31	431	16	16	137	74	33	34	77
LT10	217	14	33	72	127	2	16	24	21	30	84	36	412	17	20	147	75	30	33	82
LT11	253	14	32	75	118	3	15	29	19	30	84	34	489	14	26	124	70	27	31	78
WILKAWILLINA	12	1	4	83	5	2	4	16	2	2	347	2	69	21	25	17	0	3	7	*
PARACHILNA	329	14	28	58	49	3	14	7	11	7	60	27	578	63	75	50	22	21	45	7
RAWNSLY	32	1	2	9	9	1	3	6	4	4	0	3	70	124	3	7	3	3	15	0
BONNEY	106	3	6	20	57	1	3	7	5	3	3	5	285	103	10	14	4	7	21	1
WONOKA	11	1	10	77	6	2	5	11	1	20	28	3	197	19	24	15	5	3	1	*
BUNYEROO	177	18	34	61	188	2	23	21	22	9	110	53	1324	40	137	89	34	44	89	18
ABC	198	5	10	29	53	1	6	6	5	6	3	4	609	124	22	16	7	4	14	2
BRACHINA	68	3	18	15	10	0	5	13	10	14	88	43	219	38	112	95	38	18	36	10
NUCCALEENA	35	2	7	62	20	1	5	3	3	4	24	6	32	20	22	19	2	4	7	0
ELATINA	140	5	10	44	45	2	3	2	7	4	38	10	344	55	33	22	7	8	18	4
TREZONA	11	2	3	933	7	2	5	5	1	2	17	5	17	19	14	19	0	5	0	*

*** Ca too high for Sc measurement (strong interference on Sc by Ca)**

Table 7
Combined Sr and Nd data* of selected carbonate and shale units from the Flinders Ranges.

Formation	***Sample Number***	***87Sr/86Sr***
Carbonates		
Trezona[2]	Y-3	0.70785
Trezona[2]	Y10	0.70826
Wonoka[2]	WO-1	0.70861
Wonoka[3]	5.44	0.70868
Wonoka[3]	7.19	0.70874
Wonoka[3]	5.52	0.70876
Wonoka[3]	8.35	0.70876
Wonoka[3]	8.38	0.70883
Wonoka[3]	7.21	0.70888
Wonoka[3]	5.54	0.70899
Wonoka[2]	WO-2	0.70900
Wonoka[3]	6.12	0.70901
Wonoka[2]	WO-4	0.70901
Wonoka[2]	WO-3	0.70902
Wonoka[3]	5.36	0.70910
Nuccaleena[2]	N-3	0.70947
Nuccaleena[2]	N-1	0.70948
Nuccaleena[2]	N-2	0.70966
Nuccaleena[3]	22.56	0.71308
Nuccaleena[2]	28-8A	0.72043
Modern Ocean[4]		0.70906
Cenozoic Ocean[4]		0.70770

Formation	***Sample Number***	***87Sr/86Sr***
Shales		
Bunyeroo[2]	CL-x	0.73385
Bunyeroo[2]	CL-x	0.73947
Bunyeroo[2]	CL-x	0.73966
Bunyeroo[2]	CL-x	0.74241
Bunyeroo[2]	CL-x	0.74299
Brachina[1]	819-84	0.74394
Brachina[2]	Lah 124	0.74885
Bunyeroo[1]	939-90-15	0.75185
Bunyeroo[2]	CL-x	0.75528
Bunyeroo[2]	CL-x	0.75883
Bunyeroo[2]	CL-x	0.76157
Bunyeroo[2]	CL-x	0.76173
Brachina[1]	474-K	0.76928
Bunyeroo[2]	CL-x	0.77165
Bunyeroo[2]	CL-x	0.77825
Bunyeroo[2]	CL-x	0.78002
Bunyeroo[1]	939-90-15	0.78633

Formation	***Sample Number***	***143Nd/144Nd***
Shales		
Bunyeroo[1]	939-90-15	0.511803
Bunyeroo[1]	939-90-15	0.511818
Brachina[1]	819-84	0.512092
Carbonates		
Nuccaleena[2]	28-8A	0.512170

* Data sources (1) Turner et al. (1993), (2) Foden et al. (2001), (3) Calver (2000) and (4) Faure (1986).

Table 8
Sr and Nd Isotope data of the ridge top, valley fill and Lake Torrens samples.

Sample	***2AF***	***2BF***	***3AF***	***5BF***	***6AF***	***6DF***	***LT- 5***	***LT- 7***
87Sr/86Sr								
Residue	0.736638	0.751616	0.771339	0.754183	0.742748	-	0.727685	0.732058
2SE	0.000010	0.000020	0.000009	0.000010	0.000027	-	0.000013	0.000011
Leachate	0.710339	0.710402	0.715272	0.715058	0.712618	0.713209	0.714771	0.715549
2SE	0.000012	0.000008	0.000010	0.000008	0.000013	0.000014	0.000012	0.000012
143Nd/144Nd								
Residue	0.5119945	0.5111947	0.5119771	0.5119584	0.5119470	-	0.5120965	0.5119908
2SE	0.000009	0.000009	0.000010	0.000010	0.000009	-	0.000009	0.000008