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Geochemistry and identification of Australian red ochre deposits

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Note
This information has been prepared for students and researchers interested in identifying ochre in archaeological contexts. It is open to use by everyone with the proviso that its use is cited in any publications, using the URL as the place of publication. Any comments regarding the information found here should be directed to the authors at the above address.

Preface

Between 1994 and 1998 the authors undertook a project to look at the feasibility of using geochemical signatures to identify the sources of ochres recovered in archaeological excavations. This research was supported by AIATSIS research grants G94/4879, G96/5222 and G98/6143.The two substantive reports on this research (listed below) have remained unpublished until now and are brought together in this *Palaeoworks Technical Paper* to make them more generally accessible to students and other researchers.

Smith, M. A. and B. Fankhauser (1996) **An archaeological perspective on the geochemistry of Australian red ochre deposits: Prospects for fingerprinting major sources.** A report to the Australian Institute of Aboriginal and Torres Strait Islander Studies, Canberra.

Smith, M. A. and B. Fankhauser (2003) **G96/5222 - Further characterisation and sourcing of archaeological ochres.** A report to the Australian Institute of Aboriginal and Torres Strait Islander Studies, Canberra.

The original reports are reproduced substantially as written, with the exception that the tables listing samples from ochre quarries (1996: Tables II/ 1-11) have been revised to include additional samples. We also include the associated datasets as separate word or excel files. Users should note that the 2005 dataset is the latest and most comprehensive of these and includes a listing of laboratory codes cross-referenced to ochre specimen ID. Other publications associated with this project are listed below.

Smith, M. A. and S. Pell (1997) Oxygen-isotope ratios in quartz as indicators of the provenance of archaeological ochres. **Journal of Archaeological Science** 24: 773-778.

Smith, M. A., B. Fankhauser and M. Jercher (1998) The changing provenance of red ochre at Puritjarra rock shelter, central Australia: Late Pleistocene to present. **Proceedings of the Prehistoric Society** 64: 275-292.

Mooney, S. D., C. Geiss and M. A. Smith (2003) The use of mineral magnetic parameters to characterise archaeological ochres. **Journal of Archaeological Science** 30: 511-523.

Smith, M. A. (1999) Ochres. In S. Kleinert and M. Neale (eds), **The Oxford Companion to Aboriginal Art and Culture,** pp.665-666.

Smith, M. A. (2000) Ochre Tracks. **Australian Geographic**. Oct-Dec 2000:19-20. [Giving an account of the Lawa ochre mine]

O'Connor, S. and Fankhauser, B. (2001) Art at 40,000 BP? One step closer: An ochre covered rock from Carpenter's Gap Shelter 1, Kimberley Region, Western Australia. In Anderson, A., Lilley, I. and O'Connor, S. (eds.) **Histories of Old Ages: Essays in Honour of Rhys Jones**, pp. 287-300. Canberra: Pandanus Books.

An archaeological perspective on the geochemistry of Australian red ochre deposits: Prospects for fingerprinting major sources

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Part I - Rationale and general approach

Introduction

The prospect of being able to examine prehistoric trade, customary exchange systems, social boundaries and regional inter-connections has attracted some notable studies of the distribution and petrology of ground-edge axes and grindstones (Binns and McBryde 1972; McBryde 1987) and of pearl shell and baler shell (Akerman and Stanton 1994; Mulvaney 1976) in Australia and of obsidian in the south-west Pacific (e.g.. Ambrose 1975; Kirch 1988; Specht 1981). Of all the materials that lend themselves to such approaches in Australia, red ochre has had the least sustained attention though prehistorians have recognised the potential for such work (Clarke 1976; David et al. 1993; Mulvaney 1976). High-grade red ochre was a much-valued commodity in Aboriginal Australia. The finest and most desirable red ochres in the arid interior of the continent were from celebrated sources such as Wilgie Mia, Bookartoo, Karrku, and Ulpunyali (Clarke 1976; Jones 1984a & b; Peterson & Lampert 1985; Hamilton and Vachon 1985). Ochre from such sources was exchanged over hundreds of kilometres (Mulvaney 1976), often by way of highly organised exchange networks, with formal expeditions to procure red ochre from distant sources (McBryde 1987).

Like grindstones and stone axes, red ochre is amenable to geochemical or petrological sourcing. Our review of the diagenesis of ochre deposits below shows that they are often small discrete sources easily distinguished from one another. Ochre also has some distinct advantages over stone axes and grindstones for studying prehistoric exchanges systems:

a) Unlike stone axes and grindstones, red ochre is frequently found in archaeological excavations (ie. in dated contexts) promising the opportunity to add a time dimension to studies of spatial distribution.

b) It is frequently found in late Pleistocene contexts, where increasingly sophisticated questions about regional networks, boundaries and patterns of movement are being framed. Haematite and other red ochres are found in the earliest levels of archaeological sites across the continent (eg. Bowler and Thorne 1976; Morse 1993; Smith 1987), including sites dating to 40-60,000 years ago (Roberts, Jones and Smith 1990; Roberts et al. 1994).

c) Ochre is often found in sufficient quantity to permit systematic study of temporal changes in prehistoric exchange systems.

The first step towards realising the archaeological potential of these materials is to determine the geochemical and petrological signatures of the major sources. In this study we have attempted to do this for a series of ochre deposits in the interior of the continent - Wilgie Mia, Bookartoo, Karrku, Ulpunyali and Lawa.

Scope of this project

This project is part of a wider study by Smith to investigate the sourcing of red ochres in the Australian arid zone (eg. Smith and Pell in press). In this project we have concentrated on the characterisation of red ochre from:

a) Two major ethnographic ochre mines: Bookartoo in the northern Flinders Ranges (SA) and Wilgie Mia in the Weld Ranges (WA).

b) A series of regional ochre quarries in the western part of central Australia (NT); Karrku in the Campbell Range; Ulpunyali, an ochre mine SW of Kings Canyon; and Lawa believed to be situated near Wallara in the Levi Range.

In order to gain a better appreciation of the potential range of chemical variability in red ochres across the continent we have also analysed a variety of other ochres. These are individual specimens from either museum collections or archaeological collections. None are sourced but all are provenanced at least loosely as to find spot. Our sample includes material from Malakunanja II in western Arnhem Land; Kutikina cave in southwestern Tasmania; as well as miscellaneous material from the MacDonnell ranges in central Australia; the Olary region, north east South Australia; the lower Murray valley; and the Lake Eyre basin.

As a test of the utility of our approach a case study is then presented dealing with geochemical sourcing of red ochres from archaeological excavations at Puritjarra rock shelter in western central Australia Notwithstanding an application to immediate questions about late Pleistocene land use at Puritjarra, the research outlined below is primarily strategic rather than tactical in nature. Potential applications extend beyond archaeology. For instance, if it can be shown that Bookartoo ochre has a distinctive chemical signature there is obvious application to the sourcing of ochre-covered ethnographic objects held in museum collections and perhaps, more problematically, to identifying rock paintings using Bookartoo ochre.

General approach to the problem

In ideal circumstances a study of the geochemistry of red ochre would begin with the diagenesis of such deposits and the geochemical variability introduced by different modes of formation. Unfortunately the diagenesis of such deposits is not well understood except in very general terms (see below). We have found it necessary therefore to structure our analyses of ochres as a first-order exploration of geochemical variability.

There are several aspects to such an investigation:

a) At least in the first instance analysis needs to be restricted to samples of raw ochre (ie unmodified pigments). Ground, powdered or processed ochres may well have an altered chemical composition - something noticed by Smith in a comparison of raw Karrku ochre with material prepared as a cake for exchange. Paints are not suitable at this stage, for the same reasons. Our analysis below does however include two examples of cakes of prepared ochre, one from Bookartoo and the other from Karrku, in order to make some assessment of the extent of the problem this poses.

b) The sensitivity, precision and consistency of the analytical techniques need to be determined to distinguish instrument variability from sample variability.

c) The natural (within-source) variability of each ochre deposit needs to be determined, taking into account factors such as: differential weathering of deposits (and its likely effects upon mobile elements); facies differences across a sedimentary unit (which may effect the grain-size and relative concentrations of iron oxides and quartz); and small stratigraphic differences within a geological unit (eg. beds of ferruginised sandstone may contain thin layers of specular haematite). As some within-source variability is expected to be due to differences in organic content or in the proportion of coarse-grained inclusions we have experimented with different methods of sample preparation (see below): contrasting samples fired to remove organics with unfired samples; and contrasting whole ground samples with settled fines. Primary research on the ochre deposits is the optimal way to study chemical variability at source. However the collapse of the main ethnographic workings at Bookartoo (in ~1870) and at Ulpunyali, and subsequent European exploitation of the ochre deposits at Wilgie Mia (removing the greater part of the ethnographic workings) suggests that such fieldwork would not resolve questions about internal variability of these deposits. Logistical problems (Karrku) and problems in negotiating access with Aboriginal communities (Bookartoo and Ulpunyali) also make direct work on the major ochre mines difficult. The approach we have adopted is to use the variability in museum samples collected from these ochre sources at different times over the last 100 years as a proxy for variability in the deposit. For instance, the S. A. Museum holds well-provenanced samples of ochre from Bookartoo, collected over the last 80 years. Taken together these samples should give some measure (albeit imperfect) of the degree of variability in the Bookartoo source.

d) It is necessary to compare the composition of ochre from a wide range of sources - analysing for a wide range of elements - in order to establish which chemical components best characterise ochre from a particular source. In such comparisons we have worked on the basis that at this stage of research major/minor oxide composition and trace element composition should both be determined and that compositional data will need to be supplemented by data on fabric/petrology, colour and mineralogy.

Structure of this report

Our report in five parts. Part I (above) sets out the rationale for this work and outlines our approach. Part II reviews pertinent data about the major ochre sources and places our samples in historical and geological context. Part III details our analytical methods. Part IV presents results of multivariate analysis of our compositional data. Part V discusses some of the implications of the results and directions for further research.

Part II: Quarries, sources and samples analysed

Bookartoo

Alternative names: Bookatoo, Bukartu, Pukardu Hill

References: Broughton n.d.; Masey 1882; Curr 1886:70; Gason 1874:27; Horne and Aiston 1924:129-130; Howitt 1904:711-13; Jones 1984a and b; Keeling 1984; Shanahan 1904.

Bookartoo is a comparatively well-known ochre quarry in the northern Flinders ranges, South Australia. In the late nineteenth century, Aboriginal people traded Bookartoo ochre extensively throughout the central sector of the Lake Eyre basin, as far north as Boulia (450 km from Bookartoo), as far east as the Darling river and as far west as Oodnadatta (Jones 1984a: 6). Historical and ethnographic sources indicate that this was by means of well-organised expeditions that followed established trade routes, with men carrying red ochre in the form of prepared cakes weighing ~28-35 kg each. None of these large cakes appear to survive in museum collections today and it has yet to be determined whether tangible archaeological evidence of the operation of this exchange system can be identified on the ground. It follows that we know almost nothing about the antiquity of the system. It may equally well have been a product of the contact period, as a long established trading network. This issue could be resolved if future archaeological investigations are allied with the type of geochemical sourcing methods being developed in this project.

The quarry

Bookartoo is located on the western face of Heysen Range, near Parachilna, in the northern Flinders Ranges. The ochre workings cover ~80m^2 and are located on a spur within the foothills. The earliest published account of the Bookartoo workings is by Masey (1882). However, by this time the main mine had collapsed and he could examine only part of the complex. Masey writes

> Owing to the rains and want of support the extensive native workings had fallen in, and could not be explored... (Masey 1882:3).

Although Masey gives an impression that the collapse occurred shortly before his visit in 1882, Shanahan writing in 1904 suggests it occurred in the early 1870s

> About 30 years ago [1874] whilst natives were at the Murragurta site, 30 natives were entombed in the excavations.... (Shanahan 1904 cited in Jones 1984a)

Horne and Aiston (1924:129) also refer to a landslip that buried part of the workings in the 1870s, though it is not clear if they rely on Shanahan or on an independent source for their information. The main ethnographic workings may have consisted of a large subterranean chamber (cf. Karrku - see below) with one or more narrow entrances, excavated into the hillside following the ochre seam.

Dr George Ulrich (cited in Masey 1882), who visited Bookartoo sometime before Masey, provides the earliest description of the ochre quarry, one that closely matches the appearance of the workings today (cf. Keeling 1984).

> ...four narrow openings or burrows made by the natives in extracting the stuff for painting their bodies, and between these places, the deposit is from eight to twelve feet thick. (Ulrich cited in Masey 1882:3)

Later European observers describe a series of small mining pits and at least one cutting into the hillside in the form of a small cave (Broughton n.d.; Jack 1928; Keeling 1984; Masey 1882; Shanahan 1904). For instance, Jack (1928), referring to an earlier report in 1905 by F. R. George, assistant government geologist, describes the workings as

> ... a series of small pits and excavations in the ochre lode; and a small cave about 5 chain [~100m] S.W. there from. (Jack 1928:61)

Keeling (1984:7) describes that the present condition of the workings as comprising

> ...three or four burrows which have since collapsed into four shallow pits now less than 2 m deep.
>
> Five metres south is the entrance to a small underground working 2.4 m deep by 1.2 m wide and 1.5 m high. Here earthy hematite (ochre) mixed with red and white calcite was gouged from joints and fractures 0.2 to 0.6 m wide in pink dolomite.
>
> A smaller burrowing in hematite stained dolomite was found 22 m east of the underground workings.

<u>Diagenesis of the ochre deposit</u>

George (1904 cited in Jack 1928:61) describes the ochre deposit as an inter-stratified lode of haematite and earthy iron oxide, between beds of dolomitic and crystalline limestone ~30 feet (10m) thick. Ulrich (in Masey 1882) commented that to him the deposit had '...less the character of a lode than that of a layer..'. A recent appraisal of the Bookartoo deposit resolves the issue. The deposit is an earthy haematite, infilling joints and fractures in dolomite directly below the contact with a layer of silty limestone (Keeling 1984). Both the dolomite and limestone are lower facies of the early Cambrian <u>Wilkawillina</u> formation of marine origin. Keeling suggests that the diagenesis of this deposit began with initial deposition of iron sulphides (pyrite) in karst cavities in the dolomite. Prolonged oxidation and arid weathering of this surface led to formation and redistribution of haematite in joints and fractures above the water table. This indicates that Bookartoo ochre is of sedimentary rather than hydrothermal origin. The deposit appears to be small and is restricted to an area of strong fracturing where earthy haematite has infilled joints and fractures, in an area approximately 50 x 50 m.

Samples analysed in this project

Our sample includes 8 specimens of Bookartoo ochre collected over the last 90 years, by at least four different people (see Table II/1). As the ochre deposit is relatively small there is a good chance that our sample will take in much of the range of variability in the original deposit. The earliest of the specimens (A1863) was collected in 1904. This is a prepared cake of Bookartoo ochre, obtained by P. F. Shanahan during a red ochre expedition. Two other specimens, (A66497 and A66498), were collected between 1890 and 1905 by J. G. Reuther, a Lutheran missionary, near Killalpaninna on the ochre trade route. On hand examination they closely resemble Bookartoo material. Reuther himself was interested amongst other things in Aboriginal use of red ochre and in the red ochre expeditions and recorded key details in his comprehensive treatise on the Diari ((Reuther 1981 - see Jones 1984a). We are fortunate therefore to have an excellent series of samples from Bookartoo to work with.

Appearance of Bookartoo ochre

On hand examination Bookartoo ochre is a distinctive, soft friable purple or dark pink ochre, often with a greasy appearance (see Table II/2). It has a uniform texture. Quartz inclusions are rare or absent. Our samples often contain large calcite inclusions up to 10 mm. Some specimens contain small angular grains or flakes of a brilliant black or grey mineral that we assume is specularite (haematite crystals). Bookartoo ochre has good covering properties and a high sheen. It does not appear to be micaceous. As XRD analysis also fails to show the presence of mica it is likely that in this case crystalline flakes of haematite produce the sheen (see below).

Petrology

One specimen (Bookartoo - MAS) was embedded in resin and polished to allow examination of petrology by backscatter SEM in conjunction with EDXA analysis. Fe (presumably haematite) is present in the form of large flakes (to 1mm) and as smaller grains and clots. Si is present in the form of rounded quartz grains, ranging in size from 10 mm to 100 mm. Carbonates, carbonate minerals (Ca, Mg) and silicates (Al, K, Si) make up a fine ground mass.

Previous geochemical analyses

J. Cosmo Newberry (Technological Museum, Melbourne) analysed samples of Bookartoo ochre collected by Ulrich (Masey 1882). He found it to be '.. a nearly pure oxide of iron' but noted a small percentage of mercury in the silt or mud fraction of the sample. Although many people since Masey have focussed on the presence of mercury in this ochre subsequent analyses have not confirmed this finding. Keeling used XRD and XRF techniques to analyse earthy haematite from the Bookartoo workings (see below). This shows the major constituents of the ochre to be haematite, dolomite, quartz and calcite. Jercher et al (in preparation) report the results of recent analyses of Bookartoo ochre (specimens: A59022, A66496, A67980, A67979) using Rietveld (QPA) and XRF techniques. Initial results show the following constituents: haematite (51%), quartz (3.9%), calcite (1.5%), ankerite (8.6%) (a carbonate mineral) and dolomite (6.1%), together with 30% amorphous material. Perhaps the most interesting XRF result is the high level of Vanadium in this material (~2000 ppm).

Wilgie Mia

Alternative names: Wilgamia; Wilga mia; Wilgi Mia

References: Clarke 1976; Crawford 1963; Davidson 1952; Elias 1982; Kretchmar 1936; Woodward 1914.

Wilgie Mia is renowned for the sheer scale of the ethnographic excavations and the quantity of red ochre removed at this site. Davidson (1952) thought that this quarry provided most of the red ochre used in the western part of Western Australia. He reports that in 1939 the quarry was known to Aboriginal people as far north as Carnarvon (450 km north west) and as far south as Kellerberrin (525 km south). Clarke (1976) reports that in the 1970s Aboriginal people in Wiluna (300 km north east of the quarry) were able to identify Wilgie Mia ochre. This suggests that the ochre was traded over an enormous region.

The quarry

Wilgie Mia is on the southern side of Weld Range in the Murchison region, Western Australia. The locality is marked by a prominent hill. The workings form a large open cut quarry and a series of tunnels on the northern side of this hill. Davidson provides the following description of the quarry in 1939:

> The site comprises a huge hill which rises high above the general surface of the rough and hilly surrounding country. From the summit on the north side a great open cut varying between fifty and one hundred feet in width and possibly sixty-five feet in depth has been laboriously excavated. On the sides around the bottom are deeper chambers, while underneath them numerous tunnels follow the seams of red and yellow ochre, often for several yards. In some instances admission to these cramped working pockets must be gained by wriggling through such small openings that large individuals would find entrance impossible. (Davidson 1952:82)

From Davidson's account it seems that the main means of extracting the ochre was by tunnelling along ochre seams. Parts of the face of the open cut were undermined, either deliberately or inadvertently, and collapsed. This allowed access to ochre in the rock-fall. Wooden scaffolds were also used to provide access to seams of ochre otherwise beyond reach. The unusually large open cut at Wilgie Mia appears to be a consequence of the usual method of extracting ochre by driving small tunnels along ochre seams (as seen at Bookartoo and Karrku) combined with the structural instability of this deposit which led to continual collapse of the workings. Whatever the case the workings were extensive. Woodward (1914) gives the dimensions of the two main caverns within the mine as 20 m wide x 20 m deep x 14 m high and 40 m wide x 35 m deep x 10 m high respectively. This suggests that about 19,600 m^3 of rock and ochre were quarried away. Woodward's own estimate of the amount of pigment removed from the second of these caverns is 14,000 m^3. These estimates should probably be increased somewhat to account for material removed from the tunnels extending off the main chamber. Working on the basis that 1 m^3 weighs about 2 tonnes we estimate that Aboriginal people extracted up to 40,000 tonnes of material from this quarry (including an unknown proportion of quarry waste) (Note: - density of ochre is ~2.1g/cm^3).

Commercial exploitation of the deposit began in 1945 and continued until 1978. Elias (1982:20) records that during this period 9,131 tonnes of ochre were removed, giving a further indication of the size of the deposit. It appears that European mining activities have substantially destroyed the earlier workings.

I. M. Crawford carried out an archaeological excavation in 1963 in part of the main chamber left undisturbed by commercial mining (1963). This revealed more than 6 m of haematite dust, quartzite rubble and other quarrying waste. Two ^{14}C dates obtained from wood in layer 12 (Gak 176a 560±70 BP) and in layer 23 (Gak 1770 1100±90 BP) (at approximately 6m depth) show that the mine was in use for at least a millennium.

Two other ochre sources are known in the Weld Range. About 3 km southwest of Wilgie Mia, at a hill known as Little Wilgie Mia, there is a smaller deposit of ochre. From Davidson's account it seems that was exploited by Aboriginal people but perhaps not extensively so (1952:82). He also notes that mythologically it was more important than Wilgie Mia. Elias notes a small deposit of yellow ochre in laterite at the western end of the Weld Range (1982:20). This was commercially exploited by Europeans, and yielded 403.47 tonnes of pigment, but it is not clear whether it was originally exploited by Aborigines or not.

<u>Diagenesis of the ochre deposit</u>

The Weld Range is in an area of strong mineralisation. The range is made up of a series of steeply dipping Archaean metasediments, mainly banded ironstones, into which dolerite has intruded. According to Elias (1982) the banded iron formations consist of silica, haematite, magnetite and iron silicates in various proportions. The Wilgie Mia deposit is formed in a large lens of jaspilite - characterised by red (haematite dust), white (silica) and black (magnetite) bands. Most of the jaspilites in the Weld Range contain 20 to 60% magnetite, an important iron ore mineral. In the case of Wilgie Mia the jaspilite is interbedded with argillaceous sediments (Clarke 1978). Intense deep chemical weathering and laterisation during the Tertiary led to supergene enrichment of the banded iron formations. This process produced a series of iron ore bodies in the Weld Range (at least 20 such lenses with an estimated 152 mt of ore). The same process led to secondary enrichment of the Wilgie Mia jaspilites with haematite (and also yellow goethite) and deep weathering of the argillaceous sediments to form clay minerals. Little Wilgie Mia, 3 km to the southeast, is probably part of the same formation and could be expected to have similar geochemical characteristics to Wilgie Mia. The ochre deposit probably owes its origin to a pocket of argillaceous sediments in this part of the range. Therefore, although it is a large ochre deposit it is also a relatively discrete pocket of ochre.

<u>Samples analysed in this project</u>

Our sample includes 5 specimens of Wilgie Mia ochre, collected over a span of 80 years (see Table II/4). The earliest of the specimens (A2839) is of particular interest as it was obtained before commercial exploitation of the deposit by Europeans. This sample was donated to the S. A. Museum by E. C. Stirling and was registered in 1911-1918 only as red ochre from Weld Range. However, Stirling was Museum director from 1884-1912 and specifically developed the ethnographic collection. Given his interests it is likely that, as a result of Woodward's report in 1914, he would have taken steps to obtain material specifically from the main Wilgie Mia mine. One specimen (WAM) is from archaeological excavations carried out by I. M. Crawford in 1963. These investigations were restricted to an undisturbed pocket of loose ochre and quarry debris in the main chamber (Crawford 1963). Unfortunately, the specimen supplied us by the Western Australian Museum appears to be quarry waste rather than ochre. It is a soft fine-grained sandstone stained with haematite dust and is probably derived from quartz rich white bands within the banded ironstone bedrock (Elias 1982:7). The samples collected from the mine by M. Nobbs represent two different types of material. N-2A is a soft red ochre. N-2B appears to be a soft weathered specularite. These are probably the same material subject to different degrees of weathering.

There are two further specimens that may come from Wilgie Mia but do not have secure provenance. There is some possibility that we might be able to rectify this. In the meantime we include them as a potential test of our methods.

One of the samples (A+A) is from a box labelled "Wilga Mia ochre" in the teaching collection of the Department of Archaeology and Anthropology, Australian National University. Several characteristics set this apart from the other Wilgie Mia specimens in our sample. For instance, it is noticeably harder than the other specimens of Wilgie Mia ochre in our sample. It is also a different shade of red and has a greasy rather than waxy appearance. We can think of several possible explanations. 1) The Wilgie Mia deposit may be very variable. 2) The A+A sample may be from one of the other ochre sources in the Weld Range; either Little Wilgie Mia or the outcrop of yellow lateritic ochre recorded at the western end of Weld Range. 3) The teaching collection may have become jumbled over time (the sample was probably received in the 1970s) and A+A may not derive from <u>any</u> of the Weld Range sources. The other specimen in doubt is WCC. This is not in fact attributed to Wilgie Mia but we note its strong resemblance to Wilgie Mia ochre, especially to N-2A. In 1991 a large quantity of ochre was brought to Canberra, for the World Council of Churches, by Aboriginal women from Balgo Hills. Our WCC sample is from this material. At present we do not know where the Balgo women obtained their ochre but we cannot rule out Wilgie Mia.

Appearance of Wilgie Mia ochre

The ochre from this source is a soft uniform red ochre with a waxy appearance (see Table II/5). It is fine-grained but small crystalline flakes of haematite, or perhaps of iron silicates, are abundant. Some specimens contain occasional grains of a black mineral, possibly magnetite. Quartz inclusions are rare or absent. One of the Wilgie Mia specimens in our sample (N-2B) is a soft greyish specular haematite with a metallic lustre. This produces a bright red colour when rubbed. A60508 includes both red ochre and a harder sandy yellow ochre. Another of the specimens, (A+A), grades from red to yellow ochre. We are not certain that A+A is actually from Wilgie Mia. However, Davidson records the presence of yellow ochre (presumably goethite) at the quarry (1952:82).

Petrology

At the time of writing we have not examined the petrology of Wilgie Mia ochre.

Previous geochemical analyses

Clarke (1976) carried out an analysis of Wilgie Mia ochre using XRD and qualitative spectrographic techniques (Table II/6). The former showed that the ochre was mainly haematite with minor goethite and kaolinite. Spectrographic analysis also showed the sample to be substantially Fe with minor Si and Al. M. Jercher (pers. comm.) recently obtained similar results using Rietveld (QPA) and XRF techniques to analyse two samples from Wilgie Mia (N-2A and N-2B). Initial results show that N-2A has a greater percentage of Si and Al than N-2B and is made up of haematite (83.8%) combined with kaolinite (1.3%) (a clay mineral). N-2B is made up of haematite (59.99%), goethite (1.23%), calcite (2.61%) and dolomite (0.07%). The presence of carbonates is unexpected given the geology of the formation and requires some explanation. The presence of kaolinite is consistent with intense weathering of the deposit, as described by Elias (1982).

Karrku

Alternative names: Campbell Ranges mine; Karko.

References: Peterson and Lampert 1985; Strehlow 1971:Map; Terry 1934:506; Tindale 1974:86.

Karrku is a major red ochre mine in the Campbell Ranges in the western part of Central Australia. Although the term *karrku* more properly refers to the ochre from the Campbell Ranges mine, in local parlance it is also used to refer to the locality. This is the usage we follow here. Warlpiri people today still use the mine and exchange ochre from Karrku widely. Before about 1940 it was traded locally to the north and south of the Campbell Ranges, reaching the Ehrenberg Ranges ~65 km south of Karrku. The wider regional extent of its distribution at this time is not recorded (but see below).

The mine

Karrku is near the top of a low hill in the Campbell Ranges, close to Mt Cockburn. The ochre workings form a large underground chamber, about 35 m long x 5-12 m wide x 1m high, following a seam of ochre into the hillside. The entrance to the mine is a small hole (1 m x 0.6 m) that leads into this chamber. Peterson and Lampert estimate that 240 m^3 of ochre have been removed, weighing about 300 tonnes (1985:2).

Diagenesis of the ochre deposit

The Karrku deposit is formed in joints in Vaughan Springs quartzite. This is a white or pink orthoquartzite with basal pebbly haematic sandstone and conglomerate. According to Wells (1972) it is closely jointed and thick bedded and was laid down in a shallow marine environment. The formation has been uplifted subsequently and subject to a long period of weathering. Photographs in Peterson and Lampert (1985) show that the ochre forms a sub-horizontal seam between beds of quartzite. As Wells reports only limited mineralisation in the Ngalia basin, and none near Mt Cockburn, the most likely diagenesis of the ochre is as sedimentary infill in joint lines. The petrology of the ochre indicates that it is not primarily of hydrothermal origin (see below). Peterson and Lampert (1985) do not discuss the extent of the deposit, but it does not appear to be a widespread formation.

Samples analysed in this project

Our sample includes two specimens of Karrku ochre. One is a sample of raw ochre collected from the seam in 1988 by S. Dunlop, an anthropologist then with the Aboriginal Areas Protection Authority. The other is from a prepared cake of ochre collected by N. Peterson at the mine between 1972 and 1982. Peterson and Lampert record the process by which such cakes were prepared.

> It is clear from the three grinding grooves immediately outside the mine entrance that it was not unusual for initial treatment of the ore to take place on the spot. This involved simply grinding the ochre into a fine powder by hammering and rubbing. ...any minor impurities or slightly inferior ochre would be left behind... Back in camp the ochre is further treated by mixing with a little water and made into balls or cakes called *kapardu*. (Peterson and Lampert 1985:6)

Appearance of Karrku ochre

Raw Karrku ochre is a soft red ochre (7.5R 4/6 red) with a metallic sheen. There are no obvious inclusions on hand examination.

Petrology

We embedded a small piece of ochre from the seam in resin, and polished it to allow examination of petrology by backscatter SEM in conjunction with EDXA analysis. Nearly pure Fe (presumably haematite) is present as a fine ground mass. Si is abundant and is present as prominent rounded or sub-angular quartz grains up to 400 mm. A clear K-Al-Si mineral forms abundant large platey aggregates throughout the sample. This is probably muscovite or sericite. Peterson and Lampert describe the ochre as a soft specular haematite (1985). While this assessment is probably correct we did not find discrete crystals of specularite. This suggests the deposit has been heavily weathered. The heterogeneous nature of the ochre and presence of quartz clasts also points to reworking of the deposit, perhaps as sedimentary infill in joints in the local quartzite.

We also examined a sample of the prepared cake. This also showed a fine Fe rich groundmass with quartz inclusions and K-Al-Si rich mica. However the inclusions are smaller, suggesting some sorting of the ochre, or destruction of mica aggregates, during preparation of the cake. This process also seems to have introduced Mg into the sample. This could have been introduced either by way of carbonates in local water (mixed with the ochre to form the cake), or by contact with carbonate rich rocks during the processing. Local formations contain lenses of dolomite (in the Mount Doreen formation) and there are extensive areas of Quaternary limestone on the southern side of the Campbell Ranges.

Previous geochemical analyses

Smith submitted samples of Karrku ochre for XRD analysis at the ANU in 1988 and 1990. The results shows that the raw ochre (#6) is dominantly haematite with minor quartz and some mica (possibly muscovite) and kaolinite. The prepared cake (#7) is dominantly quartz and haematite with minor kaolinite and muscovite.

Ulpunyali

Alternative names: Ulbunalli; Ulpanyalli

References: Bagas 1988; Bowman and Scherer 1948; Hamilton and Vachon 1985.

Ulpunyali is an important regional ochre quarry, west of Kings Canyon, in Central Australia. Although it is not as well known as Bookartoo, Ulpunyali may have served an area nearly as large. According to Hamilton and Vachon (1985:43-46) people from Uluru (165 km south), the Petermann Ranges (~200 km south west) and Bloods Range (170 km south west) travelled north and north-east to Ulpunyali to obtain the ochre. Ulpunyali ochre also reached Pipalyatjara (~350 km south) in north western South Australia, in this case by exchange with people in the Petermanns rather than direct visits to the quarry.

> The ochre from *Ulpunyali* constituted....one of the most important cultural and spiritual resources of the region...
>
> On visits to *Ulpunyali* women claimants, especially from the Petermann and Blood Ranges area, described how they would come across the desert during times after rain and collect *Ulpunyali* ochre; they would grind it to a fine powder and make it into 'cakes, then carry it in this form on wooden dishes back towards the ranges where it would be distributed among kin and used in a number of ceremonies, especially (but not only) those involving the *kungka kutjara* ritual traditions. The ochre was also used in trade .....
> (Hamilton and Vachon 1985:46)

The northern limit of the distribution of Ulpunyali ochre is not recorded. However, today the major cultural and totemic links of people at Ulpunyali are to the south west, with communities in the Petermann Ranges. The distribution of ochre may have followed this pattern.

<u>The quarry</u>

At Ulpunyali there are two discrete ochre quarries, about a kilometre apart (both are known by the name *Ulpunyali*). Smith was shown both by local Matuntara men (Ben Clyne and Leo Williams) in 1984. The first of these (<u>Locality 1</u>), near a distinctive pair of conical hills, consists of a series of pits dug into a prominent area of red stained earth on the lower slopes of a low rubbly hill. The workings cover about 5-10 m^2 and consist of two circular quarry pits about 1 m in diameter. Their depth could not be estimated as both are now silted up. However it is evident that no great depth was needed to extract high-grade ochre as it outcrops in the exposed rim of the workings. A metal digging stick, and sections of cut wood, could be seen in one of the pits. A third pit, much less obvious, occurs nearby and there may be others that escaped notice during Smith's brief visit. The second set of workings (our <u>Locality 2</u>) are about 1 km west of the first and are on the mid-slope of a rubbly hill, near a small gap in the range at this point. Smith's informants saw this as the most important of the two sites both mythologically and in terms of the extent of the workings. There was said to be a tunnel into the hill at this site. Certainly the workings proved to be more extensive. These consist of 4 poorly defined pits (1 m diameter) cut into the hill side, forming a slumped area about 10 m x 10 m. The workings appear to exploit the same distinctive ferruginised bed as that at <u>Locality 1</u> but the ochre exposed at the surface did not appear to be as good. The pits penetrated up to 50 cm into soft ochreous earth, but - as at the first site - their full depth could not be determined. One of the pits does appear to have been extended as a narrow low tunnel (now collapsed) into the hillside, beneath a thin bed of sandstone.

According to Hamilton and Vachon (1985:46)

> The [Ulpunyali] ochre comes from two 'mines' and there is a third elsewhere nearby, the location of which is secret.

The two 'mines' in this case refer to the two prominent quarry pits at Locality 1, and the secret mine is our Locality 2.

Diagenesis of the ochre deposit

The workings in Locality 1 are dug into a weakly cemented coarse-grained ferruginous sandstone. This outcrops on the lower slopes of a low rubbly hill. The deposit appears to underlie - or is associated with - a bed of dark siltstone, pieces of which outcrop around the rim of the quarry pits. In places this has weathered to produce a large patch of dark stained earth on the lower slopes of the hill. In Locality 2 the workings are dug into what appears to be the same bed of ferruginised sandstone. In this case however the dark siltstone is less evident and there are thin beds of fine-grained sandstone on the lower slopes of a rubbly hill. The workings appear to tunnel beneath these.

According to Bagas (1988:17) the Ulpunyali ochre deposit is formed in Horn Valley siltstone. This is a fossiliferous siltstone with interbedded limestone and fine-grained quartz sandstone. Bagas notes that

> Following a marine transgression which began during the deposition of the upper part of the Pacoota Sandstone, marl, mud and partly pyritic and calcareous black silt were deposited in a pelagic (open-marine) environment.... Oolitic pyrite in the black siltstone is indicative of stagnant, anaerobic and strongly reducing bottom conditions... (Bagas 1988:11)

This is broadly consistent with Smith's observations at the quarry but as the ferruginised sandstone is very coarse-grained it is likely it represents the upper unit of the underlying Pacoota sandstone - a well-sorted coarse-grained quartz sandstone. We suspect that the ochre deposit formed at the contact of Horn Valley siltstone and Pacoota sandstone. The likely diagenesis is redeposition of iron sulphides from the dark siltstone as haematite in the underlying sandstone. If as we suggest, the ochre derives from a bed of ferruginised sandstone there may be several exposures of high-grade ochre in this area, with potential for some variability in geochemical characteristics.

Samples analysed in this project

Our sample includes a sample of ochre collected by Smith in 1984 from in-situ ochre exposed in the face of one of the quarry pits at locality 1. We believe that an earlier sample (A16845), collected in 1932 by Finlayson, is from Ulpunyali but cannot suggest which of the two localities this is likely to be from. H. H. Finlayson was Honorary Curator of mammals at the South Australian Museum from 1926-1968. In the 1930s he travelled extensively in central Australia and wrote a best-selling account of the natural history of the region, The Red Centre: Man and beast in the heart of Australia, published in 1935. A map of his 1931-35 route suggests that Finlayson visited Ulpunyali or at least passed close by on his way to *Kutjinti* (his Quajinta) waterhole (see Finlayson 1935: map) though his book contains no direct reference to the quarry. A16845 is labelled only as from hills southwest of Kings Creek.

The third specimen in our sample (Paterson X) is less securely provenanced to Ulpunyali. This specimen was given to S. Dunlop, then an anthropologist with the Aboriginal Areas Protection Authority, by Mrs Nellie Paterson, a local Aboriginal woman at Uluru. Mrs Paterson is one of the senior female custodians for Ulpunyali and the context was a request by Smith to make a second visit to the quarry. The request was turned down but as a small courtesy Smith was sent this sample of ochre, said by Mrs Paterson to come from Ulpunyali. We do not know whether Mrs Paterson was given the sample or collected it herself. As it is very different in appearance to the other Ulpunyali samples we have doubts as to whether it is from this source. An origin in the Petermann Ranges cannot be ruled out.

Appearance of Ulpunyali ochre

Ulpunyali ochre is a crumbly, dark red or purple ochre with a very greasy appearance. The ochre is coarse-grained with large rounded quartz grains set in a ferruginous cement. Despite this it appears to be of high quality and gives a definite metallic sheen when rubbed on one's skin. Haematite coatings on quartz grains strongly adhere to the surfaces of the grains, giving the quartz a greasy 'coated' appearance even on fresh breaks.

Petrology

Two different samples of Ulpanyali ochre were mounted in resin, polished and examined using backscatter SEM and EDXA techniques.

The first sample (Ulpanyali - MAS), from Locality 1, is composed of sub angular to rounded quartz grains in a very fine-grained ferruginous cement. The quartz is moderately well sorted and coarse-grained and makes up the greater part of the sample. The cement is Fe rich (probably very fine-grained haematite) but also contains a fine-grained Al-Si-minor K silicate (possibly sericite). The cement represents cavity fillings as it shows fine botryoidal banding and concentric concretions around quartz grains. These are retained as shiny coatings on the grains when the ochre is lightly disaggregated by hand, giving the quartz a greasy 'coated' appearance.

The second sample (Paterson X) is ochre obtained from N. Paterson at Uluru and attributed by her to Ulpanyali. As we have said (see above) it bears no resemblance to the other Ulpunyali samples. It is homogenous and extremely fine-grained with a Al-Si-K-Fe rich groundmass, with minor Mg and Cl. Within this there are occasional angular clasts of the same material up to 40 mm, consistent with it being a siltstone.

Previous geochemical analyses

Smith submitted samples of Ulpunyali ochre from Locality 1 for XRD analysis at the ANU in 1988 and again in 1990. The results showed the ochre to made up of quartz (~70%) and haematite (~30%). XRD analysis of Paterson X in 1990 showed it to be made up of quartz, calcite and haematite.

Lawa

References: Chewings 1886, 1936:19.

This is an ochre quarry near Yowa creek in the Levi Range, Central Australia. Very little is known about this source but it was clearly an important regional quarry serving the same general region as Karrku and Ulpunyali. The earliest and most detailed reference is by Charles Chewings in a series of articles ('*The sources of the Finke River*') published in The Adelaide Observer in 1886. Chewings reconnoitred the George Gill Range and surrounding area on two trips, in 1881/82 and 1885, prior to taking up a pastoral lease at Tempe Downs. Chewings is known as a reliable observer and it is relevant here to note that he later received formal training in geology and worked, amongst other things, as a mining consultant. In his piece for June 5 1886 he notes

> I discovered a vein of red ochre with a large percentage of iron in it. The natives come from hundreds of miles to gather it. They dig it out and break it into powder, mix a little water with it and make it up into balls, dry it in the sun, and carry it about with them. I am told that only at Parachilna [ie. Bookartoo] is the same kind of ochre found in the colony. The vein is situated in Levi's Range South.

The quarry

In a later column (June 19 1886) Chewings provides a description of the quarry in which it is clear that the workings were similar to those at Ulpunyali.

> Our guide told us to halt, but I could not see why until he pointed to a hole similar to a wombat hole, and in which about 6 feet deep I saw the end of the vein at which the natives had been working, perhaps for the last century. The mineral is so rich that they do not require to take a large quantity with them, and it is rather hard to get out; consequently such a little depth has been reached. Two or three similar holes are in the vicinity, and have been abandoned. This vein originally protruded in the bank of the creek, but now is several feet back from it.

Diagenesis of the ochre deposit

The geological setting of the Levi Range is similar to that at Ulpunyali, which raises the possibility that diagenesis of the Lawa deposit followed a similar route (ie. friable Ordovician ferruginised sandstone).

Samples analysed in this project

We have only one sample of ochre from Lawa (A52812). This was collected in 1960 by J. E. Johnson, a South Australian government geologist. His notes identify the sample as 'from native mine called 'lawa' in the George Gill Range'. We identify this with Chewing's mine because Chewings' travelling directions place his ochre mine on Yowa (Yaua) creek. We note that Levi Range is effectively the eastern end of the George Gill Range and that Yowa occurs as a place name only in the former. Strehlow (1971) gives Ijauwi as a general place name for the southern part of Levi Range. It is likely that Johnson's field notes, lodged with the South Australian Museum, contain more details and we plan to follow this up.

Appearance of Lawa ochre

A52812 is a hard dark red ochre (Munsell colour 7.5R 3/4 red). It appears to consist of fine-grained dark red haematite with clear sand-sized quartz inclusions. Unlike Ulpunyali ochre, the quartz grains in A52812 are not dominant and appear as clean grains in fresh breaks rather than coated with haematite. Other inclusions include fine flakes (and some larger platy aggregates) of clear mica and occasional rounded grains of a translucent dark mineral, which may be smoky quartz. The ochre develops a greasy appearance when rubbed. The ochre from Lawa is clearly distinguished from the Ulpunyali material in terms of its petrology even if it proves to share a similar geological setting and diagenesis.

Other samples analysed in this project

In addition to samples from documented ochre quarries, we have analysed a series of samples from other sources or from archaeological sites. The rationale here is to gain a better appreciation of the potential variability in the geochemical characteristics of ochres.

From central Australia we have several unprovenanced samples (Purara; A1122; A1175) and a specimen from a putative ochre source (Wangiana) near Lake Eyre. A1122 and A1175 were collected by Rev. O. Liebler. Oskar Liebler was a Missionary at Hermannsburg, central Australia, from 1910-1913. Both specimens are part of a collection of ethnographic items he sold to the S.A. Museum in 1914. Hermannsburg at that time received frequent visits from Luritja and Pintupi people living in the bush further west. Liebler's ethnographic collection was probably built up of material acquired from these visitors as well as local Western Arrernte people. The source(s) of the two ochre specimens could therefore be anywhere in the western MacDonnell Ranges, perhaps as far west as the Ehrenberg Range. On hand examination A1175 resembles material from Lawa, except for the presence of small clots of geothite and the limestone inclusions. A1122 does not match any of the quarries that we have analysed. The Purara sample is from an open campsite, between Uluru and Lake Amadeus. A source in either the Petermann Ranges or in the area north of Lake Amadeus is possible. Wangiana is an ochre source near Lake Eyre, suggesting that the presence of evaporites, especially halite or gypsum, may be useful in characterising this material.

The specimen from Moana is of particular interest as it is from the source at Red Ochre Cove in this area. Jones (1984b) notes that four tons of ochre from Red Ochre cove were transported to Koppermanna on the lower Cooper in 1874 in an attempt to forestall further red ochre expeditions by the Diari to Bookartoo. The experiment failed and presumably a large dump of Moana ochre remains to be found at Koppermanna. Cathedral Rock and Mt Howden are ochre sources in the Olary region, north-east South Australia. The former is also a site with occupation deposit and was excavated by Mawson and Hossfeld in 1926. Rockleigh and Overland Corner are specimens from regional ochre quarries on the lower River Murray, South Australia.

The archaeological ochre specimens fall into two series. From Puritjarra rock shelter in central Australia we have analysed a series of specimens from archaeological excavations carried out at the site by Smith between 1986 and 1990 (Smith 1987, 1988, 1989). Our aim here is to test Smith's visual division of the ochres into a number of groups, and to see if the ochres can be sourced to any of the central Australian quarries. The material analysed is representative of two groups of ochres at the site. Group 1 ochres make up the majority of ochre in the Pleistocene occupation levels of the site. It is a fine-grained dark red ochre with mica and clear quartz inclusions and most closely resembles the ochre from Karrku or Lawa, which respectively are 150 km north and 155 km south east of Puritjarra. Group 2 ochres are less common and are restricted to the mid to late Holocene part of the Puritjarra sequence. This is a coarse-grained greasy dark red or purple ochre closely resembling material from Ulpunyali, 65 km to the south.

Our second archaeological case study is from Kutikina, in southwest Tasmania. Our sample is a small series of ochre specimens from the 1981 excavations reported by Kiernan, Jones and Ranson (1983). Once again our aim is to determine whether the specimens in our sample represent material from one or a range of sources, and whether any match material from the Dial Range (our only Tasmanian reference material at this stage).

Table II/1 Bookartoo samples: collection details

Sample code	Locality and collection date	Comments
Samples from Bookartoo		
A1863	Bookartoo 1904 [Parachilna]	This is a small prepared cake of Bookartoo ochre collected by P.F. Shanahan during one of the red ochre expeditions in 1904 (see Shanahan 26/12/04 in Jones 1984a:6)
A59022	Bookartoo 1968 [Mount Hayward mine]	Collected by G.L. Pretty (S. A. Museum archaeologist) & O. M. Broughton.
A66496	Bookartoo [Mount Hayward mine]. Collected prior to 1978	
A66500	Bookartoo [Mount Hayward mine]. Collected prior to 1978	
A67979	Bookartoo 1983 [Mount Hayward mine]	Collected by S. A. Museum expedition
A67980	Bookartoo 1983 [Mount Hayward mine]	Collected by S. A. Museum expedition
Bookartoo (MAS)	Bookartoo 1988 [Mount Hayward mine]	Collected by P. Jones (S. A. Museum)
#13	as for Bookartoo (MAS)	as for Bookartoo (MAS) but previously prepared for analysis by grinding in agate mortar.
N-9	Bookartoo [no collection date]	Collected by M. Nobbs for spectrographic analysis, probably in the late 1970s.
Other related samples		
A66497	Marakato, Cooper Creek 1890-1905	As this sample is from the Reuther collection it may have been collected at a campsite [Marakato] near Killalpaninna, on one of the major red ochre trade routes.
A66498	as for A66497	as for A66497

Table II/2 Bookartoo samples: description

Sample code	Munsell colour	Description
Samples from Bookartoo		
A59022	7.5R 3/3 dark reddish brown	Friable, earthy purple ochre. Some inclusions >10mm of calcite.
A66496	7.5R 3/3 dark reddish brown	Friable purple ochre. Greasy appearance. Some large inclusions of calcite to 10 mm as rounded pebbles.
A66500	7.5R 4/4 dusky red	Friable purple ochre. Greasy appearance. Sand-sized clear quartz inclusions (rounded), black crystals of sphalerite, and calcite grains .
A67979	7.5R 3/4 dark red	Hard purple ochre. Greasy appearance. Some calcite inclusions >10 mm.
A67980	7.5R 4/4 dusky red	Friable, earthy, purple ochre. Quartz grain aggregates and calcite inclusions.
Bookartoo (MAS)	7.5R 3/4 dark red	Friable purple ochre. Greasy appearance. Specularite inclusions.
N-9	7.5R 4/3 dull reddish brown	Soft greasy purple ochre.
Other related samples		
A66497	7.5YR 3/4 dark red	Powdered version of A66498
A66498	7.5R 3/4 dark red	Friable, earthy purple ochre. Greasy appearance. Specularite inclusions.

Table II/3 Bookartoo samples: previous analyses

Geochemistry	Method	Reference
The friable substance extracted by the natives		
Nearly pure oxide of iron with 0.5% mercury in the silt fraction	Not given	Masey 1882
Earthy haematite A5173/83		
Mineralogy: Haematite and dolomite with minor calcite and quartz.	XRD	Keeling 1984
% Composition:		
SiO_2 13.5, TiO_2 0.07, Al_2O_3 1.34, Fe_2O_3 45.1, MnO 0.13, MgO 7.10, CaO 13.5, Na_2O 0.13, K_2O 0.20,P_2O_5 0.07. \LOI 18.9.	?XRF	
Colour: 10R4/6 reddish brown - 10R3/4 dark reddish brown	Munsell	

Table II/4 Wilgie Mia samples: collection details

Sample code	Locality and collection date	Comments
Samples from Wilgie Mia		
A2839	Weld Range prior to 1911-1918.	This sample was donated to the S. A. Museum by E. C. Stirling and was registered in 1911-1918. Stirling was Museum director from 1884-1912 and developed the ethnographic collection. He died in 1919. The sample may be material personally collected or one sent to him.
A60508	Wilga Mia ochre mine 1970	Collected by V. A. and H Tolcher after a visit to the ochre mine. This samples includes specimens of both red and yellow ochres.
N-2A	Wilgie Mia [no date]	Sample collected from ochre mine by M. Nobbs, probably in late 1970s.
N-2B	as for N-2A	As for N-2A
WAM	Wilgie Mia 1963	Sample of ochre or ochreous sediment from I. Crawford's excavations at the mine in 1963.
Other related samples		
A + A	Wilga mia [collection date not recorded]	From sample labelled "Wilga Mia" in teaching collection of Department of Archaeology & Anthropology, ANU. Collection date not recorded but probably 1970s. Provenance uncertain (see text). If label accurately identifies the specimen it may be a sample collected at Wilgi Mia in 1977 during a field trip associated with the ICOM Rock Art Conservation Meeting in Perth.
Gara Widgie	Gara Widgie, Western Australia [no collection date]	Sample is from collection of the Queen Victoria Museum, Launceston TAS. It is possible that Gara Widgie is the Little Wilgi Mia source [Gara = kara = little]. The sample appears to be a fresh quarry sample rather than utilised ochre.
WCC	[Locality not given but either Balgo Hills or Wilgie Mia] 1991	Sample of ochre brought to Canberra for the World Council of Churches by Aboriginal women from Balgo Hills. Provenance of the ochre is not known but closely resembles Wilgie Mia material.

Table II/5 Wilgie Mia samples: description

	Munsell colour	Description
Samples from Wilgie Mia		
A2839	7.5R 4/8 red	Soft fine-grained red ochre. No quartz inclusions. Abundant crystalline flakes of haematite (specularite), or perhaps of iron silicates, and occasional grains of a black mineral (?magnetite).
A60508	7.5R 4/8 red	Soft fine-grained ochre. Bright red in colour. Waxy appearance. No quartz inclusions. Abundant crystalline flakes of haematite (specularite), or perhaps of iron silicates, and occasional grains of a black mineral (?magnetite). A60508 also includes a specimen of a hard, fine-grained yellow ochre with a sandy appearance.
N-2A	7.5R 3/6 red	Soft fine-grained ochre. Bright red in colour. Waxy appearance. No quartz inclusions. Abundant crystalline flakes of haematite (specularite), or perhaps of iron silicates.
N-2B	7.5R 3/3 dark reddish brown	Soft grey ochre with metallic lustre. Smears to a bright red. Probably weathered specularite.
WAM	5YR 6/8 orange	Soft fine-grained sandstone stained with haematic dust. Bedding planes evident. Part of banded ironstone bedrock. Probably quarry waste.
Other related samples		
A + A	7.5R 4/6 red to 7.5YR 6/8 orange.	Hard fine-grained red ochre. Greasy appearance. No quartz inclusions. Some crystalline flakes of haematite (specularite), or perhaps of iron silicates,. Occasional large grains of a black mineral (?magnetite) and clots of yellow goethite. Thin band of brilliant grey metallic crystals (specularite). Specimen grades to a fine-grained yellow ochre.
Gara Widgie	10R 5/8 - 10R 4/8 red	Hard fine-grained red ochre. Bright red in colour. Homogenous ground mass with fine flakes of ?mica and occasional grains of a dark mineral. No visible quartz grains. Possibly of lateritic origin.
WCC	7.5R 3/6 dark red	Powdered sample. Fine-grained dark red ochre with abundant flakes of crystalline haematite (?specularite), or perhaps of iron silicates. No inclusions.

Table II/6 Wilgie Mia samples: previous analyses

Geochemistry		Method	Reference
Ochre from floor of mine (<200 mm)			
Mineralogy: haemaite (>10%), goethite (<10%) and kaolinite (<10%)		XRD	Clarke 1976
Composition: >10%	Fe	qualitative spectrographic analysis (?OES)	
1-10%	Si Al		
0.1 - 1%	K Na Ti Mg Ca		
0.01 - 0.1%	Mn		
0.001 - 0.01%	Ni Cu W Cr Sr V Zr		
0.0001 - 0.001%	Pb Co Be Mo Li		

Table II/7 Karrku samples: collection details

Sample code	Locality and collection date	Comments
#6	Karrku 1988	Sample of raw ochre collected from the seam by S. Dunlop.
#7	Karrku 1972-1982	Prepared cake of Karrku ochre collected by N. Peterson.
96/1	Karrku (?1995)	Chunk of raw ochre collected from the Karrku mine by C. Freer (Community Arts Advisor at Nyirripi) in about 1995.
96/2	Karrku (?1995)	Chunk of raw ochre collected from the Karrku mine by C. Freer (Community Arts Advisor at Nyirripi) in about 1995.
98/1	Karrku 1998	High-grade raw ochre collected at Karrku by M. A. Smith in May 1998. This sample formed part of about 7 kilograms of ochre dug from the ochre seam in the south chamber of the mine by two Walpiri women [Mary and Lina Morris Nungarrayi] on this visit. The sample is from ochre excavated from the seam in the southern chamber of the mine by Mary Morris Nungarrayi and is representative of the ochre she retained for her own use.
98/2	Karrku 1998	High-grade raw ochre collected at Karrku by M. A. Smith in May 1998. This sample formed part of about 7 kilograms of ochre dug from the ochre seam by two Walpiri women [Mary and Lina Morris Nungarrayi] on this visit. The sample was explicitly selected by Lina Nungarrayi as an example of the 'proper Karrku'.
98/3	Karrku 1998	Chunk of raw ochre collected from the Karrku mine by M. A. Smith in May 1998. The sample represents lower grade ochre left in the mine as part of the detritus of mining activities.
98/4	Karrku 1998	Powdered ochre and ochre pieces from the floor of the Karrku mine. Representative of fresh mining debris at the base of the working face of the ochre seam in the south chamber of the Karrku mine. Collected by M. A. Smith in May 1998.
JW	Karrku 2004	Powdered ochre and ochre pieces from the floor of the Karrku mine. Representative of fresh mining debris including pieces of quartzite bedrock. Collected by James Warden in 2004.

Table II/7a Karrku samples: description

Sample code	Munsell colour	Description
#6	7.5R 4/6 red	Soft red ochre with metallic sheen. No obvious inclusions.
#7	-	Prepared cake of ground ochre.
96/1	7.5R 4/6 red	Hard dark pink micaceous ochre with foliate structure. Large plates of clear mica to 1mm.
96/2	10R 4/8 red	Hard coarse-grained dark pink ochre. Large clear rounded quartz grains up to 2mm. Moderately sorted. Fine flecks of clear mica.
98/1	7.5R 4/6 red	Hard fine-grained dark red ochre. Foliate structure. Abundant fine flecks of clear mica.
98/2	7.5R 4/8 red	Hard fine-grained dark rd ochre. Fine flecksof clear mica. Thin white veins of kaolin clay - 1mm thick.
98/3	7.5R 4/6 red	Hard dark pink micaceous ochre with foliate structure. Large plates of clear mica to 1mm.
98/4	7.5R 4/8 red	Powdered ochre and ochre pieces.

Table II/8 Ulpunyali samples: collection details

Sample code	Locality and collection date	Comments
Samples from Ulpunyali		
Ulpunyali MAS	Ulpunyali locality 1 1984	Sample of raw ochre collected from the quarry pits by M. Smith. (equivalent to #1)
A16845	Hills south west of Kings Creek 1932	Collected by H. H. Finlayson in 1932. Although no further details are given the collection locality suggests that Finlayson visited Ulpunyali. A map of his 1931-35 route shows that he must have passed very close to Ulpunyali on his way to *Kutjinti* (his Quajinta) waterhole (see Finlayson 1935: map). The sample closely matches Ulpunyali - MAS in appearance.
Other related samples		
Paterson X	Uluru [attributed to Ulpunyali] 1988	Ochre supplied to S. Dunlop (AAPA anthropologist) by Nellie Paterson, a local Aboriginal women, at Uluru [equivalent to #3]. Mrs Paterson claimed it was from Ulpunyali. However the sample differs greatly from other Ulpunyali samples.

Table II/9 Ulpunyali samples: description

	Munsell colour	Description
Samples from Ulpunyali		
Ulpunyali MAS	7.5YR 4/6 red	Dark red to purple ochre. Can be soft, or hard and crumbly. Very coarse-grained with abundant, prominent rounded quartz grains set in fine haematite cement. Greasy granular appearance. Quartz grains retain greasy haematitic coatings when sample is broken.
A16845	7.5R 4/4 dark red	Crumbly purple ochre. Abundant large rounded quartz grains in a fine haematite cement. Greasy granular appearance. Closely matches Ulpunyali MAS sample.
Other related samples		
Paterson X	10R 5/8 red	Hard bright red ochre. Very fine grained without visible inclusions except very fine crystalline flakes (?a silicate). Sandy appearance.

Table II/10 Other samples: collection details

Sample	Locality and collection date	Comments
Other ochre sources		
Lawa A52812	Probably Lawa ochre mine in Levi Range, C. Australia	Collected in 1960 by JE. Johnston. The Lawa mine is described by C Chewings 1886 and was recently relocated by MA Smith.
Lawa 98/1	Lawa ochre mine in Levi Range, C. Australia 1998	Raw ochre from outcrop adjacent entrance to the Lawa mine. Collected by M. Smith in May 1998.
Lawa 98/2	Lawa ochre mine in Levi Range, C. Australia 1998	Rounded pebble of high-grade red ochre found on hillslope north of the road, Lawa area. Collected by M. Smith, May 1998. Possibly indicative of high-grade material removed from the mine.
Lawa 98/3	Lawa ochre mine in Levi Range, C. Australia 1998	Raw ochre from the interior of the mine. Collected by M. Smith, May 1998.
Wangiana N-1	south west Lake Eyre 1983	Collected by M. Nobbs in October 1983. Described as from an ochre quarry, in limestone, near the south west side of Lake Eyre.
Arkaba Burana N-5	South west Lake Eyre 1983	Collected by M. Nobbs in October 1983. Said to have been collected from an ethnographic quarry used to produce pigment. This sample appears to us to be baked clay rather than ochre. .
Moana N-6	Moana, SA. 1977	Collected by M. Nobbs in July 1977. From the Red Ochre Cove source, on the coast south of Adelaide.
Overland corner N-7	Overland corner, lower River Murray, SA. 1977	Collected by M. Nobbs in March 1977. From known Aboriginal quarry near Barmera, River Murray SA.
Overland Corner (A) (Ward)	Overland corner, lower River Murray, SA. [no date]	Collected by G. Ward in ? . From known Aboriginal quarry near Barmera, River Murray SA.
Overland Corner (B) (Ward)	Overland corner, lower River Murray, SA. [no date]	Collected by G. Ward in ? From known Aboriginal quarry near Barmera, River Murray SA.
Overland Corner (C) (Ward)	Overland corner, lower River Murray, SA. [no date]	Collected by G. Ward in ? From known Aboriginal quarry near Barmera, River Murray SA.
Tirnu 96/1	Tirnu, Great Sandy Desert 1996	Collected by M. A. Smith in July 1996 from Tirnu ochre quarry. Sample is utilised piece of ochre found adjacent to quarried lateritic outcrop.
Tirnu 96/2	Tirnu, Great Sandy Desert 1996	Collected by M. A. Smith in July 1996 from worked lateritic outcrop Tirnu ochre quarry.
Djibitgun 95/1	Djibitgun, Keep River, NT 1995	Collected by R. Jones in August 1995 from open site adjacent worked outcrop.

Toolumbunner #1	Toolumbunner, Gog Range ?1986	Collected by J. A. Webb from excavations at Site B at the Toolumbunner ochre quarry.
Toolumbunner #5	Toolumbunner, Gog Range ?1986	Collected by J. A. Webb from excavations at Site B at the Toolumbunner ochre quarry.
Bloodstone Point	Bloodstone Point, Maria Island	From collections of Queen Victoria Museum, Launceston TAS. From worked lateritic outcrop. Bloodstone Point is the only outcrop of laterite on Maria Island. The quarry is described by Plomley (1983) .
<u>Potential sources</u>		
Mt Howden N-4A and B	Mt Howden, Olary uplands, SA. 1989	Collected by M. Nobbs in June 1989. From Mt Howden, west of Bimba Hill, Olary District SA. Potential source only.
Cathedral Rock N-3	Cathedral Rock, Olary uplands,. 1972.	Collected by M. Nobbs in April 1972 from locality to the west of the Cathedral Rock site excavated by Mawson and Hossfeld (1926). Identified by geologist J. E. Johnson as potential ochre source.
Rockleigh N-8A	East Mt Lofty Ranges SA. 1977	Collected by M. Nobbs in June 1977. Potential source only.
Dial Range #1	Dial Range, western Tasmania. 1995.	Collected by R. Cosgrove from creek bed below source outcrop of haematite. No evidence of exploitation by Aboriginal people.
<u>Archaeological or ethnographic specimens</u>		
Purara	Purara well, south of Lake Amadeus, Central Australia. 1986	Piece of faceted red ochre from an open site in the Uluru - Lake Amadeus region.
A1122	MacDonnell Ranges, Central Australia. [prior to 1914]	Collected by Rev. O. Liebler prior to 1914. No data on source. Oskar Liebler was a Missionary at Hermannsburg, central Australia, from 1910-1913. The specimen is part of a collection of ethnographic items he sold to the S.A. Museum. It was most likely collected from Aboriginal people visiting the mission and the source could be anywhere in the western MacDonnell Ranges, or perhaps as far west as the Ehrenburg Range.
A1175	MacDonnell Ranges, Central Australia. [prior to 1914]	As above.
<u>Malakunanja II</u> MII'89/DEF30/40	Malakunanja II rock shelter, western Arnhem Land NT. 1989.	High-grade haematite from the 1989 excavation reported in Roberts, Jones and Smith (1990). Specimen is from spit 40, in the lower part of the occupation sequence.

<u>Puritjarra rock shelter</u> <u>Group 1 ochres</u> PJ#21 N12/24-1 PJ#25 N11/30 PJ#28 N11/26 PJ#31 N5/15 PJ#32 N5/24-6 PJ#47 N13/2-1	Puritjarra rock shelter, Cleland Hills, Central Australia. 1986-1990.	Red ochre from archaeological excavations carried out at his site between 1986 and 1990 by M. A. Smith. Specimens in Group 1 resemble ochre from either Lawa or Karrku.
<u>Group 2 ochres</u> PJ#42 N5/6 PJ#43 N5/5	as above	As above. Specimens in Group 2 resemble Ulpunyali ochre.
<u>Kutikina Cave</u> A2SW A3SW A6SW A5SW	Kutikina Cave, southwest Tasmania. 1981.	Samples of ochre from the 1981 excavations reported in Kiernan, Jones and Ranson (1983).

Table II/11 Other samples: description

	Munsell colour	Description
Wangiana N-1	10R 4/6 red	Hard fine-grained red ochre. Mottled red and white appearance due to soft ?calcium carbonate inclusions. Occasional large clear rounded quartz grains. Frequent large flakes or decks of ?gypsum. Sandy appearance.
Purara	7.5R 4/3 dull reddish brown	Hard dark red ochre. Homogenous and very fine-grained. Abundant fine crystalline flakes of silicate mineral. Sandy appearance.
A1122	7.5R 3/6 dark red	Soft, friable red ochre. Uniformly fine-grained with a sandy appearance. Abundant fine crystalline flakes of a silicate mineral.
A1175	10R 5/8 red or 2.5YR 4/8 reddish brown.	Hard dark red ochre. Generally fine-grained with occasional large clear sub-angular quartz grains, rounded grains of ?calcite, small clots of yellow goethite, and fine crystalline flakes (?silcates). Sandy appearance. Colour is orange when rubbed.
MII'89/DEF30/40		Heavy, grey -dark red, vein haematite.
Puritjarra Group 1		Friable fine-grained red or dark red ochre. Clear sand-sized quartz grains and fine flakes of clear mica set in a matrix of dark red haematite.
Puritjarra Group 2		Friable dark red or purple ochre. Greasy, appearance. Abundant large rounded quartz grains with haematite coatings.

Part III - Analytical methods

Previous work

Various methods have been used to investigate the chemical composition of ochres: X-Ray diffraction (Culican 1986); QPA/Rietveld XRD (Jercher, pers. comm.); X-ray fluorescence (Sagona and Webb 1994)); PIXE/PIGME (David, Clayton & Watchman 1993; David et al 1995); EDXA and AAS (Smith, unpublished); ICP/AES (Weinstein-Evron and Ilani 1994). Clarke (1976) appears to have used optical emission spectrography. To date none of these have been entirely satisfactory and none - except Weinstein-Evron & Ilani (1994) - have been systematically applied to source archaeological ochres.

Of these methods XRD is the most widely employed. In most circumstances however XRD is unsuitable as an exploratory technique. It provides qualitative or semi-quantitative data on mineralogy but only for crystalline components >10%. Amorphous material - which often makes up 20-30% of ochre - cannot be analysed. As most ochres have dominant haematite (or goethite), quartz or calcite with lesser amounts of clay minerals (eg. kaolinite) and micas (eg. muscovite) the technique is of limited use in discriminating between sources although it may distinguish ochres originating in carbonate sedimentary rocks. Quantitative Phase Analysis (QPA) techniques (Howard, Hill and Sufi 1988) are promising and may overcome some of these problems (eg. Jercher et al 1996). X-ray fluorescence techniques appear to have been used by Sagona and Webb (1994) to determine major element and trace element composition of ochres. The technique has potential application in characterising sources but as it requires 3-5g samples for trace element determination it is not applicable to most archaeological specimens. Trace element determination by XRF is also labour intensive, limiting the number of samples, which can be run in a project. David et al (1993) used PIXE (Proton induced X-ray emission) analysis to determine 20 elements in samples of red ochre from the Northern Territory and Fern Cave, an excavated site in north Queensland. Multivariate analysis showed that the most important factor in distinguishing between ochres from the two regions is the proportion of Ca, hardly surprising given that the Fern Cave ochres originate in a region where carbonate rocks dominate (the Chillagoe limestone) and the Northern Territory ochres are from a region with extensive Palaeozoic sandstones. Analysis of 12 major and minor oxides by Smith (unpublished) using EDXA/SEM methods has shown that ratios of Fe/Si and Ca+Mg/Fe + Si distinguish between ochres from various sources but this study suffers from the same limitations as evident in David et al (1993). The results broadly distinguish ochres from different regions and from sources with different diagenetic histories rather than finger-print specific sources. The small number of oxides determined is also a serious drawback in investigations of this nature. Smith also experimented with AAS (Atomic absorption spectroscopy) methods to determine trace element composition of central Australian ochres. As only a small series of trace elements could be determined for each sample the results were inconclusive. NAA (Neutron activation analysis) to determine trace element composition has not as far as we are aware been applied to ochres but appears to be a very promising technique. It has been used extensively in archaeology for other provenance studies (Rapp 1985; Wilson 1978). It was not available to us in this study.

Methods used in this project

In contrast to previous investigations, Inductively Coupled Plasma Spectroscopy with Mass Spectrometry (ICP/MS), which is used in this study, offers absolute concentrations for a wide range of trace elements with high sensitivity. The method requires very small sample sizes (<0.1 g) making it applicable to the small samples of ochre found in archaeological sites and museum specimens. Following previous work by Smith we have continued to use SEM/EDXA to determine major and minor oxides, and have combined this with examination of the fabric/petrology of the ochres.

Sample preparation

Ambrose (1992, 1993) found that separation of coarse and fine fractions from potsherds, followed by EDXA elemental analysis of fines, gave good results in sourcing clays. Following Ambrose's lead we have experimented with alternative methods of preparing samples for compositional analysis. Many ochres consist of coarse-grained inclusions - usually quartz, mica or flakes of crystalline haematite - in a fine-grained matrix. Initially we thought that separation of fines, should offer better characterisation of sources. Therefore for each ochre source we have analysed the fines, extracted by the settling method described below, as well as whole pulverised samples. Tables III/1 and III/2 list the samples used in this study.

<u>Drying and Firing of Samples</u>

All samples or cuts from samples were dried at 115 ^{o}C for a minimum of 12 hours. Initially, some samples were settled or pulverised and again oven dried at 115 ^{o}C. The majority of samples, after being settled or pulverised, were fired in a muffle furnace at 360-390 ^{o}C for 6.5-12.5 hours. Some were unfired and were used as a comparison to fired samples in EDXA.

<u>Preparation Procedure: Settled Samples</u>

The following procedure was used to extract the fines.

1. Gently crush ochre into small pieces in a plastic bag with a hammer.

2. Weigh 1 gram of crushed ochre into 50 mL conical flask.

3. Add 40 mL of 0.01 M ammonium hydroxide. To make 0.01 M NH_4OH weigh 0.60g (0.68 mL) of concentrated (14.8 M) ammonia and dilute to 1 L with ultrapure water (UPW).

4. Sonicate for 10 min at a setting of 7 (Sonifier Cell Disrupter B-30, Branson Sonic Power Co.). Cool suspension.

5. Transfer to a 100 mL graduated cylinder ,which is marked with depths of 2 and 12 cm to give a 10 cm column for settling and 2 cm at the bottom for undisturbed sediment which has settled.

6. Add 0.01 M NH_4OH up to 12 cm depth.

7. Check temperature (should be 25 ^oC or convenient temperature for all samples).

8. Stir well and settle for 15 min.

9. Draw off 10 cm column and transfer to a centrifuge tube.

10. Centrifuge for 45 min at 3400 rpm.

11. Pour off supernatant and dry sample in centrifuge tube overnight at 115 ^oC.

12. Scrape out sample and weigh on weighing paper. Transfer to vial.

<u>Preparation Procedure: Pulverised Samples</u>

The following procedure was used to prepare pulverised (whole ochre) samples for analysis.

1. Weigh samples directly into pulverising cylinders. Cylinders and balls made of zirconium. Pulveriser: Retsch Mill, Type MM2, manufactured by GmbH & Co., 5657 Haan, Germany.

2. Drop in two crushing balls, cap and pulverise samples for 6 minutes at a setting of 70.

3. Invert cylinders and bang on weighing paper to empty. Scrape out with a spatula to dislodge ochre sticking to cylinder walls and invert again. Repeat procedure.

4. Blow out cylinders with high pressure air. Wash with UPW and ethanol. Wipe with Kimwipes and blow out again.

5. Add a small amount of acid purified sand (GPR grade, Prod 33094, BDH Chemicals, Kilsyth, VIC) to cylinders and pulverise for 2 min.

6. Repeat steps 4 and 5.

7. When pulverising is finished put acid purified sand through cylinders two times and then scrub cylinders and balls with abrasive pads and cleanser. Repeat pulverising quartz two times, blow out cylinders, rinse with ethanol, and blow dry.

Analytical instruments

ICP/MS analysis

For ICP-MS we used a VG^+ Elemental PQ2 Plus instrument. The procedures of Jenner et al (1990) were followed with the exception of the instrument and operating conditions which are described in Totland et al (1992). A variant of the microwave dissolution procedure of Totland et al (1992:Sec. 4.3) was used and is described below.

Milestone microwave procedure:

1. Add to microwave vessel: ~100 mg sample + 2 mL 16M HNO_3 + 5 mL 29M HF.

2. Heat above mixture for 5 min at 250W, 15 min at 450W, 15 min at 370W, and 30 min at 320W.

3. Transfer contents of microwave vessels to screw-top beakers and evaporate on hotplate at 140 ^oC.

4. Add 3 mL 6M HNO_3 and reflux overnight at 120 ^oC. Evaporate at 140 ^oC.

5. Add 95 mL of 2% HNO_3 to residue along with a 2% HNO3 solution containing ~100 ppb of isotopically normal Rb, In, Tm, Re, Bi and isotopically enriched Li-6, Sr-84, Sm-147, and U-235. (This solution is used to calculate drift correction factors as described in Jenner et al (1990).)

Standardisation was done by calibration against U.S.G.S. rock standard BHVO-1. Forty-four trace elements were analysed. These are listed in Table III/3 along with the BHVO-1 calibration values. As our analysis was exploratory we required a wide range of trace element analyses, preferably including a suite of immobile elements. The 44 elements analysed are standard on the ICP/MS system available to us but suit our purposes very well.

Energy Dispersive X-ray Analysis

The EDXA-SEM instrument is located in the EM Laboratory at the Research School of Biological Sciences, ANU. The instrument used was a JEOL JSM6400 scanning electron microscope (SEM) fitted with an Oxford 138 eV SATW $10mm^2$ detector. The analysis system was an Oxford ISIS using SEMQUANT. Analyses were done using 15 keV at 1 nA for 100 seconds, and adjusted using the ZAF correction procedure. Samples were mounted in a jig holding 30 samples, specially made for the mounts available for the electron microscopes. Samples were pressed into the 2.75 mm diameter holes with a drill press from the back forming a flat surface on the front. Sample size required was an average of 25 mg. Most analyses were done at 140X magnification (100X covers a surface area ~1 x 0.6 mm^2) except in cases where surface imperfections made it difficult to use an area this large. In these instances samples were analysed at 200-280X. Ninety-six analyses were done on settled and pulverised ochres. We chose to analyse for oxides likely to be the dominant constituents of ochres (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, and CaO) supplemented by other oxides commonly present at concentrations above the minimum detection level of the instrument (>0.1% - 0.01%).

Evaluation of sample preparation methods

Drying and Firing of Samples

Dry samples are necessary for preparation and analysis. Ochre samples were found to contain only a small amount of moisture when heated to 115 ^{o}C. This loss in weight includes losses from hygroscopic, adsorbed, and absorbed water (Grimshaw 1971:254-262). Weight loss on firing at 360-390 ^{o}C was also very small with an average loss of 1.1%. To be consistent all samples should be heated up to a maximum temperature of 400 ^{o}C. Archaeological samples may be mixed with organic materials such as fat and plant materials. Firing below 400 ^{o}C prevents any organic material from contaminating an analysis without changing the structure of any minerals present and prevents variations due to loss of structural water from clay minerals (Ball 1964).

Settled Samples

With the exception of one sample the yield of fines was sufficient for ICP/MS and EDXA from 1 g of starting material. The amount of fines recovered varied from 2.2 to 73.9% with an average of 35.9% on 12 samples.

The settling time of 15 minutes at 25 ^{o}C gives particle sizes less than 12 mm in the 10 cm column, which corresponds to medium to fine silt (Folk 1961:24). Control and monitoring of temperature is important because temperature has an influence on the settling rate of particles. The fine samples lend themselves to EDXA analysis where homogeneity is important for consistent and reliable results.

The use of NH_4OH as a dispersing agent was found to be necessary to prevent flocculation of fine particles and subsequent settling (Müller 1967:78). NH_4OH was chosen because it does not contaminate the prepared sample with an increase in concentration of certain elements and evaporates during the drying of the sample (Day

1965:547; Galehouse 1971:70-71). Low yields of fines were due to ochres either containing large amounts of quartz or not being completely broken up in the sonifier. It is important that the initial crushing is as gentle as possible so as not to introduce additional fines into the settling column (Galehouse 1971:70). The use of a vice to crush samples in a plastic bag is recommended.

The ochre must be stirred well before settling to ensure that it is distributed evenly throughout the cylinder. A special stirring rod was constructed for this purpose (Galehouse 1971:82). An alternative method is to shake the stoppered cylinder in a horizontal position several times before beginning timing (Müller 1967:80).

Pulverised Samples

For samples less than 1 g it is necessary to use a mill such as those manufactured by Spex or Retsch which contain the sample in a small cylinder (~10 cm^3) The use of larger crushers will result in the loss of too much sample. Ochres are "sticky" and extremely difficult to remove from any crushing device. The percentage recovery of ochre samples (29 samples) from the pulverising process varied from 79.7 to 97.6% with an average recovery of 88.9% on 1 g samples. Approximately 125 mg was lost from each sample in the pulverising process. Archaeological samples as small as 0.35 g were successfully pulverised in the Retsch Mill. Samples less than 0.3 g can not be pulverised in a mill. The only alternative is to use a small agate mortar and pestle, but long grinding times are required to produce the fine-grained homogeneous samples necessary for EDXA and ICP analyses.

As mentioned above, ochres adhere to the crushing device and it is necessary to remove them so as not to contaminate further samples. For this reason a sand "wash" is used between samples. The pulverised sand which removes the adhering ochre is easily removed from the crushing cylinders and acid purified quartz has extremely low concentrations of trace elements. Note that the sand is completely removed from the crushing cylinders by using high pressure air and an ethanol rinse.

EDXA results

Results for unfired settled and pulverised samples are presented in Tables III/4 and III/5 respectively. Results for fired settled and pulverised ochres are presented in Tables III/6 and III/7 respectively.

There are few general trends in the comparison of major and minor element concentrations between like samples prepared by settling and pulverising. Settled samples generally contain a greater amount of phosphorus whereas pulverised have a higher concentration of SiO_2, CaO, and, not surprisingly, Cl.

Looking at the results for Karrku #6 and #7, which are source and prepared cake respectively, the settled samples have a tighter fit of concentrations than the pulverised samples (correlation = 1.00 versus 0.98). If this trend carried over to other samples then one of the objectives of this study would have been realised. However, the same cannot be said for Bookartoo source materials and sample 1863, a prepared cake from the Bookartoo quarry. On major and minor oxide composition sample 1863 does not resemble any of the Bookartoo sources, settled or pulverised, and closely resembles Wilgie Mia (where the correlation coefficient is 1.00 for both settled and pulverised samples). These samples will be discussed again (see below) in connection with trace element analysis.

Three ochres (Wangiana, Mt Howden and Cathedral Rock) are exceptional for their high SO_3 values (Table III/7). Wangiana and Cathedral Rock ochres also contain high percentages of the minerals bassanite and natrojarosite, respectively (Jercher, pers. comm.).

Two ochres in Table III/7 are of low quality and will be excluded from further analyses. They were both yellow and of low quality before being fired. The best ochres with an intensely red colour are generally high in Fe_2O_3. However, ochres with less than 35% Fe_2O_3 can still be deep red, for example, Ulpunyali (MAS), MacDonnell Ranges, and Rockleigh. The two excluded samples are:

a) No. 25. Arkaba Burana. This sample appears to be baked clay rather than ochre.

b) No. 35. This is a yellow ochre, from an ochreous pebble collected from an archaeological site in the Kimberley region (S. O'Connor, pers. comm.).

Some of analyses were done in duplicate to check on analytical reproducibility. This involved duplicate analyses of different areas of the same sample surface and analyses of two different mountings of a sample. Table III/8 is a compilation of results for all duplicate analyses. The standard deviation is used as a measure of the closeness of concentrations for elements. The standard deviation (SD) is presented as a percentage of the mean value: percent relative standard deviation (%RSD) = 100(SD/Mean).

%RSDs vary from 0 to 133%. As expected, %RSDs are largest for low element concentrations where a small numerical distance can represent a considerable SD. %RSDs for the major elements, SiO_2, AL_2O_3, Fe_2O_3, are generally less than 10%.

ICP/MS is used for the analysis of trace elements, which are usually many orders of magnitude lower in concentration than the major and minor elements. However, two samples were analysed for major and minor elements using ICP/MS to give a comparison to EDXA (see Table III/9). The agreements are good except for TiO_2 and Na_2O. The reasons for the large differences in these samples is not known. Note that Ti is one of the elements included in all ICP/MS analyses.

Some of the ochre sources are represented by several samples from different locations in a quarry. Multiple analyses of a quarry can give an indication of element variations to be expected in a particular source, and whether or not inter-source is greater than intra-source variation. In this study samples were initially unfired (ie. not heated in a muffle furnace to remove organic compounds). Following these initial samples all samples were fired. Table III/10 gives the mean percentage concentrations of settled samples for Wilgie Mia and Bookartoo for fired, unfired, and these results combined. One can see that there is no statistical difference between fired and unfired samples (and combined). Therefore, it is better to combine the results and in so doing get, as far as possible, a chemical signature or "fingerprint" for a quarry. In Table III/10 the bottom column gives chemical signatures for Wilgie Mia and Bookartoo based on the EDXA results. The most striking differences between Wilgie Mia and Bookartoo in settled samples are in the SiO_2, Fe_2O_3 and CaO concentrations. A closer look reveals that MgO, K_2O, and SO_3 are also concentrated differently in the two ochre quarries. .

Table III/11 contains similar information to that of Table III/10, but is for pulverised samples. Once again there is no difference in concentrations of oxides between fired and unfired samples. In addition, the same elements are concentrated differently in the Wilgie Mia and Bookartoo sources. The EDXA fingerprints for pulverised samples of Wilgie Mia and Bookartoo are given at the bottom of the table.

Other sources with mean concentrations for pulverised (and fired) samples include Coopers Creek, MacDonnell Ranges, Mt. Howden, and Ulpunyali (Table III/12). All sources have reasonable SDs except for Ulpunyali. The large SDs and differences between minimum and maximum values is largely influenced by analyses 117A and 117B. These two analyses illustrate that samples from the same source can exhibit substantial differences in the concentration of iron oxide cement and coarse-grained quartz inclusions.

ICP/MS results

Table III/3 lists the 44 trace elements analysed in this research along with the calibration values of the BHVO-1 standard and the %RSD for 23 analyses of different aliquots of a Kilauea basalt. These low RSDs on a suite of elements demonstrate why ICP/MS has found routine application in the geosciences.

<u>Settled Samples (fines)</u>

ICP/MS results for settled ochre samples are presented in Table III/13. There are some large variations in elemental concentrations between samples from the same source, see for example, Li, Zn, Rb, Cd, etc. from S1 as compared to S2 and S3 of Wilgie Mia. The authenticity of this sample from both EDXA and ICP/MS analyses is in doubt. The close agreement between Karrku analyses S8 and S9 which are respectively from source and prepared cake samples is astonishing (correlation = 0.98). This closeness is not shared by the prepared cake, 1863 (S7) in the Bookartoo analyses although all of the Bookartoo concentrations are more highly correlated with each other (including the prepared cake) than for any other samples. For the settled samples there are only two sources with multiple analyses - Bookartoo and Wilgie Mia. The means and other information for these sources are given in Table III/14. A comparison is made for Wilgie Mia with and without the inclusion of analysis S1 in Wilgie Mia A and B. Most of the element concentrations for S1 fall outside the minimum or maximum values for S2 and S3. The correlation for S1 is 0.58 with S2 and 0.55 with S3 while the correlation between S2 and S3 is 0.99. The A+A(S1) sample may actually be from Wilgie Mia but represent an extreme of the source's composition (see below). The mean concentrations for Bookartoo and Wilgie Mia A are presented in a graph (Figure III/1) which visually is more easily followed than results in Table III/14. Concentrations are presented in logarithmic form because of the large range of concentrations. The means in Table III/14 and Figure III/1 represent the trace element signatures of these sources based only on settled samples.

<u>Pulverised Samples (whole ochres)</u>

Table III/15 gives ICP/MS analytical results for pulverised ochre samples. These are listed in order of analysis numbers. There is quite a good agreement between concentrations for the Karrku source and cake (MS#6 and MS#7, correlation coefficient = 0.95). Once again trace element concentrations for all Bookartoo samples including the prepared cake from Parachilna are highly correlated with each other and nothing else.

Table III/16 gives means, SDs, and ranges of concentrations for sources where we were able to analyse multiple samples. Wilgie Mia A and Wilgie Mia B differ in the inclusion of analysis 101 in B (as in the settled means above). For the pulverised samples there are more samples and the addition of 101 does not dramatically alter the mean of B compared to A. The ranges of concentrations for most trace elements in all sources are large. Rare earth elements have higher concentrations in Ulpunyali than in Bookartoo and Wilgie Mia (this is characteristic of central Australian ochres - see below). The means of Bookartoo, Wilgie Mia, and Ulpunyali are plotted in Figure III/2. These means give chemical signatures for Bookartoo, Wilgie Mia, and Ulpunyali.

Correlation of Element Concentrations

Table III/17 gives correlation coefficients > 0.89 for trace element concentrations in settled samples. Most of these elements are rare earths or lanthanides, which is a group of rare metallic elements with atomic numbers from 57 to 71. The properties of these metals, which occur in monazite and other rare minerals are all very similar. The settling process has concentrated or selected those minerals richer in rare earth elements. Phosphorus, strontium, and yttrium are also highly correlated with the rare earths. Multivariate statistical analysis deals with elements, which are highly correlated. If other statistical methods are used it is not necessary to analyse for and include highly correlated elements (Wilson 1978).

Several of the trace element concentrations (mainly rare earth elements) are highly correlated in the pulverised samples (Table III/18). The list is not as extensive as that in Table III/17.

To illustrate the large ranges of trace element concentrations in these ochres Table III/19 gives means and SDs for each trace element (using ICP/MS data) combining <u>all</u> samples.

TABLE III/1. Ochre samples collected at the South Australian Museum (SAM).

Attribution	SAM number	Date registered	Mass (g)	Locality/Description
Bookartoo	1863	1911-1918	4.8	ochre prepared for use, Parachilna
Bookartoo	59022	12/9/68	23.5	Mount Hayward, southern Flinders Ranges
Bookartoo	66496	12/6/78	27.4	ochre mine at Mount Hayward, Flinders Ranges
Bookartoo	66500	12/6/78	14.7	ochre mine near summit Mt. Hayward, Flinders Ranges
Bookartoo	67979	13/9/83	26.5	2 miles northwest of Mount Hayward
Bookartoo	67980	13/9/83	27.4	2 miles northwest of Mount Hayward
Coopers Creek	66497	?	24.9	locality Marakoto, No. 96, Reuther collection
Coopers Creek	66498	?	44.5	locality Marakoto, No. 97, Reuther collection
Lawa	52812	15/1/60	7.0	from native mine called 'lawa' in George Gill Range, NT
MacDonnel Ranges	1122	1911-1918	16.5	MacDonnel Ranges, from Rev. O. Liebler
MacDonnel Ranges	1175	1911-1918	16.5	MacDonnel Ranges, from Rev. O. Liebler
Ulpunyali	16845	5/1932	6.1	hills southwest of Kings Creek
Wilgie Mia	2839	1911-1918	11.3	Weld Range, W. Aust.
Wilgie Mia	60508	24/3/70	12.6	Wilgiamia ochre mine via Cue, W. Aust.
Wilgie Mia	60508	24/3/70	11.2	yellow ochre, Wilgiamia ochre mine via Cue, W. Aust.

TABLE III/2. Further ochre samples analysed in this study.

Attribution	Source*	Locality/Description
Archaeological	MS	Malakunanja II, #55 (Def 30/40)
Archaeological	MS	Puritjarra, #21 (N12/24-1)
Archaeological	MS	Puritjarra, #25 (N11/301)
Archaeological	MS	Puritjarra, #28 (N11/26)
Archaeological	MS	Puritjarra, #31 (N5/15)
Archaeological	MS	Puritjarra, #32 (N5/24-6)
Archaeological	MS	Puritjarra, #42 (N5/6)
Archaeological	MS	Puritjarra, #43 (N5/5)
Archaeological	MS	Puritjarra, #47 (N13/2-1)
Archaeological	RJ	Kutikina, FCF 81 A2 SW
Archaeological	RJ	Kutikina, FCF 81 A3 SW
Archaeological	RJ	Kutikina, FCF 81 A5 SW
Archaeological	RJ	Kutikina, FCF 81 A6 SW
Arkaba Burana	MN	Lake Eyre Basin, (originally yellow but fired in an Aboriginal work area)
Balgo Hill	BF	from Balgo Hill, WA, for Desert Women's Project, 1991
Bookartoo	MN	Flinders Ranges
Bookartoo	MS	in film container sent by Philip Jones collected in 1988, SAM
Bookartoo	MS	pulverised sample #13 from film container immediately above
Cathedral Rock	MN	Olary district, proven use on painting site
Dial Ranges	MS	#1
Karrku	MS	collected from mine by S. Dunlop in 1989, stored in plastic bag
Karrku	MS	prepared cake collected by Nicholas Peterson, Smith sample #7
Moana	MN	south of Adelaide, known Aboriginal quarry
Mt Howden	MN	Olary, ochre source around copper-cobalt deposit (2 samples)
Overland Corner	MN	Murray River, known Aboriginal quarry
Paterson X	MS	
Purara	MS	
Rockleigh	MN	east of Lofty Ranges
Ulpunyali	MS	collected by Mike Smith from quarry pit in 1983/84
Wangiana	MN	a known ochre quarry, Lake Eyre Basin (in limestone)
Wilgie Mia	MN	near Cue, W.A., known Aboriginal ochre quarry
Wilgie Mia	MS	ANU Archaeology & Anthropology store
Wilgie Mia	WAM	sample sent by C. Dortch of Western Australian Museum

*BF = B. Fankhauser, MN = M. Nobbs, MS = M. Smith, RJ = R. Jones, WAM = Western Australia Museum

Table III/3. Trace elements analysed in this research with the calibration values of the BHVO-1 standard and the %RSD for analyses of a Kilauea basalt. Element concentrations in parts per billion.

Element	Isotope measured	BHVO-1 Calibration values	Kilauea basalt n=23	%RSD
Lithium	Li 7	4900	4800	1.4
Beryllium	Be 9	1100	918	2.3
Phosphorus	P 31	1190000	980000	3.8
Scandium	Sc 45	31800	31600	1.7
Titanium	Ti 49	16610000	14362000	2.5
Vanadium	V 51	320000	301000	4.3
Chromium	Cr 53	289000	471000	2.5
Cobalt	Co 59	45000	51000	2.3
Nickel	Ni 60	120000	160000	1.7
Copper	Cu 65	136000	123000	2.6
Zinc	Zn 66	105000	104000	1.5
Gallium	Ga 71	21000	19200	0.8
Rubidium	Rb 85	9500	7150	1.8
Strontium	Sr 86	390000	317000	0.7
Yttrium	Y 89	28000	27000	0.5
Zirconium	Zr 91	180000	147200	0.5
Niobium	Nb 93	19500	13240	0.6
Molybdenum	Mo 98	1000	740	5.5
Silver	Ag 109	55	43	13.9
Cadmium	Cd 114	69	64	13.5
Tin	Sn 120	2100	1720	2.7
Antimoy	Sb 121	160	33	7.7
Caesium	Cs 133	100	74	3.9
Barium	Ba 137	13000	99900	0.5
Lanthanum	La 139	15500	11200	0.6
Cerium	Ce 140	38000	27900	0.5
Praeseodymium	Pr 141	5450	4110	0.6
Neodymium	Nd 146	24700	19210	0.7
Samarium	Sm 149	6170	5210	0.8
Europium	Eu 151	2060	1783	0.5
Terbium	Tb 159	6220	878	0.9
Gadolinium	Gd 160	950	5590	0.8
Dysprosium	Dy 161	5250	4960	0.5
Holmium	Ho 165	1000	966	0.8
Erbium	Er 167	2440	2510	0.5
Ytterbium	Yb 174	1980	1974	1.0
Lutetium	Lu 175	278	279	1.2
Hafnium	Hf 178	4300	3580	0.8
Tantalum	Ta 181	1200	820	1.0
Tungsten	W 184	225	530	12.0
Thallium	Tl 205	58	22	3.9
Lead	Pb 208	2100	950	2.7
Thorium	Th 232	1260	853	1.0
Uranium	U 238	420	274	0.6

Table III/4. EDXA: results for analyses of unfired settled ochre samples.

No. Attribution	Analysis No.	P_2O_5	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	SO_3	Cl
1. Wilgie Mia 60508	S2	0.21	3.73	0.06	3.20	91.91	0.00	0.00	0.07	0.79	0.00	0.02	0.00
2. Wilgie Mia 2839	S3	0.14	2.81	0.00	2.46	93.46	0.12	0.12	0.06	0.69	0.03	0.11	0.00
3. Bookartoo 66496	S4	0.20	10.21	0.25	3.51	68.34	0.00	2.52	13.56	0.88	0.31	0.16	0.07
4. Bookartoo 67979	S5	0.10	5.09	0.14	1.77	82.93	0.07	3.47	5.45	0.81	0.08	0.08	0.00
5. Bookartoo MAS	S6	0.14	14.41	0.33	5.63	54.84	0.06	1.27	21.76	0.68	0.45	0.35	0.06
6. Bookartoo 1863	S7	0.00	3.47	0.10	1.21	93.19	0.01	0.35	0.77	0.80	0.05	0.00	0.05
7. Karrku #6	S8	0.56	19.50	0.30	12.95	62.03	0.12	0.53	0.35	0.42	3.11	0.13	0.00
8. Karrku #7	S9	0.63	19.30	0.34	11.18	64.09	0.00	0.44	0.54	0.69	2.59	0.21	0.00

Table III/5. EDXA: results for analyses of unfired pulverised ochre samples.

No. Attribution	Analysis No.	P_2O_5	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	SO_3	Cl
1. Wilgie Mia A&A	101A	0.00	49.06	0.65	21.04	27.13	0.00	0.23	0.45	0.50	0.35	0.53	0.06
2. Wilgie Mia 60508	102A	0.19	2.72	0.13	1.80	93.36	0.07	0.20	0.12	1.15	0.02	0.08	0.17
3. Wilgie Mia 60508	102B	0.26	2.40	0.13	1.61	94.02	0.00	0.04	0.17	0.95	0.06	0.12	0.24
4. Wilgie Mia 2839	103	0.15	2.46	0.03	1.87	94.16	0.03	0.23	0.11	0.72	0.00	0.14	0.09
5. Bookartoo 66496	104	0.04	11.06	0.10	2.53	50.05	0.17	1.97	32.49	0.90	0.21	0.34	0.15
6. Bookartoo 67979	105	0.15	9.63	0.11	2.13	67.28	0.33	5.93	13.19	0.83	0.22	0.19	0.00
7. Bookartoo MAS	106	0.00	11.19	0.12	2.79	56.53	0.08	0.81	27.72	0.41	0.33	0.00	0.00
8. Bookartoo 1863	107	0.09	4.90	0.01	0.84	91.41	0.00	0.18	1.08	0.94	0.02	0.41	0.13
9. Karrku #6	108	0.33	35.21	0.39	13.55	45.04	0.00	0.60	0.15	0.62	3.63	0.40	0.08
10. Karrku #7	109	0.29	44.72	0.22	13.52	35.32	0.07	0.51	0.46	0.42	4.01	0.41	0.05
11. Bookartoo #13	110A1	0.13	16.11	0.01	2.67	60.14	0.05	0.96	18.39	0.72	0.44	0.33	0.05
12. Bookartoo #13	110A2	0.16	14.30	0.17	2.96	62.43	0.00	0.89	17.61	0.69	0.37	0.39	0.04
13. Bookartoo #13	110B1	0.00	15.98	0.00	2.96	59.94	0.24	1.01	18.41	0.67	0.42	0.27	0.09

Table III/6. EDXA: analyses of fired settled samples.

No.	Attribution	Analysis No.	P_2O_5	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	SO_3	Cl
1.	Wilgie Mia 60508	S2	0.29	3.67	0.01	3.05	91.33	0.00	0.15	0.12	0.87	0.00	0.43	0.10
2.	Wilgie Mia 2839	S3	0.18	2.62	0.16	2.22	93.52	0.00	0.26	0.09	0.80	0.00	0.11	0.03
3.	Bookartoo 66496	S4	0.19	9.21	0.60	3.10	69.61	0.07	2.10	13.79	0.82	0.35	0.14	0.01
4.	Bookartoo 67979	S5	0.04	4.58	0.00	1.49	84.04	0.39	3.31	5.22	0.78	0.08	0.04	0.03
5.	Bookartoo MAS	S6A	0.19	14.31	0.35	5.22	53.14	0.15	1.72	20.93	0.64	0.52	2.80	0.04
6.	Bookartoo MAS	S6B	0.26	11.76	0.19	4.43	51.57	0.12	1.09	26.39	0.68	0.56	2.90	0.06
7.	Bookartoo 1863	S7	0.00	2.91	0.00	1.18	94.31	0.00	0.38	0.42	0.73	0.00	0.07	0.00
8.	Karrku #6	S8	0.54	21.27	0.35	14.95	57.79	0.00	0.67	0.10	0.54	3.65	0.12	0.02
9.	Karrku #7	S9A	0.46	18.12	0.56	10.56	65.00	0.00	0.41	0.42	0.78	2.50	1.08	0.11
10.	Karrku #7	S9B	0.29	15.84	0.38	9.59	69.39	0.00	0.37	0.26	0.67	2.13	1.03	0.04
11.	Moana N-6	S10	0.13	54.38	1.10	17.29	21.33	0.06	1.15	0.06	0.13	4.17	0.14	0.06
12.	Balgo Hill	S11	0.10	3.36	0.03	1.04	94.19	0.39	0.19	0.09	0.37	0.02	0.17	0.05
13.	Ulpunyali MS-A	S12	0.96	31.54	0.77	18.66	42.72	0.10	1.02	0.53	0.14	2.10	1.36	0.08
14.	C'Creek 66498	S13	0.01	6.32	0.48	3.12	86.40	0.00	0.65	2.39	0.35	0.08	0.15	0.04
15.	MacD Ra 1175	S14	0.51	39.21	0.60	24.72	27.88	0.11	1.69	0.14	0.10	4.86	0.16	0.01
16.	Ulpunyali MS-1	S16	0.35	15.37	0.30	6.61	73.90	0.00	0.85	0.43	0.09	1.45	0.55	0.09
17.	C'Creek 66498	S17	0.11	29.37	0.26	12.11	52.29	0.12	3.11	1.64	0.39	0.40	0.15	0.07

Table III/7. EDXA: analyses of fired pulverised samples.

No. Attribution	Analysis No.	P_2O_5	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	SO_3	Cl
1. Wilgie Mia A&A	101A	0.01	48.25	0.62	21.70	27.85	0.00	0.20	0.16	0.54	0.29	0.37	0.01
2. Wilgie Mia A&A	101B	0.10	47.49	0.58	21.24	28.91	0.17	0.17	0.20	0.42	0.29	0.38	0.05
3. Wilgie Mia 60508	102	0.05	2.74	0.20	1.97	93.43	0.00	0.14	0.14	0.90	0.12	0.13	0.19
4. Wilgie Mia 2839	103	0.00	2.50	0.03	2.04	94.17	0.01	0.25	0.10	0.86	0.00	0.04	0.00
5. Bookartoo 66496	104	0.13	10.65	0.36	2.35	51.03	0.19	1.72	32.02	0.95	0.20	0.31	0.09
6. Bookartoo 67979	105	0.20	9.07	0.19	2.03	67.98	0.32	5.60	13.40	0.86	0.26	0.09	0.00
7. Bookartoo MAS	106	0.08	11.29	0.14	2.65	53.71	0.43	0.78	28.66	0.69	0.46	1.06	0.07
8. Bookartoo #13	110	0.16	14.86	0.13	2.87	60.58	0.12	0.97	18.83	0.60	0.48	0.40	0.00
9. Bookartoo 1863	107A	0.01	4.00	0.11	0.85	92.24	0.00	0.14	1.09	0.96	0.10	0.44	0.07
10. Bookartoo 1863	107B	0.07	4.57	0.09	0.85	91.22	0.05	0.21	1.05	0.99	0.15	0.71	0.03
11. Karrku #6	108	0.37	35.01	0.28	12.79	46.14	0.00	0.52	0.15	0.53	3.62	0.55	0.05
12. Karrku #7	109	0.36	41.89	0.49	13.81	37.25	0.14	0.55	0.56	0.57	4.02	0.30	0.05
13. Bookartoo 66500	111	0.12	7.56	0.31	1.76	61.67	0.01	0.30	27.50	0.35	0.16	0.13	0.12
14. Bookartoo 67980	112	0.33	17.81	0.31	2.38	67.75	0.23	3.20	4.50	1.51	0.33	0.23	1.41
15. Bookartoo 59022	113	0.07	4.36	0.00	1.22	83.77	0.50	1.77	7.40	0.28	0.08	0.48	0.06
16. Bookartoo N-9	114	0.01	3.27	0.04	0.89	92.64	0.00	1.21	1.25	0.45	0.07	0.00	0.18
17. Wilgie Mia N-2A	115A	0.14	4.46	0.05	3.65	91.13	0.00	0.05	0.08	0.37	0.00	0.00	0.08
18. Wilgie Mia N-2B	115B	0.06	0.91	0.05	0.88	97.09	0.00	0.17	0.44	0.28	0.01	0.02	0.09
19. Ulpunyali 16845	116	0.25	26.35	0.17	2.77	68.82	0.02	0.34	0.17	0.20	0.70	0.20	0.00
20. Ulpunyali MAS	117A1	0.52	68.33	0.23	7.94	20.48	0.00	0.42	0.24	0.24	0.89	0.57	0.13
21. Ulpunyali MAS	117B1	0.62	64.24	0.41	9.29	22.97	0.00	0.37	0.33	0.09	1.03	0.53	0.13
22. Lawa 52812	118A	0.13	41.81	1.12	20.22	35.64	0.15	0.15	0.29	0.11	0.16	0.20	0.02
23. Wangiana N-1	118B	0.06	4.79	0.00	1.38	13.01	0.35	0.31	33.11	0.13	0.24	46.41	0.21
24. Moana N-6	119	0.01	46.42	0.84	14.88	30.56	0.00	1.16	0.19	1.01	4.19	0.33	0.41
25. Arkaba N-5	120	0.01	60.36	0.70	17.29	5.61	0.00	1.39	1.93	4.72	3.30	4.62	0.07
26. Balgo Hill	121	0.11	2.41	0.06	0.59	95.94	0.28	0.00	0.13	0.33	0.00	0.13	0.01
27. MIT'89 DEF30/40	122	0.33	8.61	0.00	3.52	86.61	0.00	0.13	0.22	0.24	0.30	0.05	0.00
28. C'Creek 66497	123A	0.00	7.60	0.12	1.34	88.86	0.00	0.35	0.74	0.57	0.08	0.08	0.28
29. C'Creek 66497	123B	0.00	11.39	0.12	2.17	80.36	0.02	0.63	4.08	0.58	0.14	0.18	0.33
30. C'Creek 66498	124	0.02	10.46	0.00	1.34	86.09	0.27	0.34	0.56	0.59	0.01	0.11	0.22
31. Paterson X	125	0.28	26.56	0.36	9.80	53.06	0.84	1.91	1.98	0.77	3.69	0.26	0.50
32. Purara	126	0.03	29.61	0.64	9.54	58.65	0.11	0.03	0.20	0.23	0.57	0.37	0.00
33. MacD Ra 1122	127	0.05	47.41	0.62	13.25	29.80	0.11	2.03	0.13	0.46	5.91	0.10	0.13
34. MacD Ra 1175	128	0.20	46.91	0.65	15.78	31.36	0.00	1.15	0.12	0.23	3.40	0.17	0.03
35. Sue O'C Yellow	129	0.39	24.06	0.03	1.76	5.35	0.00	0.66	67.01	0.13	0.53	0.05	0.03

Table III/7 cont.

No. Attribution	Analysis No.	P_2O_5	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	SO_3	Cl
36. PJ#21 N12/24-1	130	0.76	51.53	1.05	21.02	23.76	0.17	0.29	0.05	0.13	1.19	0.00	0.06
37. PJ#25 N11/30	131	1.53	31.99	1.10	22.11	41.17	0.03	0.21	0.11	0.25	1.14	0.35	0.01
38. PJ#28 N11/26	132	1.21	50.65	0.59	9.33	37.25	0.00	0.10	0.12	0.09	0.49	0.16	0.01
39. PJ#32 N5/24-6	133	1.11	63.66	0.96	14.86	17.32	0.02	0.22	0.21	0.43	0.99	0.16	0.05
40. PJ#42 N5/6	134A	2.01	44.50	0.47	4.24	43.30	0.07	0.39	3.44	0.34	0.92	0.12	0.21
41. PJ#42 N5/6	134B	2.12	42.95	0.45	4.30	44.80	0.13	0.29	3.62	0.10	0.77	0.27	0.21
42. PJ#43 N5/5	135	0.56	25.13	0.39	6.79	60.41	0.00	0.69	4.23	0.42	0.70	0.21	0.47
43. PJ#31 N5/15	136	2.19	59.30	0.89	10.92	25.21	0.02	0.16	0.27	0.18	0.74	0.00	0.10
44. PJ#47 N13/2-1	137	0.01	21.78	0.49	14.55	61.04	0.09	0.20	0.40	0.25	1.02	0.13	0.03
45. Wilgie Mia N-2A	138	0.39	1.69	0.00	0.97	96.18	0.00	0.12	0.16	0.35	0.02	0.02	0.10
46. Kutikina A2 SW	139	1.65	23.87	0.25	6.87	63.90	0.16	0.92	0.79	0.30	1.27	0.00	0.02
47. Kutikina A3 SW	140	0.56	29.49	0.74	8.48	35.79	0.15	1.82	20.72	0.10	2.13	0.00	0.00
48. Kutikina A6 SW	141	1.28	11.97	0.09	3.18	81.49	0.24	0.61	0.66	0.15	0.32	0.00	0.01
49. Kutikina A5 SW	142	6.02	25.00	0.32	9.21	47.85	0.28	1.19	7.47	0.35	2.22	0.04	0.03
50 Mt Howden N-4A	143	0.07	18.51	0.30	3.47	22.90	0.01	0.14	17.98	0.49	1.50	34.56	0.08
51. Mt Howden N-4B	144	0.27	17.41	0.13	1.86	34.27	0.06	0.04	14.96	0.44	0.81	29.64	0.11
52. C'dral Rock N-3	145	0.30	15.89	0.91	0.24	45.45	0.13	0.09	0.05	3.30	2.93	30.55	0.16
53. Overland Cnr N-7	146	0.69	22.87	0.00	0.78	74.25	0.01	0.36	0.17	0.50	0.06	0.21	0.09
54. Rockleigh N-8A	147	0.48	32.53	0.21	29.86	30.76	0.00	0.31	0.30	0.14	1.21	4.06	0.14
55. Dial Ranges #1	148	0.15	3.30	0.23	1.10	94.58	0.15	0.05	0.08	0.22	0.01	0.13	0.01
56. Ulpunyali MS#1	149A	0.26	39.23	0.30	5.50	52.67	0.02	0.48	0.34	0.10	0.66	0.42	0.02
57. Ulpunyali MS#1	149B	0.31	41.61	0.22	4.75	51.16	0.03	0.45	0.32	0.25	0.58	0.31	0.01
58. Wilgie Mia WAM	150	0.69	31.54	0.21	32.69	30.81	0.04	0.58	0.61	0.54	0.80	0.42	1.08

Table III/8. EDXA: comparison of results for duplicate analyses.

Oxide	Wilgie Mia A&A 101A,101B Mean	%RSD	Bookartoo MAS S6A,S6B Mean	%RSD	Wilgie Mia 60508 102A,102B Mean	%RSD	Bookartoo #13 110A1,110A2 Mean	%RSD	Coopers Creek 66497 123A,123B Mean	%RSD	Puritjarra #42 134A,134B Mean	%RSD
P_2O_5	0.06	100.00	0.23	22.00	0.23	22.00	0.15	14.63	0.00	0.00	2.07	3.77
SiO_2	47.87	1.12	13.04	13.83	2.56	8.84	15.21	8.42	9.50	28.22	43.73	2.51
TiO_2	0.60	4.71	0.27	41.90	0.13	0.00	0.09	122.22	0.12	0.00	0.46	3.07
Al_2O_3	21.47	1.51	4.83	11.58	1.71	7.88	2.82	7.28	1.76	33.44	4.27	0.99
Fe_2O_3	28.38	2.64	52.36	2.12	93.69	0.50	61.29	2.64	84.61	7.10	44.05	2.41
MnO	0.09	133.33	0.14	15.71	0.04	125.00	0.03	133.33	0.01	100.00	0.10	42.43
MgO	0.19	11.47	1.41	31.71	0.12	94.28	0.93	5.35	0.49	40.41	0.34	20.80
CaO	0.18	15.71	23.66	16.32	0.15	24.38	18.00	3.06	2.41	98.00	3.53	3.61
Na_2O	0.48	17.68	0.66	4.29	1.05	13.47	0.71	3.01	0.57	1.23	0.22	77.14
K_2O	0.29	0.00	0.54	5.24	0.04	70.71	0.41	12.22	0.11	38.57	0.85	12.55
SO_3	0.38	1.89	2.85	2.48	0.10	28.28	0.36	11.79	0.13	54.39	0.20	54.39
Cl	0.03	94.28	0.05	28.28	0.21	24.15	0.05	15.71	0.31	11.59	0.21	0.00

Oxide	Ulpunyali MS#1 149A,149B Mean	%RSD	Bookartoo 1863 107A,107B Mean	%RSD	Karrku #7 S9A,S9B Mean	%RSD	Bookartoo #13 110A1,110A2,110B1 Mean	%RSD	Ulpunyali MAS 117A1,117B1 Mean	%RSD	Coopers Creek 123A,123B,124 Mean	%RSD
P_2O_5	0.29	12.41	0.04	100.00	0.38	32.06	0.07	142.86	0.57	12.41	0.01	100.00
SiO_2	40.42	4.16	4.29	9.41	16.98	9.49	15.59	3.51	66.29	4.36	9.98	6.84
TiO_2	0.26	21.76	0.10	14.14	0.47	27.08	0.05	120.00	0.32	39.77	0.06	133.33
Al_2O_3	5.13	10.35	0.85	0.00	10.08	6.81	2.89	3.55	8.62	11.08	1.55	18.96
Fe_2O_3	51.92	7.10	91.73	0.79	67.20	4.62	60.61	1.57	21.73	8.10	85.35	1.23
MnO	0.03	28.28	0.03	133.33	0.00	0.00	0.13	115.38	0.00	0.00	0.14	128.57
MgO	0.47	4.56	0.18	28.28	0.39	7.25	0.97	6.21	0.40	8.95	0.42	25.56
CaO	0.33	4.29	1.07	2.64	0.34	33.28	18.21	1.59	0.29	22.33	1.49	88.09
Na_2O	0.18	60.61	0.98	2.18	0.73	10.73	0.69	3.60	0.17	64.28	0.58	1.82
K_2O	0.62	9.12	0.13	28.28	2.32	11.30	0.41	2.57	0.96	10.31	0.06	116.67
SO_3	0.37	21.31	0.57	33.20	1.06	3.35	0.32	20.20	0.55	5.14	0.12	11.79
Cl	0.02	47.14	0.05	56.57	0.08	66.00	0.07	47.14	0.13	0.00	0.26	22.90

Notes:
Analysis numbers included in the mean (see Tables III/5, /6, /7) are given below the source name.
%RSD = 100(SD/Mean)

Table III/9. Comparison of EDXA and ICP/MS analyses.

	Bookartoo, 106		Karrku, 108	
	EDXA	ICP	EDXA	ICP
P_2O_5	0.00	0.00	0.33	0.012
SiO_2	11.19	*	35.21	*
TiO_2	0.12	0.01	0.39	0.02
Al_2O_3	2.79	2.56	13.55	14.38
Fe_2O_3	56.53	46.73	45.04	45.21
MnO	0.08	0.19	0.00	0.01
MgO	0.81	0.91	0.60	0.73
CaO	27.72	22.10	0.15	0.09
Na_2O	0.41	0.13	0.62	0.17
K_2O	0.33	0.25	3.63	3.70
SO_3	0.00	*	0.40	*
Cl	0.00	*	0.08	*

* indicates value not determined. (Si, S, and Cl cannot be determined with ICP/MS using the methods given above.

Table III/10. EDXA: percentage concentrations for Wilgie Mia and Bookartoo settled ochre samples which were fired, unfired, and these combined.

Oxide	Wilgie Mia fired Mean	SD	Min	Max	Bookartoo fired Mean	SD	Min	Max
P_2O_5	0.24	0.08	0.18	0.29	0.17	0.09	0.04	0.26
SiO_2	3.15	0.74	2.62	3.67	9.97	4.15	4.58	14.31
TiO_2	0.09	0.11	0.01	0.16	0.28	0.25	0.00	0.60
Al_2O_3	2.64	0.59	2.22	3.05	3.56	1.63	1.49	5.22
Fe_2O_3	92.43	1.55	91.33	93.52	64.59	15.32	51.57	84.04
MnO	0.00	0.00	0.00	0.00	0.18	0.14	0.07	0.39
MgO	0.21	0.08	0.15	0.26	2.06	0.93	1.09	3.31
CaO	0.11	0.02	0.09	0.12	16.58	9.17	5.22	26.39
Na_2O	0.84	0.05	0.80	0.87	0.73	0.08	0.64	0.82
K_2O	0.00	0.00	0.00	0.00	0.38	0.22	0.08	0.56
SO_3	0.27	0.23	0.11	0.43	1.47	1.59	0.04	2.90
Cl	0.07	0.05	0.03	0.10	0.04	0.02	0.01	0.06

Oxide	Wilgie Mia unfired Mean	SD	Min	Max	Bookartoo unfired Mean	SD	Min	Max
P_2O_5	0.18	0.05	0.14	0.21	0.15	0.05	0.10	0.20
SiO_2	3.27	0.65	2.81	3.73	9.90	4.67	5.09	14.41
TiO_2	0.03	0.04	0.00	0.06	0.24	0.10	0.14	0.33
Al_2O_3	2.83	0.52	2.46	3.20	3.64	1.93	1.77	5.63
Fe_2O_3	92.69	1.10	91.91	93.46	68.70	14.05	54.84	82.93
MnO	0.06	0.08	0.00	0.12	0.04	0.04	0.00	0.07
MgO	0.06	0.08	0.00	0.12	2.42	1.10	1.27	3.47
CaO	0.07	0.01	0.06	0.07	13.59	8.16	5.45	21.76
Na_2O	0.74	0.07	0.69	0.79	0.79	0.10	0.68	0.88
K_2O	0.02	0.02	0.00	0.03	0.28	0.19	0.08	0.45
SO_3	0.07	0.06	0.02	0.11	0.20	0.14	0.08	0.35
Cl	0.00	0.00	0.00	0.00	0.04	0.04	0.00	0.07

Oxide	Wilgie Mia combined Mean	SD	Min	Max	Bookartoo combined Mean	SD	Min	Max
P_2O_5	0.21	0.06	0.14	0.29	0.16	0.07	0.04	0.26
SiO_2	3.21	0.57	2.62	3.73	9.94	3.98	4.58	14.41
TiO_2	0.06	0.07	0.00	0.16	0.27	0.19	0.00	0.60
Al_2O_3	2.73	0.47	2.22	3.20	3.59	1.61	1.49	5.63
Fe_2O_3	92.56	1.11	91.33	93.52	66.35	13.71	51.57	84.04
MnO	0.03	0.06	0.00	0.12	0.12	0.13	0.00	0.39
MgO	0.13	0.11	0.00	0.26	2.21	0.94	1.09	3.47
CaO	0.09	0.03	0.06	0.12	15.30	8.17	5.22	26.39
Na_2O	0.79	0.07	0.69	0.87	0.76	0.09	0.64	0.88
K_2O	0.01	0.02	0.00	0.03	0.34	0.20	0.08	0.56
SO_3	0.17	0.18	0.02	0.43	0.92	1.32	0.04	2.90
Cl	0.03	0.05	0.00	0.10	0.04	0.03	0.00	0.07

Notes: Calculations were done using the following analyses (see Tables III/4 and /6): Wilgie Mia: (fired) S2,S3; (unfired) S2,S3; Bookartoo: (fired) S4,S5,S6A,S6B; (unfired) S4,S5,S6. "Combined" concentrations above were calculated from a combination of fired and unfired analyses.

Table III/11. EDXA: percentage concentrations of pulverised ochre samples from Wilgie Mia and Bookartoo which were fired, unfired, and these combined.

Oxide	Wilgie Mia fired Mean	SD	Min	Max	Bookartoo fired Mean	SD	Min	Max
P_2O_5	0.13	0.15	0.00	0.39	0.14	0.10	0.01	0.33
SiO_2	2.46	1.33	0.91	4.46	9.86	4.93	3.27	17.81
TiO_2	0.07	0.08	0.00	0.20	0.19	0.13	0.00	0.36
Al_2O_3	1.90	1.12	0.88	3.65	2.02	0.69	0.89	2.87
Fe_2O_3	94.40	2.35	91.13	97.09	67.39	14.34	51.03	92.64
MnO	0.00	0.00	0.00	0.01	0.23	0.18	0.00	0.50
MgO	0.15	0.07	0.05	0.25	1.94	1.71	0.30	5.60
CaO	0.18	0.15	0.08	0.44	16.70	11.86	1.25	32.02
Na_2O	0.55	0.30	0.28	0.90	0.71	0.40	0.28	1.51
K_2O	0.03	0.05	0.00	0.12	0.26	0.16	0.07	0.48
SO_3	0.04	0.05	0.00	0.13	0.34	0.33	0.00	1.06
Cl	0.09	0.07	0.00	0.19	0.24	0.48	0.00	1.41

Oxide	Wilgie Mia unfired Mean	SD	Min	Max	Bookartoo unfired Mean	SD	Min	Max
P_2O_5	0.20	0.06	0.15	0.26	0.08	0.08	0.00	0.16
SiO_2	2.53	0.17	2.40	2.72	13.05	2.78	9.63	16.11
TiO_2	0.10	0.06	0.03	0.13	0.09	0.07	0.00	0.17
Al_2O_3	1.76	0.13	1.61	1.87	2.67	0.31	2.13	2.96
Fe_2O_3	93.85	0.43	93.36	94.16	59.40	5.79	50.05	67.28
MnO	0.03	0.04	0.00	0.07	0.14	0.13	0.00	0.33
MgO	0.16	0.10	0.04	0.23	1.93	2.01	0.81	5.93
CaO	0.13	0.03	0.11	0.17	21.30	7.25	13.19	32.49
Na_2O	0.94	0.22	0.72	1.15	0.70	0.17	0.41	0.90
K_2O	0.03	0.03	0.00	0.06	0.33	0.10	0.21	0.44
SO_3	0.11	0.03	0.08	0.14	0.25	0.14	0.00	0.39
Cl	0.17	0.08	0.09	0.24	0.06	0.06	0.00	0.15

Oxide	Wilgie Mia combined Mean	SD	Min	Max	Bookartoo combined Mean	SD	Min	Max
P_2O_5	0.16	0.13	0.00	0.39	0.11	0.09	0.00	0.33
SiO_2	2.49	1.01	0.91	4.46	11.22	4.33	3.27	17.81
TiO_2	0.08	0.07	0.00	0.20	0.14	0.12	0.00	0.36
Al_2O_3	1.85	0.85	0.88	3.65	2.30	0.64	0.89	2.96
Fe_2O_3	94.19	1.81	91.13	97.09	63.96	11.86	50.05	92.64
MnO	0.01	0.03	0.00	0.07	0.19	0.16	0.00	0.50
MgO	0.15	0.08	0.04	0.25	1.94	1.77	0.30	5.93
CaO	0.17	0.12	0.08	0.44	18.67	10.07	1.25	32.49
Na_2O	0.70	0.32	0.28	1.15	0.71	0.31	0.28	1.51
K_2O	0.03	0.04	0.00	0.12	0.29	0.14	0.07	0.48
SO_3	0.07	0.06	0.00	0.14	0.30	0.26	0.00	1.06
Cl	0.12	0.08	0.00	0.24	0.16	0.36	0.00	1.41

Notes: Calculations based on the following analyses (see Tables III/5 and /7): Wilgie Mia: (fired) 102,103,115A,115B,138; (unfired) 102A,102B,103; Bookartoo (fired) 104,105,106,110,111,112, 113,114; (unfired) 104,105,106,110A1,110A2,110B1. "Combined" concentrations above are a combination of fired and unfired analyses.

Table III/12. EDXA: percentage concentrations of some additional pulverised ochre samples.

Oxide	Coopers Creek Mean	SD	Min	Max	MacDonnell Ranges Mean	SD	Min	Max
P_2O_5	0.01	0.01	0.00	0.02	0.13	0.11	0.05	0.20
SiO_2	9.82	1.98	7.60	11.39	47.16	0.35	46.91	47.41
TiO_2	0.08	0.07	0.00	0.12	0.64	0.02	0.62	0.65
Al_2O_3	1.62	0.48	1.34	2.17	14.52	1.79	13.25	15.78
Fe_2O_3	85.10	4.34	80.36	88.86	30.58	1.10	29.80	31.36
MnO	0.10	0.15	0.00	0.27	0.06	0.08	0.00	0.11
MgO	0.44	0.16	0.34	0.63	1.59	0.62	1.15	2.03
CaO	1.79	1.98	0.56	4.08	0.13	0.01	0.12	0.13
Na_2O	0.58	0.01	0.57	0.59	0.35	0.16	0.23	0.46
K_2O	0.08	0.07	0.01	0.14	4.66	1.77	3.40	5.91
SO_3	0.12	0.05	0.08	0.18	0.14	0.05	0.10	0.17
Cl	0.28	0.06	0.22	0.33	0.08	0.07	0.03	0.13

Oxide	Mt. Howden Mean	SD	Min	Max	Ulpunyali Mean	SD	Min	Max
P_2O_5	0.17	0.14	0.07	0.27	0.39	0.17	0.25	0.62
SiO_2	17.96	0.78	17.41	18.51	47.95	17.77	26.35	68.33
TiO_2	0.22	0.12	0.13	0.30	0.27	0.09	0.17	0.41
Al_2O_3	2.67	1.14	1.86	3.47	6.05	2.59	2.77	9.29
Fe_2O_3	28.59	8.04	22.90	34.27	43.22	20.83	20.48	68.82
MnO	0.03	0.04	0.01	0.06	0.01	0.01	0.00	0.03
MgO	0.09	0.07	0.04	0.14	0.41	0.06	0.34	0.48
CaO	16.47	2.14	14.96	17.98	0.28	0.07	0.17	0.34
Na_2O	0.47	0.04	0.44	0.49	0.18	0.08	0.09	0.25
K_2O	1.16	0.49	0.81	1.50	0.77	0.18	0.58	1.03
SO_3	32.10	3.48	29.64	34.56	0.41	0.15	0.20	0.57
Cl	0.10	0.02	0.08	0.11	0.06	0.07	0.00	0.13

Notes: Concentrations based on the following analyses (see Table III/7): Coopers Creek: 123A, 123B, 124; MacDonnell Ranges: 127, 128; Mt. Howden: 143, 144; Ulpunyali: 116, 117A1, 117B1, 149A, 149B.

Table III/13. ICP/MS: analyses of settled ochre samples.

		Wilgie Mia				Bookartoo			Karrku	Moana	Balgo Hill	Uipunyali
	A&A,S1	60508,S2	2839,S3	66496,S4	67979,S5	MAS,S6	1863,S7	MAS,S8	MAS#7,S9	N-6,S10	BF,S11	MAS#1,S16
Li	22353	410	356	10086	4198	8016	1715	4915	7408	14638	1567	1637
Be	1254	1358	621	1995	1094	1568	1599	4633	3994	2734	296	5304
P	468702	947006	611168	437769	355717	456269	143637	2110093	1998355	260033	519245	1445779
Sc	43452	23351	8898	2743	1467	3298	467	12507	12708	12438	365	8042
Ti	3638044	729187	442932	1348203	561629	1334708	493275	2123135	2858270	6325950	337549	1532719
V	236332	326812	104243	2111822	1901585	1750058	2560137	358539	335976	149674	84564	1147434
Cr	145923	293167	234458	31675	22730	25848	29406	45871	57135	621250	3358695	419047
Co	8259	6297	2994	6893	4865	11730	4018	3592	3756	5627	37108	2841
Ni	170998	33352	19763	19888	7643	38450	32813	14367	65278	17972	215749	9259
Cu	48147	12835	14383	8188	3880	8412	3837	4733	8823	29001	647996	59804
Zn	88850	9557	13589	231016	392177	271615	86114	8030	26626	23923	610772	5264
Ga	28497	7319	5317	5231	3534	5794	3395	10689	10239	27056	7338	28883
Rb	17166	247	298	14829	4362	18230	2832	89132	67618	187998	566	21811
Sr	24063	43660	31772	143073	181626	113750	15727	580196	483172	36895	11820	399037
Y	12272	23373	4497	7400	2843	7809	1106	191388	156762	19289	5349	67522
Zr	73820	74502	22045	32760	15746	35192	11102	55443	101504	175492	8440	57583
Nb	3209	6775	518	3005	1762	3004	1106	12622	12490	20301	6447	4974
Mo	7588	4570	9582	19191	12539	14432	18954	18435	22785	7007	119020	26113
Ag	75	37	71	88	47	80	43	63	166	156	209	71
Cd	2070	122	82	311	224	406	34	7	22	446	126	119
Sn	620507	225	1773	3592	815	2590	304	1267	4167	8499	66953	6699
Sb	2680	613264	398485	129278	141597	104090	172918	3962	6058	1509	28127	1469
Cs	995	98	131	1281	682	1428	573	2072	2225	11096	46	1329
Ba	303192	23722	31968	71942	35095	88670	18466	593350	401568	332432	160542	654250
La	13643	39000	10811	24512	9602	17714	14077	136189	134202	70846	4173	39903
Ce	22542	70871	35796	33924	17750	27447	16252	465669	436886	91893	8512	136122
Pr	2916	10089	5266	3080	1545	2713	1177	59203	54486	13020	930	17659
Nd	10976	36589	26571	9642	5101	9019	2819	275310	245145	43431	3565	89613
Sm	2193	8115	6940	1487	802	1505	229	78111	61082	7189	646	25589
Eu	482	3506	2260	301	138	299	39	9663	7780	1139	176	5167
Tb	332	953	377	193	86	198	27	7407	5930	608	100	3140
Gd	2056	6399	3500	1329	621	1332	175	61596	46308	4473	682	24347
Dy	1937	5006	1473	1088	470	1139	152	33220	27621	3293	616	13064
Ho	387	867	204	220	88	230	32	5308	4545	660	131	2184
Er	1039	2125	420	575	228	624	89	11728	10295	1968	375	5692
Yb	1014	2035	351	543	205	599	89	8219	7935	2226	343	5658
Lu	151	297	50	81	30	93	14	1138	1106	337	59	865
Hf	1767	1466	368	834	422	910	272	1725	2901	4403	178	1578
Ta	248	66	24	220	126	235	84	1614	1294	1633	142	268
W	811	51136	18353	2962	4037	2300	4494	8248	20713	2723	10276	5660
Tl	411	6	4	151	115	174	31	374	316	983	71	101
Pb	15622	7807	8178	101279	115506	89734	96522	15455	20075	19358	36271	7568
Th	3980	1623	399	3534	2214	3817	1315	30069	40423	28514	604	15704
U	2586	43422	34034	3544	3009	2226	3738	26135	24846	2004	540	13987

Table III/14. ICP/MS: concentrations in parts per billion for settled samples.

	Bookartoo				Wilgie Mia A				Wilgie Mia B			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Li	7433	2987	4198	10086	383	38	356	410	7706	12684	356	22353
Be	1552	451	1094	1995	990	521	621	1358	1078	399	621	1358
P	416585	53519	355717	456269	779087	237473	611168	947006	675625	245580	468702	947006
Sc	2503	939	1467	3298	16125	10220	8898	23351	25234	17354	8898	43452
Ti	1081513	450284	561629	1348203	586060	202413	442932	729187	1603388	1767867	442932	3638044
V	1921155	181674	1750058	2111822	215528	157380	104243	326812	222462	111931	104243	326812
Cr	26751	4540	22730	31675	263813	41514	234458	293167	224516	74124	145923	293167
Co	7829	3527	4865	11730	4646	2336	2994	6297	5850	2661	2994	8259
Ni	21994	15511	7643	38450	26558	9609	19763	33352	74704	83669	19763	170998
Cu	6827	2554	3880	8412	13609	1095	12835	14383	25122	19956	12835	48147
Zn	298269	83822	231016	392177	11573	2851	9557	13589	37332	44661	9557	88850
Ga	4853	1176	3534	5794	6318	1416	5317	7319	13711	12844	5317	28497
Rb	12474	7228	4362	18230	273	36	247	298	5904	9754	247	17166
Sr	146150	34042	113750	181626	37716	8406	31772	43660	33165	9872	24063	43660
Y	6017	2757	2843	7809	13935	13347	4497	23373	13381	9487	4497	23373
Zr	27899	10595	15746	35192	48274	37093	22045	74502	56789	30091	22045	74502
Nb	2590	717	1762	3005	3647	4424	518	6775	3501	3139	518	6775
Mo	15387	3427	12539	19191	7076	3544	4570	9582	7247	2523	4570	9582
Ag	72	22	47	88	54	24	37	71	61	21	37	75
Cd	314	91	224	406	102	28	82	122	758	1136	82	2070
Sn	2332	1406	815	3592	999	1095	225	1773	207502	357674	225	620507
Sb	124988	19118	104090	141597	505875	151872	398485	613264	338143	309732	2680	613264
Cs	1130	395	682	1428	115	23	98	131	408	509	98	995
Ba	65236	27410	35095	88670	27845	5831	23722	31968	119627	159025	23722	303192
La	17276	7465	9602	24512	24906	19933	10811	39000	21151	15522	10811	39000
Ce	26374	8140	17750	33924	53334	24802	35796	70871	43070	24972	22542	70871
Pr	2446	802	1545	3080	7678	3410	5266	10089	6090	3657	2916	10089
Nd	7921	2462	5101	9642	31580	7084	26571	36589	24712	12907	10976	36589
Sm	1265	401	802	1505	7528	831	6940	8115	5749	3135	2193	8115
Eu	246	94	138	301	2883	881	2260	3506	2083	1520	482	3506
Tb	159	63	86	198	665	407	377	953	554	346	332	953
Gd	1094	410	621	1332	4950	2050	3500	6399	3985	2212	2056	6399
Dy	899	372	470	1139	3240	2498	1473	5006	2805	1920	1473	5006
Ho	179	79	88	230	536	469	204	867	486	342	204	867
Er	476	216	228	624	1273	1206	420	2125	1195	863	420	2125
Yb	449	213	205	599	1193	1191	351	2035	1133	848	351	2035
Lu	68	33	30	93	174	175	50	297	166	124	50	297
Hf	722	263	422	910	917	776	368	1466	1200	736	368	1767
Ta	194	59	126	235	45	30	24	66	113	119	24	248
W	3100	877	2300	4037	34745	23181	18353	51136	23433	25544	811	51136
Tl	147	30	115	174	5	1	4	6	140	234	4	411
Pb	102173	12909	89734	115506	7993	262	7807	8178	10536	4409	7807	15622
Th	3188	856	2214	3817	1011	866	399	1623	2001	1820	399	3980
U	2926	663	2226	3544	38728	6638	34034	43422	26681	21388	2586	43422

Note: Concentrations based on the following analyses (see Table III/13): Bookartoo: S4, S5,S6; Wilgie Mia A: S2, S3; Wilgie Mia B: S1, S2, S3.

Table III/15. ICP/MS: analyses of pulverised ochre samples.

		Wilgie Mia				Bookartoo			Karrku		Bookartoo	
	A&A,101	60508,102	2839,103	66496,104	67979,105	MAS,106	1863,107	MS#6,108	MS#7,109	66500,111	67980,112	59022,113
Li	21588	332	246	5725	4777	4722	1830	8358	10269	2103	8422	3056
Be	1088	1333	750	1387	890	1362	2085	3771	3416	782	1425	1109
P	247893	876813	436259	315954	386046	208310	80281	1255027	1037494	157686	697994	207488
Sc	42251	24563	6743	1649	1392	2065	188	12854	11164	448	633	485
Ti	5139280	613296	212395	508736	385292	661118	233996	1689473	2513891	497665	991924	299882
V	253451	342829	116641	1654577	1484807	1002746	2417913	209193	162715	2779706	3651194	1827639
Cr	125863	311171	204568	23979	20675	17975	38841	36909	42489	11647	27104	25163
Co	4716	4781	7761	4204	3105	4843	2008	2315	3001	13692	11360	12974
Ni	154375	35502	20134	10079	7830	10433	13237	14898	8831	8059	6174	17551
Cu	34506	17372	12311	3909	3539	5080	1943	4388	6119	88464	252045	69716
Zn	71879	13945	16049	200484	604443	161582	88034	8398	30491	122698	760751	529479
Ga	27097	7376	4373	2700	2710	3132	3172	14084	14526	2647	4176	3074
Rb	14680	552	515	6727	4472	12470	2173	107666	115950	2539	9742	3445
Sr	21479	36624	18448	116427	271566	82310	16598	348391	240605	55536	194891	186798
Y	10754	24624	3355	5971	4049	8021	1111	154116	101784	3826	4609	2575
Zr	165412	348848	101040	192430	91398	160704	107281	1631909	1309697	91290	111761	80240
Nb	3658	6507	616	1754	1574	2090	902	13698	17395	2412	3706	1773
Mo	421	1722	4771	6311	6792	3904	18473	5828	3973	2774	5814	7802
Ag	30	36	17426	26	18	35	21	26	62	27	71	29
Cd	5	158	197	1057	1901	451	55	25	44	193	145	275
Sn	10479	10922	12047	12079	10340	11529	8849	11631	11747	21240	29537	12136
Sb	2000	600326	250667	65565	81836	56001	134388	2788	3502	65696	84036	118818
Cs	637	101	124	536	524	829	515	2156	2407	303	1021	545
Ba	302533	39873	34711	56117	51445	73022	27563	503293	363441	28289	47255	128454
La	9664	35271	6848	26095	9267	11811	22014	99491	80038	25475	61864	34708
Ce	15551	61015	21831	31262	16214	19694	23700	321180	246790	29572	85225	47440
Pr	1968	8761	3107	2685	1587	2152	1605	37400	26769	2398	6254	3423
Nd	7456	32978	16105	8169	5671	7992	3745	179810	122885	5952	14524	8725
Sm	1545	7504	4190	1138	932	1484	255	51412	30694	612	884	713
Eu	376	3292	1381	213	166	288	36	6329	3845	114	134	115
Tb	266	943	243	146	109	209	24	5611	3215	83	109	76
Gd	1555	6221	2233	987	772	1369	163	43386	23439	553	685	520
Dy	1631	5094	1010	840	606	1222	155	26909	16672	497	597	394
Ho	348	938	152	174	121	254	34	4625	3124	103	128	76
Er	984	2389	336	483	328	706	105	10702	7986	291	364	199
Yb	1044	2351	311	488	316	702	127	8268	7188	293	398	192
Lu	163	351	49	78	50	112	23	1183	1055	48	68	32
Hf	3975	7529	2152	4321	2100	3673	2406	35701	28650	2090	2675	1814
Ta	307	57	43	142	123	167	89	1154	1477	149	312	88
W	1383	59921	84053	2275	3513	1195	9368	5880	11468	1135	1954	4512
Tl	462	8	6	76	115	109	28	471	536	42	108	316
Pb	44473	601159	141302	405585	360400	273756	325975	303807	541812	65950	134420	211437
Th	3440	1683	291	2165	1801	2489	1229	20830	22668	2519	4669	1903
U	3072	42499	27194	2382	2968	1959	4466	19049	14347	1323	3247	3076

Table III/15 cont. ICP/MS: analyses of pulverised ochre samples.

	Bookartoo	Wilgie Mia	Ulpunyali		Lawa	Wangiana	Moana			Puritjarra		
	N-9,114	N-2B,115B	16845,116	MS(A),117	52812,118A	N-1,118B	N-6,119	#21,130	#25,131	#28,132	#32,133	#42,134
Li	2401	411	1792	4052	4641	20856	11656	5970	4941	3099	5101	5462
Be	909	902	5282	6395	1415	5674	2521	1871	2731	2250	2312	2480
P	114329	200845	907010	1768808	248725	814893	320028	2646677	4634869	3817532	3553799	5788273
Sc	531	10720	5240	6849	8894	3564	14043	18326	25295	48895	18543	8381
Ti	153317	22972	536679	672597	5056751	473153	4877838	4102492	5034805	2545892	4981216	2461467
V	1920006	88653	716157	568237	242331	945263	113505	193753	231992	280948	162115	412077
Cr	25485	48721	34588	18200	37817	5028	83171	197398	305313	431494	198700	25120
Co	10804	16989	13790	15183	20861	18069	13311	15982	24813	9881	12192	5300
Ni	9217	65865	5620	8234	29364	77659	21422	15630	13929	8125	60408	11086
Cu	115629	59120	106537	98080	168090	123432	216537	541101	382228	602806	312008	103176
Zn	200199	5667	2924	5753	52322	141607	27117	18020	27473	10844	18448	14860
Ga	2924	2410	12156	14666	53512	2026	22298	34460	45363	53909	31242	7780
Rb	1595	648	9201	9863	6739	7409	148783	41575	42179	19179	36397	25666
Sr	115170	5806	192724	378706	22736	426489	32600	155000	203619	151427	314876	295254
Y	842	948	47140	60240	9825	20274	20070	29973	35269	33569	61465	93805
Zr	61223	127833	722865	489968	659003	88845	224170	899962	126788	2700964	3817113	1560412
Nb	1049	223	3204	2460	81340	1039	20051	16573	21053	9933	18618	7305
Mo	10752	11377	3714	2621	11789	2709	625	4341	6319	5000	4190	2921
Ag	22	9	26	72	88	1	114	117	221	1486	97	149
Cd	17	12	9	75	31	7	38	32	56	104	3	157
Sn	23385	4932	19475	115499	40490	14271	58441	78107	61175	87915	62459	22289
Sb	131773	100079	760	535	940	695	999	703	1093	925	875	355
Cs	418	59	404	565	80	1021	8241	1765	1513	769	1380	1126
Ba	68957	25076	456723	766388	72919	31862	268872	457840	586797	574149	954343	401327
La	3299	2619	27455	54950	29906	7695	58671	99676	133785	83317	173417	38670
Ce	4633	5057	88983	123462	60957	14001	88297	119129	176692	162866	282689	128054
Pr	351	592	10561	20554	4117	2079	11434	21310	31784	20202	47580	15187
Nd	1131	2622	48656	96344	12541	8772	39645	84719	128812	81463	219730	72121
Sm	163	532	12358	25495	2242	1872	6557	18582	27996	18181	50915	19083
Eu	31	163	2552	5667	487	550	1013	3814	5746	3700	10664	3922
Tb	21	38	1776	3592	342	401	626	1351	1943	1421	3528	2865
Gd	148	251	11884	26527	1850	2475	4451	11084	16298	11304	30362	19432
Dy	129	215	8947	15783	2068	2457	3571	6489	8862	6934	14990	15753
Ho	27	43	1611	2417	422	525	695	1158	1497	1290	2451	3049
Er	75	126	4391	5691	1195	1312	1959	2869	3497	3437	5955	7858
Yb	86	175	4898	5530	1426	1021	2189	2957	3178	3819	6065	7431
Lu	16	31	751	802	228	149	341	444	463	655	1037	1133
Hf	1446	2821	15770	11012	17913	1864	5758	19960	3388	83314	107878	45650
Ta	54	16	200	170	4751	68	1554	1174	1569	776	1414	489
W	5138	31991	3220	1831	1929	362	2449	1668	2212	1145	1739	1780
Tl	47	5	45	76	155	152	769	254	228	120	219	169
Pb	91694	3310	8965	11563	21404	7776	18600	43126	56425	57780	96807	12661
Th	1027	652	5596	14852	40234	884	27545	18505	27999	21881	24311	8379
U	3152	24379	8610	7342	1952	2749	2009	3699	5254	7606	3712	9759

Table III/15 cont. ICP/MS: analyses of pulverised ochre samples.

	Puritjarra			Balgo Hill	Malak.II	C'Creek	MacD Ra	Wilgie Mia	Kutikina				Ulpunyali
	#43,135	#31,136	#47,137	BF,121	DEF30/40,122	66498,124	1122,127	N-2A,138	A2 SW,139	A3 SW,140	A6 SW,141	A5 SW,142	MS(1),149
Li	5432	4106	5067	1159	1860	3352	30667	177	8447	5820	11177	21029	3102
Be	2372	2897	1757	425	1000	2543	6627	1258	1290	1413	2681	3952	7733
P	1704468	4169263	428005	403393	1501238	134162	283688	612217	3068803	641690	3374720	11330286	864643
Sc	6466	34037	10478	760	4275	430	12815	28778	30786	16438	5777	11517	3624
Ti	1301921	4616560	3699947	256921	474616	340095	3985952	590087	1540259	3269850	318851	2506792	1140879
V	586838	335998	216957	63148	987613	4605163	143781	411417	348646	109263	339909	138758	665199
Cr	43455	297342	233936	929778	115084	205334	224418	1072029	741715	290389	974814	876559	178705
Co	11598	16249	19811	24021	2111	1021	18314	6271	2996	35711	2901	19827	4878
Ni	5503	22287	7584	138924	3716	6757	30046	24092	13779	22397	175019	68133	15632
Cu	392633	285820	80101	673649	123535	27533	118715	66670	58579	35842	13881	442429	16427
Zn	17019	21096	16066	429011	12152	123510	69280	8758	429160	50628	112311	661314	5988
Ga	7854	31116	21501	5133	8373	3730	15724	7787	10460	10038	6575	11750	7944
Rb	19256	27278	51745	551	9636	1612	187093	597	40628	58054	27989	60176	8519
Sr	357363	532659	86394	9134	143991	28930	87826	5356	29106	139744	60882	51813	238943
Y	56901	77882	7578	6919	6511	2708	39072	69134	83597	113141	49110	76501	183678
Zr	98526	10119257	1120210	245228	486370	428502	290038	28642279	37348400	22793447	5976823	9560806	164082
Nb	4880	15590	14022	4681	2588	1507	13611	8108	9490	15233	7217	10261	4566
Mo	2178	5963	459	70171	13948	15299	3320	1674	2391	2032	1383	2207	3239
Ag	105	375	25	144	53	26	15	1056	898	91	221	370	57
Cd	81	41	43	1	1	13	2	108	262	77	82	521	42
Sn	92137	57954	25842	95706	203829	27350	25868	15548	7760	4312	3776	5606	3632
Sb	516	1297	729	19537	58390	148939	541	789700	8607	5861	90017	517644	930
Cs	852	952	3879	56	320	454	11240	90	2377	1655	2325	2455	504
Ba	975275	1169253	256236	123621	30771	23126	386394	13828	108037	221654	109392	151538	553068
La	43671	172740	39827	3459	97440	13085	31380	5159	17123	55436	7603	44340	34850
Ce	126312	294176	61913	6917	144765	14732	64039	10082	41510	177738	16351	51735	107329
Pr	14509	51392	5928	746	13918	1293	7253	1308	4383	16869	1886	12385	12644
Nd	65610	229558	19526	2822	43776	3676	28643	5507	17725	71779	7853	49512	58386
Sm	17498	52639	2859	549	4878	437	6894	2442	5204	14347	1981	10073	16357
Eu	3617	11114	437	155	863	77	1319	993	1044	2210	455	1870	3590
Tb	2600	3756	189	103	206	58	1062	817	1181	1750	574	1582	3802
Gd	17129	32207	1474	654	1918	378	6754	3470	6007	10667	2735	10184	20296
Dy	12799	16848	1085	662	1058	350	6099	6962	8668	12469	4445	9796	24748
Ho	2063	2954	259	172	214	81	1274	2148	2637	3367	1274	2220	5502
Er	4709	7953	833	519	629	254	3524	8650	10811	12025	4489	7043	15900
Yb	3930	9646	1199	565	714	312	3339	14891	18067	16953	5817	8556	14822
Lu	575	1840	224	102	125	62	528	3200	4067	3195	1074	1664	2036
Hf	2660	290768	25946	5267	10453	9220	6564	650579	867074	498321	144015	228349	4282
Ta	337	1168	1219	125	249	101	1195	156	564	1012	108	727	280
W	2556	1655	2492	7024	81178	6581	2127	53400	2457	1749	9549	4485	3320
Tl	118	167	275	49	68	47	1390	5	355	276	27	382	75
Pb	21808	99985	32815	23210	4780	334126	16218	6873	164653	31301	94120	971765	31819
Th	9357	25921	37137	649	14369	2272	15776	5377	38904	15718	3834	12965	9186
U	6954	6739	4366	849	2587	4511	6336	50771	14453	9837	10255	5654	7023

Notes:
Samples are identified by an attribution number (see Tables III/1 and /2) followed by an analysis number.
Concentrations are in parts per billion.

Table III/16. ICP/MS: concentrations in parts per billion for pulverised ochre samples.

	Bookartoo				Wilgie Mia A				Wilgie Mia B				Ulpunyali			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Li	4458	2207	2103	8422	292	102	177	411	4551	9524	177	21588	2982	1135	1792	4052
Be	1123	269	782	1425	1061	280	750	1333	1066	243	750	1333	6470	1227	5282	7733
P	298258	199051	114329	697994	531534	285283	200845	876813	474805	277724	200845	876813	1180154	510230	864643	1768808
Sc	1029	662	448	2065	17701	10624	6743	28776	22611	14324	6743	42251	5238	1613	3624	6849
Ti	499705	271239	153317	991924	359688	290100	22972	613296	1315606	2152213	22972	5139280	783385	316970	536679	1140879
V	2045811	888356	1002746	3651194	239885	161329	88653	411417	242598	139846	88653	411417	649864	75143	568237	716157
Cr	21718	5427	11647	27104	409122	454889	48721	1072029	352470	413812	48721	1072029	77164	88316	18200	178705
Co	8712	4492	3105	13692	8951	5495	4781	16989	8104	5122	4716	16989	11284	5591	4878	15183
Ni	9906	3671	6174	17551	36398	20697	20134	65865	59994	55722	20134	154375	9829	5193	5620	15632
Cu	76912	89656	3539	252045	38868	27991	12311	66670	37996	24319	12311	66670	73681	49764	16427	106537
Zn	368519	256656	122698	760751	11105	4747	5667	16049	23260	27488	5667	71879	4888	1705	2924	5988
Ga	3052	531	2647	4176	5487	2554	2410	7787	9809	9914	2410	27097	11589	3397	7944	14666
Rb	5856	4010	1595	12470	578	57	515	648	3398	6307	515	14680	9194	672	8519	9863
Sr	146100	75152	55536	271566	16559	14689	5356	36624	17543	12910	5356	36624	270124	96833	192724	378706
Y	4270	2308	842	8021	24515	31591	948	69134	21763	28042	948	69134	97019	75334	47140	183678
Zr	112721	47042	61223	192430	7305000	14225286	101040	28642279	5877082	12726501	101040	28642279	458972	280678	164082	722865
Nb	2051	843	1049	3706	3864	4033	223	8108	3822	3494	223	8108	3410	1068	2460	4566
Mo	6307	2605	2774	10752	4886	4563	1674	11377	3993	4428	421	11377	3191	548	2621	3714
Ag	33	18	18	71	4632	8543	9	17426	3711	7680	9	17426	52	23	26	72
Cd	577	676	17	1901	119	80	12	197	96	86	5	197	42	33	9	75
Sn	17178	7504	10340	29537	10862	4417	4932	15548	10786	3829	4932	15548	46202	60534	3632	115499
Sb	86246	28644	56001	131773	435193	315856	100079	789700	348554	335194	2000	789700	742	198	535	930
Cs	597	246	303	1021	94	27	59	124	202	244	59	637	491	81	404	565
Ba	64791	31705	28289	128454	28372	11472	13828	39873	83204	123010	13828	302533	592060	158472	456723	766388
La	24646	19774	3299	61864	12474	15297	2619	35271	11912	13307	2619	35271	39085	14228	27455	54950
Ce	33434	26498	4633	85225	24496	25340	5057	61015	22707	22307	5057	61015	106591	17251	88983	123462
Pr	2693	1839	351	6254	3442	3700	592	8761	3147	3272	592	8761	14586	5272	10561	20554
Nd	7452	4038	1131	14524	14303	13733	2622	32978	12934	12281	2622	32978	67795	25198	48656	96344
Sm	847	416	163	1484	3667	2962	532	7504	3243	2735	532	7504	18070	6734	12358	25495
Eu	152	82	31	288	1457	1324	163	3292	1241	1245	163	3292	3936	1586	2552	5667
Tb	108	59	21	209	510	438	38	943	461	395	38	943	3057	1114	1776	3802
Gd	719	385	148	1369	3044	2499	251	6221	2746	2264	251	6221	19569	7349	11884	26527
Dy	612	346	129	1222	3320	3235	215	6962	2982	2901	215	6962	16493	7924	8947	24748
Ho	126	73	27	254	820	971	43	2148	726	867	43	2148	3177	2054	1611	5502
Er	349	203	75	706	2875	3983	126	8650	2497	3551	126	8650	8661	6303	4391	15900
Yb	354	202	86	702	4432	7043	175	14891	3754	6285	175	14891	8417	5556	4898	14822
Lu	58	32	16	112	908	1535	31	3200	759	1371	31	3200	1196	728	751	2036
Hf	2588	1047	1446	4321	165770	323215	2152	650579	133411	289113	2152	650579	10355	5772	4282	15770
Ta	148	82	54	312	68	61	16	156	116	119	16	307	217	57	170	280
W	2817	1594	1135	5138	57341	21435	31991	84053	46150	31158	1383	84053	2790	832	1831	3320
Tl	116	93	42	316	6	1	5	8	97	204	5	462	65	18	45	76
Pb	220463	132056	65950	405585	188161	282724	3310	601159	159423	253138	3310	601159	17449	12612	8965	31819
Th	2368	1134	1027	4669	2001	2327	291	5377	2289	2115	291	5377	9878	4667	5596	14852
U	2587	727	1323	3247	36211	12554	24379	50771	29583	18381	3072	50771	7658	839	7023	8610

Notes: Calculations based on the following analyses (see Table III/15); Bookartoo: 104, 105, 106, 111, 112, 113, 114; Wilgie Mia A: 102, 103, 115B, 138; Wilgie Mia B: 101, 102, 103, 115B, 138; Ulpunyali: 116, 117, 149.

Table III/17. ICP/MS: Correlation of element concentrations for settled samples.

	Be	P	Ti	Cr	Co	Cu	Rb	Sr	Y	Zr	Nb	Cd	Cs	La	Ce	Pr	Nd	Sm	Eu	Tb	Gd	Dy	Ho	Er	Yb	Ta
Co				.93																						
Cu				.99	.96																					
Sr		.91																								
Y		.95						.92																		
Zr			.92																							
Nb							.92																			
Mo				.94	.92	.97																				
Sn												.96														
Cs							.94																			
La									.94																	
Ce		.92							.99					.97												
Pr		.93							.99					.97	1.0											
Nd		.94						.90	.99					.95	1.0	1.0										
Sm		.95						.92	1.0					.93	.99	.99	1.0									
Eu		.98							.96						.94	.95	.96	.96								
Tb		.96						.94	1.0					.92	.98	.98	.99	1.0	.97							
Gd		.95						.93	1.0					.92	.98	.98	.99	1.0	.97	1.0						
Dy		.96						.93	1.0					.93	.99	.99	.99	1.0	.97	1.0	1.0					
Ho		.96						.93	1.0					.94	.99	.99	.99	.99	.97	1.0	1.0	1.0				
Er		.96						.93	.99					.94	.98	.98	.99	.99	.97	1.0	.99	1.0	1.0			
Yb		.96						.92	.96					.92	.95	.95	.96	.95	.96	.97	.97	.97	.98	.99		
Lu	.90	.95						.92	.95					.90	.93	.94	.94	.94	.95	.96	.95	.96	.97	.98	1.0	
Hf			.93							.99																
Ta							.91				.91															
W			.97																							
Tl							.94						.93													
Th														.94												.92

Table III/18. ICP/MS: Correlation (≥0.90) of element concentrations for pulverised samples.

	Cs	Pr	Nd	Sm	Eu	Gd	Dy	Ho	Er	Lu	Hf	Ta	Tl
Rb	.91												.91
Y							.94	.99	.97				
Zr										.91	1.0		
Nb												.98	
Cs													.90
La		.94	.91										
Ce		.95	.95										
Pr			1.0	.97	.95								
Nd				.99	.96	.92							
Sm					.96	.96							
Tb				.90		.98	.98	.90					
Gd							.93						
Dy								.97					
Ho									.97				
Yb									.94	.98			
Lu											.91		

Table III/19. ICP/MS: concentrations in parts per billion for all settled and pulverised ochre samples.

	Settled Samples				Pulverised Samples			
	Mean	SD	Min	Max	Mean	SD	Min	Max
Li	6442	6654	356	22353	6573	6796	177	30667
Be	2204	1618	296	5304	2462	1866	425	7733
P	812814	673015	143637	2110093	1601071	2219911	80281	11330286
Sc	10811	12314	365	43452	11889	12339	188	48895
Ti	1810467	1756698	337549	6325950	1856996	1784288	22972	5139260
V	922265	916866	84564	2560137	830571	1059180	63148	4605163
Cr	440434	938337	22730	3358695	229216	299954	5028	1072029
Co	8165	9465	2841	37108	11288	8016	1021	35711
Ni	53794	67723	7643	215749	31555	42032	3716	175019
Cu	70837	182672	3837	647996	153080	181120	1943	673649
Zn	147294	193203	5264	610772	137561	205987	2924	760751
Ga	11941	10032	3395	28883	14049	14219	2026	53909
Rb	35424	55720	247	187998	30359	43512	515	187093
Sr	172066	201285	11820	580196	152871	136552	5356	532659
Y	41634	64811	1106	191388	40836	45175	842	183678
Zr	55302	47702	8440	175492	3598517	8363504	61223	37348400
Nb	6351	5943	518	20301	9478	13698	223	81340
Mo	23351	30860	4570	119020	7006	11500	421	70171
Ag	92	55	37	209	639	2854	1	17426
Cd	331	567	7	2070	171	353	1	1901
Sn	59783	177555	225	620507	35684	41502	3632	203829
Sb	133620	190450	1469	613264	90488	177258	355	789700
Cs	1830	3007	46	11096	1465	2215	56	11240
Ba	226266	227918	18466	654250	282255	305080	13828	1169253
La	42889	46847	4173	136189	46003	44602	2619	173417
Ce	113639	162115	8512	465669	89511	86629	4633	321180
Pr	14340	20553	930	59203	11578	13050	351	51392
Nd	63148	95509	2819	275310	49052	59912	1131	229558
Sm	16157	26165	229	78111	11392	14819	163	52639
Eu	2579	3302	39	9663	2220	2782	31	11114
Tb	1613	2528	27	7407	1260	1431	21	5611
Gd	12735	20598	175	61596	8968	10884	148	43386
Dy	7423	11365	152	33220	6698	7196	129	26909
Ho	1238	1827	32	5308	1336	1401	27	5502
Er	2930	4084	89	11728	3799	4077	75	15900
Yb	2435	3052	89	8219	4304	5040	86	18067
Lu	352	429	14	1138	756	990	16	4067
Hf	1402	1239	178	4403	85335	192672	1446	867074
Ta	496	624	24	1633	637	866	16	4751
W	10976	14140	811	51136	11370	21696	362	84053
Tl	228	275	4	983	209	264	5	1390
Pb	44448	42663	7568	115506	153342	209209	3310	971765
Th	11016	14123	399	40423	12136	11920	291	40234
U	13339	14943	540	43422	9085	10975	849	50771

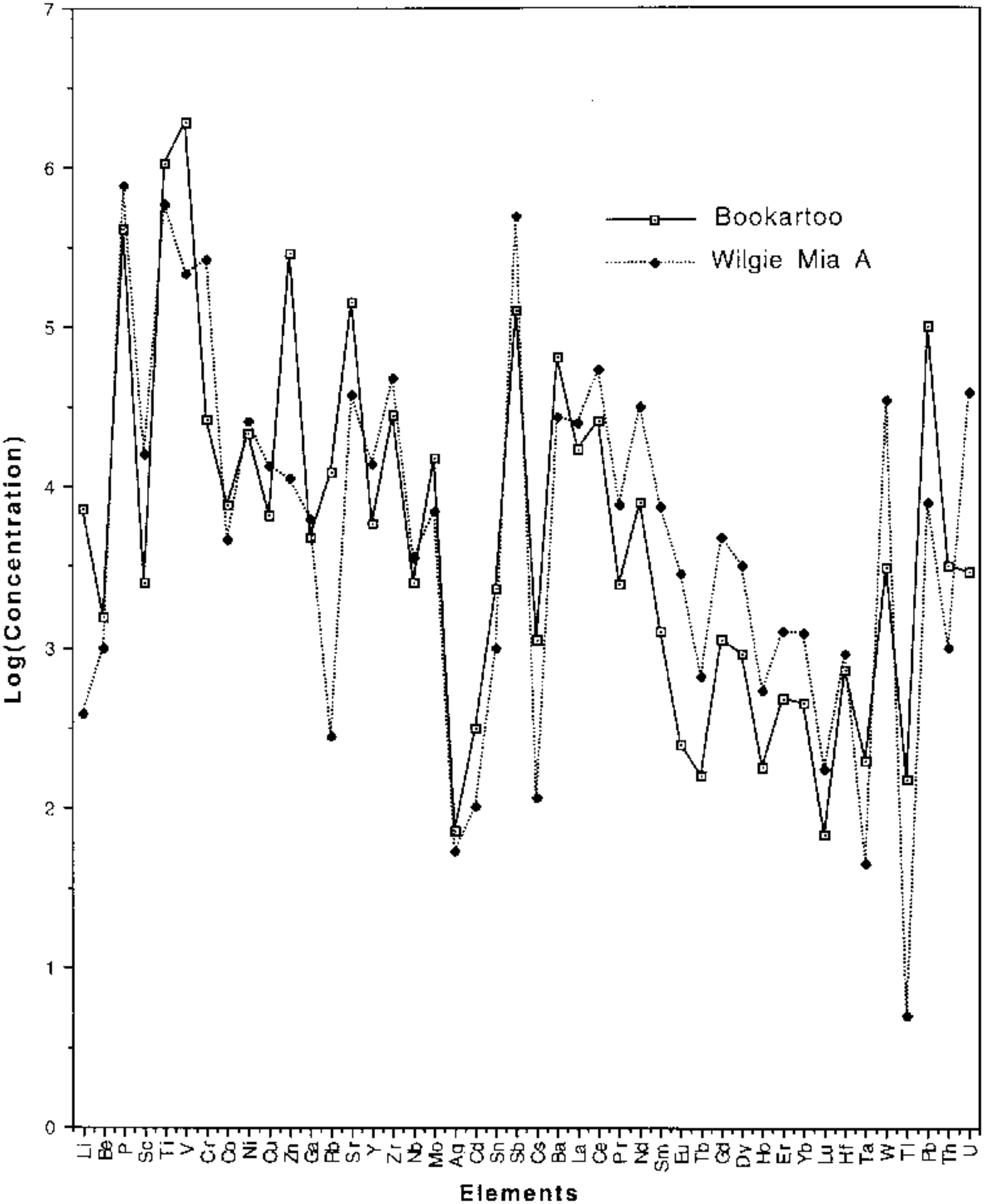

Figure III/1

Graph of mean settled concentrations
for Bookartoo and Wilgie Mia.

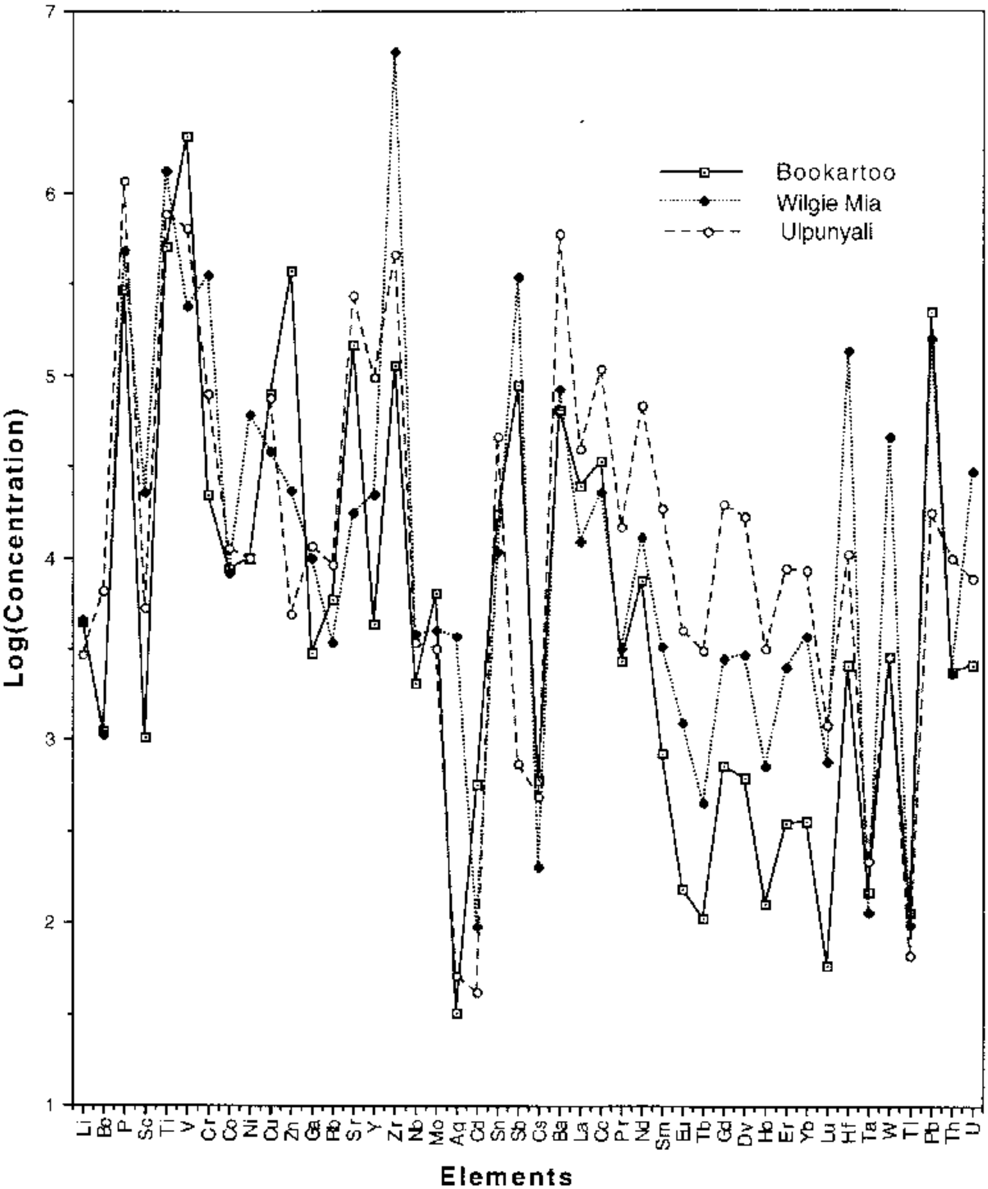

Figure III/2

Graph of mean pulverised ochre concentrations
for Bookartoo, Wilgie Mia, and Ulpunyali.

Part IV - Multivariate analysis of compositional data

Methods used in this project

The identification of unique compositional groups is the first step towards distinguishing ochres from different sources and in determining the provenance of archaeological ochres. This is almost always a multivariate statistical problem. In this study we use cluster analysis initially to discover the pattern of groupings in our compositional data, making as few assumptions as possible about the nature of the groupings. We follow this with principal components analysis (PCA) to further examine key aspects of variability in the compositional data. All the multivariate analyses below were carried out using programs in MV-ARCH (Wright 1992).

UPGMA cluster analysis

Cluster analysis is a primary tool in assessing structure in ceramic compositional data and has obvious application to similar data for ochres. In this project cluster analysis was carried out using the HIERARCH option in MV-ARCH. Unless otherwise stated we have used plain Euclidean distance and the group average (UPGMA) algorithm following the route recommended by Wright (1992:93-4) to minimise distortion. In most cases we use data normalised to 100% but where indicated have used data variously transformed (using VOTRANS) to:- give equal weight to variability in rare elements (using z scores); to suppress the influence of elements close to minimum detection levels (using square roots); or to correct for problems of skewness and non-linearity in our data (using rank order by variable). We have attempted to validate clusters in two ways. First, by testing the stability and robustness of cluster solutions using different algorithms (either Wards or Nearest Neighbour). Secondly, by adopting a procedure that produces a realistic cluster solution for samples from the one source.

Principal components analysis

Principal components analysis is a multivariate exploratory technique widely used for investigating structure in compositional analyses of archaeological artefacts (Baxter 1994; Shennan 1988). The analyses below were carried out using the BIGPCA suite of programs available in MV-ARCH. Following the strictures in Shennan (1988:262) and in Wright (1992:41) we use the covariance rather than correlation matrix and extract the first three components only. Data are normalised initially to 100%. Aitchison (1983) draws attention to problems of non-linearity and constant-sum constraints in PCA analysis of compositional data and suggests a log-linear contrast transformation of the data to correct this. However Tangri and Wright (1993) conclude that log-linear transformations introduce spurious structure into a table of compositional data. Wright (1992) recommends the less complicated procedure of transforming the data to rank order and extracting components from a Spearman rank-order correlation matrix. We have adopted this procedure as it is also useful where data has suspected outliers or is otherwise skewed. Where indicated below we have experimented with PCA on data transformed in other ways (z scores; square roots, log-linear contrasts) without substantively altering the clusters evident in our data.

Data files and MVA output

Data files used in the multivariate analyses and output results for key analyses are given in Appendix 1.

Note that figures illustrating PCA results below (eg. Figs. IV/1; IV/3B; and IV/8B) utilise sequence numbers in the original data files (see Appendix 1). To find corresponding sample codes please refer to these data files in Appendix 1.

Discrimination between sources

Major and minor oxides

Effects of different preparation methods

Using the EDXA facility on a SEM we were able to determine the composition of the ochres in terms of 12 major and minor oxides. In most cases we worked with whole pulverised samples. However several of the ochres have coarse quartz, calcite or silicate inclusions. The lack of homogeneity in source ochres and in archaeological specimens could be expected to reduce the likelihood of provenancing whole ochres using major oxide composition. To get around this we also analysed the fine fraction of a small series of samples of each major ochre. Cluster analysis and PCA of this data set (Source files: ALSEDX and ALLEDX) were carried out to determine whether the fines gave better discrimination of sources than whole ochres. Our initial expectation was that this would turn out to be the case for two reasons:

a) Sampling problems: In small specimens of ochre the fine fraction is more likely to give a representative sample of the source than the coarse fraction (where inhomogeneity presents greater difficulties for effective sampling).

b) Variability within sources: One could expect there to be variability in texture across a deposit or down a bed, with consequent variability in chemical composition. Whereas fine-grained cement may have a relatively constant chemical composition the proportion of coarse-grained quartz, mica, calcite and silicate minerals could be expected to vary from sample to sample.

Our results indicate the contrary. We found that cluster analysis of the fine fraction did not discriminate between sources as well as whole ochre analyses. PCA was carried out to compare the fine fraction with whole ochre analyses. This also showed that working with the former did not reduce within-source variability. For Bookartoo we found that there is greater variability in the fine fraction (Figure IV/1). We are not sure why this should be the case, unless it is an artefact of the settling procedure. In the case of Bookartoo ochre the coarse-grained component is made up of carbonate minerals (mainly calcite or dolomite). The settled samples predictably have less carbonates but surprisingly are much more variable in their Fe_2O_3 and silicate components. In the case of ochre from other sources, fine-grained samples have little effect on source variability. However we note the following changes compared with samples of whole ochre:

a) Settled samples of Wilgie Mia ochre have less Fe_2O_3 than whole samples presumably because some of the haematite in crystalline form (specularite) has been removed by the preparation method.

b) In the case of Karrku and Ulpunyali the settled samples have a higher proportion of Fe_2O_3, presumably because the haematite cement is concentrated in the fine fraction. Settled samples of Ulpunyali ochre also contain a higher proportion of P suggesting that this also forms part of the fine-grained cement in this ochre.

c) Settling reduced the carbonate and silica content of Moana ochre, suggesting that carbonate minerals and quartz make up the coarse component of this ochre. This is consistent with an origin in a calcareous sandstone.

Overall there appears to be little advantage in working with settled samples rather than pulverised whole ochre.

<u>Cluster analysis</u>

UPGMA cluster analysis was carried out on EDXA analyses of pulverised whole samples (source file: ALPEDX), with data normalised to 100% and transformed to rank order to mitigate any problems with outliers or non-linearity.

The results show good clustering of sources but most groupings are weak and there is considerable variability within sources (Figure IV/2). Bookartoo samples are placed in two different clusters; one representing specimens with low carbonate content (including A1863 - prepared ochre), the other representing high carbonate specimens. Wilgie Mia samples form a discrete group, except for A+A. The two Karrku samples form a sub-group within a cluster containing the Ulpunyali ochres. The latter are divided into high Fe and high Si sub-groups, reflecting variability in the quartz content of a single specimen (Ulpunyali MAS). All the central Australian ochres, except Paterson X , form a high order group suggesting this specimen is not from Ulpunyali.

Although cluster analysis gives a fair representation of the relationships between samples it is doubtful whether one could use these results to identify an unknown specimen. There is considerable variability in major and minor oxides within each source, clustering is weak and duplicate samples of the same specimen of Ulpunyali ochre are placed in different clusters.

PCA analysis

The source file for the following analyses is ALLEDX. We have corrected for any skewness or non-linearity in our data and for the effects of constant-sum closure by using the rank order transformation as recommended by Wright (1992). Components are then extracted from a Spearmans-Rank order correlation matrix. In the analyses which follow we have used the covarience option in BIGPCA to avoid giving undue weight to variability in the rarer trace elements and have opted to extract only the first three components.

Much of the variability (component 1 is 36.87%) in these samples can be expressed in terms of a ratio between Fe_2O_3 and oxides of K-Si-Ti-AL (presumably mica or other silicate minerals) (Figure IV/3A). The second dimension of variability (15.89%) reflects the importance of carbonates in these samples. The various sources can be plotted in the space of these two components (Figure IV/3B). This gives a series of groupings which are probably best interpreted as a typology of ochres or diagenetic clusters rather than individual sources. For instance Bookartoo ochre is Fe-rich with a high proportion of carbonates (Ca and Mg) reflecting an origin in limestone and dolomite rocks. PCA indicates the following types of ochres:

a) Fe-rich ochres without major carbonates or silicates:- Wilgie Mia, Dial Range, Balgo, and the Malakunanja II specimen. These are all high-grade haematite and in some cases (Malakunanja II and Dial Range) are probably vein haematite.

b) Fe-rich ochres with high carbonate content:- Bookartoo and Wangiana. These are ochres originating in carbonate sedimentary settings. Note that Wangiana ochre also has a high SO_3 content, clearly distinguishing it from Bookartoo material.

c) Silicate (K-Ti-Si-Al) rich ochres:- This category probably reflects ochres from deeply weathered, poorly mineralised landscapes. In some cases the sources are likely to be ferruginised sandstone. All the central Australian ochres, except Paterson X, fall into this category. The group includes Karrku, Ulpunyali, Lawa, and Purara, as well as Rockleigh and A+A. They are relatively poor in Fe_2O_3 and carbonates. Karrku is richer in carbonates than the other central Australian sources.

d) Silicate (K-Ti-Si-Al) rich ochres with significant carbonate content:- Moana and Paterson X. These ochres presumably originate in sedimentary rocks where carbonate rocks are interbedded in sandstone or in calcareous sandstones.

Ratios of Fe/Si/Ca+Mg may provide an equivalent classification of sources. We note that these groupings bear some similarity to three of the four prominent lithological facies of iron formation - oxide, silicate, carbonate and sulphide - recognised in the geological literature (eg. James 1954).

In certain circumstances data on the type of ochre alone may be sufficient to differentiate sources. However it is clear that in regions where most ochres are of the one type - such as in central Australia - it will be necessary to use trace elements to obtain a useful geochemical fingerprint for different ochre sources.

Trace elements

Using ICP/MS methods we were able to determine concentrations of 44 trace elements in ppb in the ochres. As with EDXA we found little difference between settled fines and pulverised whole samples in our ICP/MS results. This is not surprising given that the coarse-grained component of the ochres - mainly quartz, mica, or carbonate minerals, and occasionally specularite - is largely made up of elements (Si, K, Al, Ca, Mg, Fe) not included in our ICP/MS analyses. We decided therefore that it was preferable to work with whole pulverised samples as these were less time consuming to prepare. The high concentrations of Zr in some ochres raise the question of whether the Zirconium balls in the Retsch mill used to grind the ochres have skewed our data. We can find no evidence that this is the case. All pulverised samples were treated in the same way and ground for the same length of time. Note that Table III/17 shows that there is no significant difference between Zr levels in settled and pulverised samples. We also note that variability in concentration of Zr is closely correlated with that of Hafnium in our samples, whereas the 'Retsch' mill uses balls of pure Zr.

All results given below are for whole pulverised samples only (source file: <u>Allicppt</u>). Elemental abundances are normalised to 100% for each sample.

<u>Cluster analysis</u>

Cluster analysis was carried out in the first instance on the <u>elements</u> using the VARCLUST option in MV-ARCH. This showed that much of the variability in these ochres is due to a few elements (P, V, Zr and Ti) with a secondary cluster of some metals (Sr, Sb, Pb, Cr, Cu, Zn and Ba) and extensive chaining in lanthanide (rare earths) and actinide elements.

UPGMA cluster analysis on the ochres (normalised to 100% but without further transformation) shows strong clustering of ochres from each source (Figure IV/4).

a) The Bookartoo samples form a strong group with some separation of <u>prepared</u> ochres (A1863, and probably Coopers Creek A66498) from other samples. Note the analysis confirms the identification of A66498 as Bookartoo ochre.

b) The Wilgie Mia samples are more variable. Whereas N-2B, A60508 and A2839 (collected before European disturbance to the quarry) form a discrete cluster, other samples are very heterogenous. Sample A+A may or may not be from Wilgie Mia. However N-2A is firmly provenanced to this source and on hand examination is indistinguishable from other Wilgie Mia samples, yet has a very different composition. When we inquired into the nature of these differences we found that A+A has high Ti levels and N-2A has anomalously high Zr. More will be said about these two samples below. It is interesting however that N-2B which <u>is</u>

different in appearance to A2839 and A60508 shares a similar trace element chemistry. The sample of ochre collected from Balgo women (Balgo WCC) does not appear to be from Wilgie Mia, though this conclusion must be tentative until such time as we fully understand variability within this source.

c) The two Karrku samples - one of which is prepared ochre - cluster satisfactorily. Many of the Puritjarra samples fall into this group. Most of these are Group 1 ochres which on hand examination were attributed to Karrku in any case. These are discussed separately below.

d) The Ulpunyali samples also cluster satisfactorily, though the sample collected in the 1930s (A16845) is slightly different to the samples collected by Smith in 1984. The Puritjarra specimen in this cluster (N5/5) is consistent with our prior attribution of this material to Ulpunyali. An obvious anomaly is the inclusion of the Malakunanja specimen in this cluster (note that this specimen would be culled out on petrology).

e) The other sources in our run are all distinguished by the analysis from Bookartoo, Wilgie Mia, Karrku and Ulpunyali. Material from Lawa and Moana are clearly very different in trace element composition to the other sources. Material from Wangiana however could be confused with Ulpunyali on trace element composition, though not on petrology or texture.

The importance of the more abundant trace elements (P, V, Zr and Ti) in discriminating between sources can be illustrated by running the same analysis on data transformed respectively to weight the analysis in favour of these elements (square root transformation) (Figures IV/5) or to give all elements equal weight (z scores). The former strengthens clusters evident in the previous run, groups the Kutikina specimens together, and shows the geographical relationship of sources more realistically. Malakunanja, Wilgie Mia N-2A and A+A remain as anomalies. The latter using z scores fails to consistently discriminate between sources even in the case of the Bookartoo samples.

Principle Components analysis

Whereas cluster analysis derives a distance matrix from overall differences in the composition of samples, PCA is a data reduction method designed to identify the major axes (components) of variability in a table of data. In the case of compositional data the components are often ratios between elements or groups of elements. We use PCA here to determine the factors most useful for discriminating between the ochre sources in our sample.

The source file for the following analyses is ALLICPPT corrected for any skewness or non-linearity in our data and for the effects of constant-sum closure by using the rank order transformation. In the analyses which follow we have used the covarience option in BIGPCA to avoid giving undue weight to variability in the rarer trace elements (ie.

elements close to minimum detection limits of our technique) and have opted to extract only the first three components.

Plotting the element scores for the components on scattergrams (Figure IV/6) shows that the first component (37.33%) reflects the ratio of Zn-Sb-V to the Lanthanide elements as a group, the second (16.39%) reflects variability within the Lanthanide elements (arranged by atomic weight) and in Zr content, and the third component (10.02%) is essentially a ratio between U and Ti. When samples from the various ochre sources are plotted on these axes we can see that internal variability within the Lanthanide series is not useful in discriminating between the central Australian quarries. Plotting the ochres against the first and third components however shows good separation between sources (Figure IV/7). Two of the Central Australian sources - Ulpunyali and Karrku - have relatively high concentrations of the Lanthanides but can be distinguished on their U/Ti ratio. The Bookartoo samples all have high Zn-Sb-V concentrations. The Wilgie Mia samples have high U/Ti ratios. Once again A+A and N-2A are anomalous. Both have higher Ti than the other Wilgie Mia samples. This is also the case for the Balgo WCC sample. Lawa, the third Central Australian source, and Moana both have relatively high Ti concentrations.

PCA can also be carried out on data transformed (to square roots) to give most weight to the major trace elements. The effects of this can be seen in the plot of elements in Figure IV/8A, emphasising the contribution of Zr, V, Ti and P (third component not shown in Fig. IV/8A). Plotting the ochres against these axes allows us to see more clearly the contribution of each of these elements to the analysis (Figure IV/8B). High levels of V separate Bookartoo and Wangiana ochre from each other and from the other sources. Most Wilgie Mia samples have intermediate Ti/Zr ratios. A+A has a very high Ti/Zr ratio. N-2A has the highest Zr/Ti of any of our samples. Both samples are depleted in P compared to the other Wilgie Mia samples. If all of these samples are actually from Wilgie Mia they must be from different beds within the banded iron formation and/or parts of the deposit subject to different diagenetic processes. The relative levels of P also discriminate between the Central Australian sources with Ulpunyali being the richest in P and Lawa the poorest.

These results indicate that ratios between a small series of trace elements are effective in discriminating between the sources. The following trace elements appear to us to be the most important: U, Ti, V, Zn, Zr, and P.

Stable isotopes

Stable oxygen isotope ratios of fine-grained quartz extracted from ochre samples can provide an indicator of ochre provenance (Smith and Pell in press). Although not included in the present study a pilot study on a small series of red ochres from central Australia shows that ochres from different geological provinces can be distinguished using this technique. This method is based on the premise that the stable oxygen-isotope ratio ($^{18}O/^{16}O$) of quartz grains accurately records that of their parent rock types. Fine grained sediments usually contain quartz from a number of different parent rock types, each of which has its own oxygen-isotope ratio. Quartz grains from each of these parent rocks are combined together in the sediment, thereby giving it a distinct oxygen-isotope signature. The oxygen-isotope ratios of quartz inclusions in ochres should therefore give an indication of which ochres derive from the same geological province and which are exotic.

Table IV/1 gives oxygen isotope ratios for the several of the ochres discussed above.

Bookartoo ochre (#13) has an oxygen-isotope ratio of 13.8‰d^{18}O. As one would predict, Karrku(#6) and Ulpunyali (MAS) ochre samples have very similar oxygen-isotope ratios ranging from 11.7 - 12.0‰d^{18}O and 11.6 - 12.0‰d^{18}O respectively. The values for N5/24-6 - one of the Group 1 ochres from Puritjarra rock shelter - are consistent with it being derived from a source in the same region. Patterson X however has an oxygen-isotope ratio of 12.3‰d^{18}O indicating that it must derive from either a different region altogether, or possibly from a source strongly influenced by vein quartz with a different isotopic signature. Either way these results support conclusions reached from multivariate analysis of the compositional data. Paterson X cannot be from Ulpunyali.

Key characteristics of the sources

We can now summarise key geochemical characteristics of the main sources that we have been able to study using multiple samples.

<u>Bookartoo</u>: This ochre is very distinctive as it has unusually high concentrations of V (>1,002,700 ppb) and of Zn (>122,600 ppb). The latter is presumably from the sphalerite (ZnS) formed during diagenesis of this deposit (see Keeling 1984). Any haematite rich, fine-grained dark pink or purple ochre with major carbonate content (either calcite or dolomite) and very high trace levels of vanadium could be from Bookartoo and further analyses should be undertaken with this possibility in mind.

<u>Wilgie Mia</u>: Most Wilgie Mia samples analysed here have moderate Zr/Ti and high U/Ti ratios. Some samples have anomalously high Ti (A+A) (5,139,280 ppb) or high Zr (N-2A) (28,642,279 ppb). The A+A sample also has a higher proportion of quartz than the other Wilgie Mia samples. If both of these samples are from Wilgie Mia they indicate that beds within banded iron formations may represent separate physical and chemical facies. This obviously complicates the task of characterising Wilgie Mia ochre and requires further attention.

<u>Karrku and Ulpunyali</u>: The two Central Australian quarries west of the MacDonnell ranges both have a high proportion of Lanthanide elements. These are most likely a weathering product. Both sources also have relatively high P concentrations (>800,000 ppb), probably reflecting the characteristics of local sedimentary rocks reported to have phosphatic pellets (Bagas 1988). Variability in concentration of Lanthanide elements does not discriminate between these sources. However Ulpunyali has higher U/Ti, V/Zr ratios and P content than Karrku.

Case studies

Puritjarra rock shelter

Initial assessment of likely sources

The ochre excavated from Puritjarra rock shelter can be divided into several groups on the basis of colour, texture and petrology. Of these, Group 1 ochres resemble material from Karrku and Group 2 ochres material from Ulpunyali. Group 1 ochre makes up the bulk of the ochre in layer II (dating from 7500 - 30,000 BP) and declines in importance in the mid-Holocene levels of the site. N13/2-1 from the late Holocene levels was provisionally placed in this group but differs from other Group 1 ochres in certain respects. It is much harder, has angular quartz grain inclusions, occasional clots of goethite and much more abundant mica (or fine crystalline flakes of some other mineral). N5/24-6 is a large tabular piece of ochre (~80g) from a feature dating to ~13,000 BP. Group 2 ochres are coarse-grained greasy purple or dark red ochres, closely resembling material from Ulpunyali. At Puritjarra they are concentrated in early and mid-Holocene levels of the site.

Chemical characterisation of Puritjarra ochres

Chemical analyses of these ochres confirm this general picture.

The Group 1 ochres analysed are all very similar to one another both in terms of the oxide and trace element data, with the exception of N13/2-1 which has a lower proportion of silicates than the other samples. N5/15 is also somewhat different and is not consistently clustered with the other samples in this group. With these exceptions, the Group 1 ochres appear to be drawn from the same source. The SEM-EDXA oxide results do not allow us to unambiguously identify this source, What is evident however is that the chemical characteristics of Group 1 ochres clearly identify them as central Australian material. Nearest neighbour analysis of N5/24-6 shows that this specimen most closely resembles prepared ochre from Karrku (#7) and other Group 1 specimens (N11/30, N12/24-1 and N5/15). The trace element results are more definitive. Group 1 ochres consistently cluster with material from Karrku (Figures IV/4 and IV/8B). Nearest neighbour analysis using the trace element data shows that N5/24-6 most closely resembles the two Karrku samples (raw and prepared ochre) and other Group 1 ochres (M11/26 and N12/24-1). The strength of this relationship can be demonstrated by plotting trace element concentrations for Karrku ochres against those for N5/24-6 as a regression line (Figure IV/9). The correlation coefficients in both cases are 0.977. Figure IV/10 shows a comparison of N11/30 - also from Group 1 - with Karrku ochre. This specimen is much smaller than N5-24-6 (and presumably more at risk of chemical exchange with surrounding deposits) and shows a weaker correlation with the putative source. Note however that it is more strongly correlated with the prepared ochre ($r = 0.825$). The mineralogy of two Group 1 specimens (N5/24-6 and N11/31) shows that these ochres most closely match red ochre from Karrku (see Table IV/2).

N13/2-1 does not appear to belong to this group, but clusters with material from the Lawa source (A52812) on both oxide and trace element data (Figures IV/2 and IV/4). However, in this case, the mineralogy of this specimen is not consistent with Lawa ochre (see Table IV/2).

Of the Group 2 ochres, N5/5 consistently matches ochre from Ulpunyali. Figure IV/11 shows this relationship in more detail (r = 0.936). Of the other Group 2 specimens, the MVA attribution of N5/6 is ambivalent. This specimen clusters with Group 1 on trace elements, and with Group 2 on major oxides, although the colour and texture of this specimen do not make the former a realistic option.

Some of our data bear on the general issue of whether small pieces of ochre buried for millennia in archaeological deposits are chemically stable. It is noticeable from PCA on trace element composition that the Puritjarra ochres are depleted in some trace elements, especially uranium, and enriched in others relative to the putative sources (Karrku and Ulpunyali). Figure IV/3B shows that these specimens are also depleted in carbonates relative to Karrku and Ulpunyali ochre and that this may be a systematic difference. These differences may be due to post-depositional leaching of U and carbonates. The fact that the pattern is consistent across two sources seems to us to make it less likely that this is due to variability in the concentration of these elements in the sources. If post-depositional leaching is the explanation for these differences we could expect that the smaller archaeological specimens (often <0.5 g) (eg. N11/30) would be more susceptible than large blocks of ochre (such as N5/24-6 at ~80g) and in fact this appears to be the case. The effects of weathering area also evident in the mineralogy of several archaeological specimens. Table IV/2 shows that the two Group 1 specimens (N5/24-6 and N11/31) have a higher kaolinite to muscovite content than contemporary ochre samples from the Karrku mine. In this case however we cannot tell whether this is due to post-depositional weathering of the archaeological specimens, or exploitation of a part of the Karrku lode more exposured to in-situ weathering. The apparent enrichment of the archaeological specimens in respect of some trace elements may simply be due to the difficulty of removing fine silt adhering to the outer surface, especially with the smaller specimens.

Implications

During the late Pleistocene people visiting Puritjarra rock shelter were using red ochre predominantly drawn from a single source. Group 1 ochre makes up virtually all the red ochre in levels dating between ~30,000 BP and 12,000 BP and then appears to tail off after 7500 BP as more intensive use of the shelter begins (and presumably as regional population increases and territory is increasingly partitioned). The geochemistry of these ochres unequivocally point to Karrku as the source, indicating that exploitation of this deposit had begun by ~30,000 BP. Peterson and Lampert (1985) estimated that the current mine had been in use for 5,600 years on the basis of the volume of ochre removed. The much earlier dates suggested here indicate either that the long-term average rate of ochre use was lower than they suggest, or that there were other, older mines into this deposit, presumably now collapsed. Our results also have implications for understanding prehistoric land use in the region. Karrku is located north west of Puritjarra, further into the dune field. The fact that Karrku ochre was regularly reaching Puritjarra shelter implies either that the people using the shelter were moving over a large territory west of the MacDonnell Ranges or that they were in contact with groups that had access to Karrku ochre. Either way it indicates a well established human population in the region.

Our analyses indicate unequivocal use of Ulpunyali ochre by ~2000 BP, although the stratigraphic distribution of Group 2 ochres at Puritjarra indicates that use of this source had begun somewhat earlier, by 13,000 BP. This is the closest of the major ochre quarries to Puritjarra, and people using the rock shelter during the late Pleistocene must have moved through the Ulpunyali region to gain access to important springs in the George Gill range, or at least would have been in contact with people inhabiting the region immediately to their south east. Ulpunyali ochre is not common at the site until ~13,000 BP. When it does appear it is in the context of use of a wide variety of ochres, many of which appear to be from local sources as they are of poor quality.

Moana ochre in the western MacDonnell Ranges?

One of the surprises in our analysis is that Moana N-6 and A1122 appear to be closely related samples, both in terms of major oxides (Figures IV/2 and IV/3B) and trace element composition (Figures IV/5 and IV/8B). Comparison of the trace element composition of these ochres using linear regression gives a correlation coefficient of r = 0.998 leaving little doubt that they are the same material.

As described in Part II, A1122 is red ochre ostensibly collected by Oskar Leibler in the MacDonnell Ranges between 1910 and 1913. The Moana ochre is from the source that the South Australian Government exploited when it transported 4 tons of ochre to Kopperamanna on the lower Cooper in 1874 to forestall further red ochre expeditions to Bookartoo. Our results suggest that the material dumped at Kopperamanna in 1874 may have found its way into general circulation, reaching Hermannsburg in central Australia by 1913.

There is however an alternative explanation. Hermannsburg, Kopperamanna and Killalpaninna were all Lutheran Missions and although there is no evidence that Liebler himself visited the lower Cooper Missions it is possible that Aboriginal or other people connected with the Lutherans transported the ochre to Central Australia. The link may be H. J. Hillier who taught at the Hermannsburg school after leaving Killalpaninna in 1905. Clark and Sutton (1986:55) suggest that Diyari toas in Liebler's collection were obtained from Hillier. This may also be the case with A1122. If so we can expect other specimens of Moana ochre to turn up in Hillier's ethnographic collections now held by the following institutions: the Horniman Museum, The Museum of Mankind, and the Cambridge University Museum in England and The Australian Museum in Sydney. It is a small historical irony that when the South Australian Government impounded Liebler's ethnographic collection in 1914 and obliged him to sell it to the S. A. Museum they may inadvertently have paid for the same red ochre twice (once to transport it to Kopperamanna in 1874; and later to acquire it from Liebler).

Kutikina Cave

We analysed several samples of high-grade haematite from the 1981 excavations at Kutikina Cave in southwestern Tasmania. Major oxide composition shows that these cluster satisfactorily as a discrete group but indicates that three of these samples are closely related (A2SW, A3SW and A5SW) while the fourth sample is an outlier with higher Fe_2O_3 content (Figures IV/2 and IV/3B). Analysis of trace element composition gives much the same results (Figures IV/4, IV/5 and IV/8B). The Kutikina samples form a high level cluster divided into two sub-groups - one with high Zr (A3SW and A2SW) and the other with more Ti (A5SW and A6SW). These differences may reflect variability within the one source - likely to be a vein haematite - or two related sources.

We do not have the reference materials that would allow us to identify the likely source. On the EDXA results none of the Kutikina samples match our sample of high-grade haematite from Dial Range in northwestern Tasmania. We can also unequivocally rule out Toolumbunner in the Gog Range as a possible source, using data in Sagona ((1994 Appendix 1). The Toolumbunner source is a ferruginised sandstone whereas the Kutikina ochres appear to be vein haematite. Not surprisingly they have very different concentrations of quartz and haematite. The Kutikina samples have ~100 times greater Zr than the Toolumbunner material and correspondingly high levels of Cr, Ni, Cu and Zn.

Table IV/1: Oxygen-isotope ratios and quartz percentages for ochre samples.

Sample	% SiO_2	Number of analyses	Mean $d^{18}O$ ‰ (SMOW)	Range $d^{18}O$ ‰ (SMOW)
N5/24-6	54	3	11.8 ± 0.20	11.7 - 12.1
Ulpunyali	43	3	11.7 ± 0.21	11.6 - 12.0
Karrku	30	2	11.8 ± 0.22	11.7 - 12.0
Paterson X	34	3	12.3 ± 0.15	12.1 - 12.4
Bookartoo	20	2	13.8 ± 0.50	13.5 - 14.2

Data supplied by S. Pell.

Table IV/2: Mineralogy of selected ochres

	iron oxides		Qtz	carbonate minerals			micas	clay minerals	feldspars				
	haematite	**goethite**	**quartz**	**calcite**	**dolomite**	**ankerite**	**muscovite**	**kaolinite**	**microcline**	**albite**	**anatase**	**halite**	**amorphous***
N11/31	26.38	-	22.39	-	-	-	5.28	17.12	-		1.53		27.30
N5/24-6	9.98	-	51.49	-	-	-	4.94	12.81	-		0.59		20.19
N13/2-1	40.51	9.19	0.68	-	-	-	12.59	13.68	-		-		23.35
					-	-							
Karrku #6	39.54	-	24.88	-	-	-	20.38	2.49	-		-		12.71
Karrku #7	35.57	-	30.16	-	-	-	16.86	2.98	0.42		-		14.01
Ulpunyali MAS	36.53	5.75	37.42	-	-	-	-	0.74	-		-		19.57
Lawa A52812	27.45	-	27.52	-	-	-	-	29.15	-		-		15.88
Balgo WCC	74.40	0.55	0.51	-	-	-	-	-	-		-		24.53
Bookartoo A67980	37.35	-	7.81	4.16	6.77	2.62	-	-	-		-	0.87	40.42
Bookartoo A66496	26.45	-	13.58	13.98	0.43	1.10	-	2.31	2.32	2.06	-	-	37.77
Bookartoo A59022	40.87	-	6.05	16.58	-	3.35	-	-	1.11	-	-	-	32.05
Bookartoo A67979	44.19	-	3.41	1.30	5.48	7.17	-	-	-	-	-	-	38.45
Wilgie Mia N-2A	83.80	-	-	-	-	-	-	1.30	-	-	-	0.25	14.70
Wilgie Mia N-2B	59.99	1.23	-	2.61	0.07	-	-	-	-	-	-	-	36.10

QPA/Rietveld powder XRD data supplied by M. Jercher. *Indicates non-crystalline component.

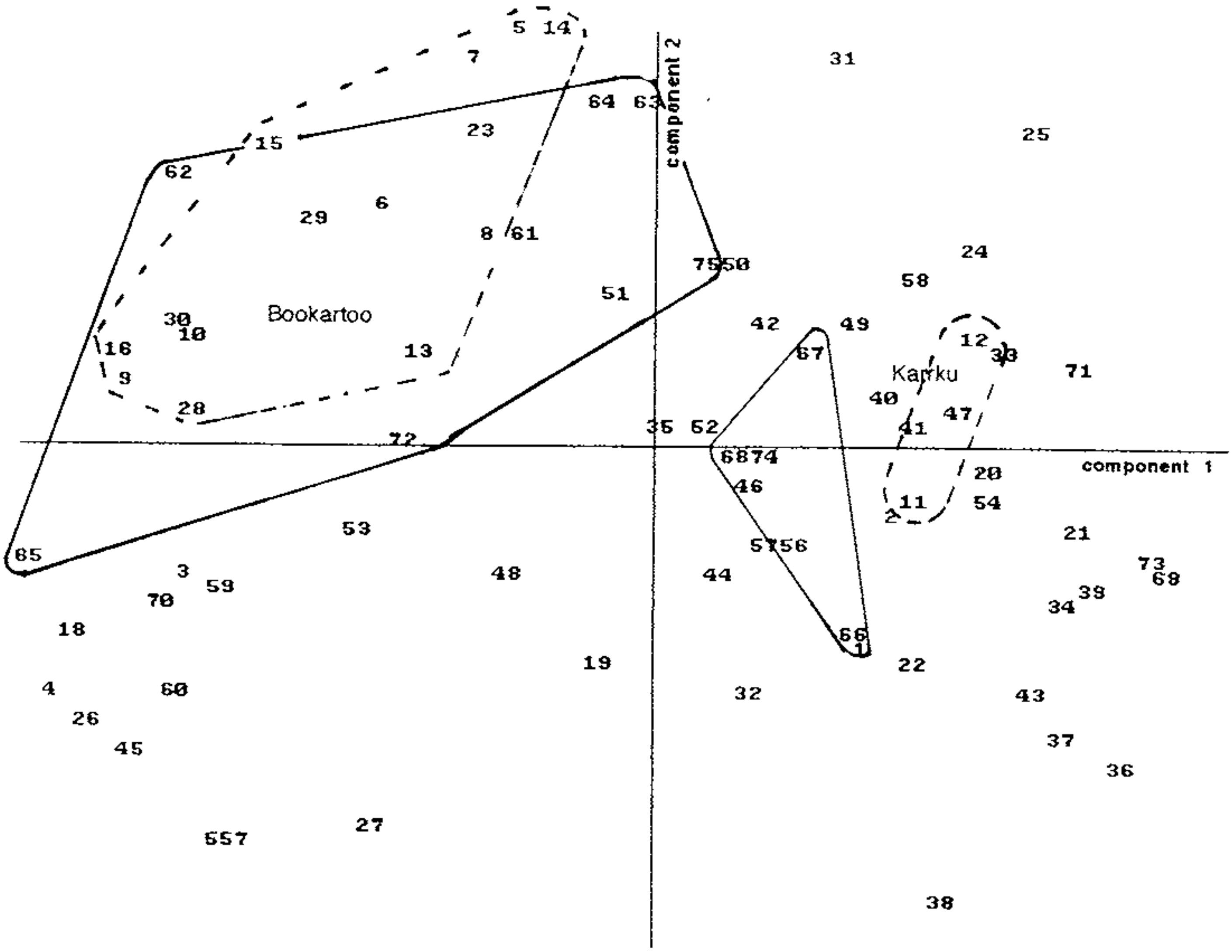

Figure IV/1

PCA of EDXA data to compare fines (settled) (solid lines) and whole (pulverised) ochres (dashed line) from selected sources.

Source file: ALLEDX (see Appendices)

Transformations: data normalised to 100%; rank order by variable.

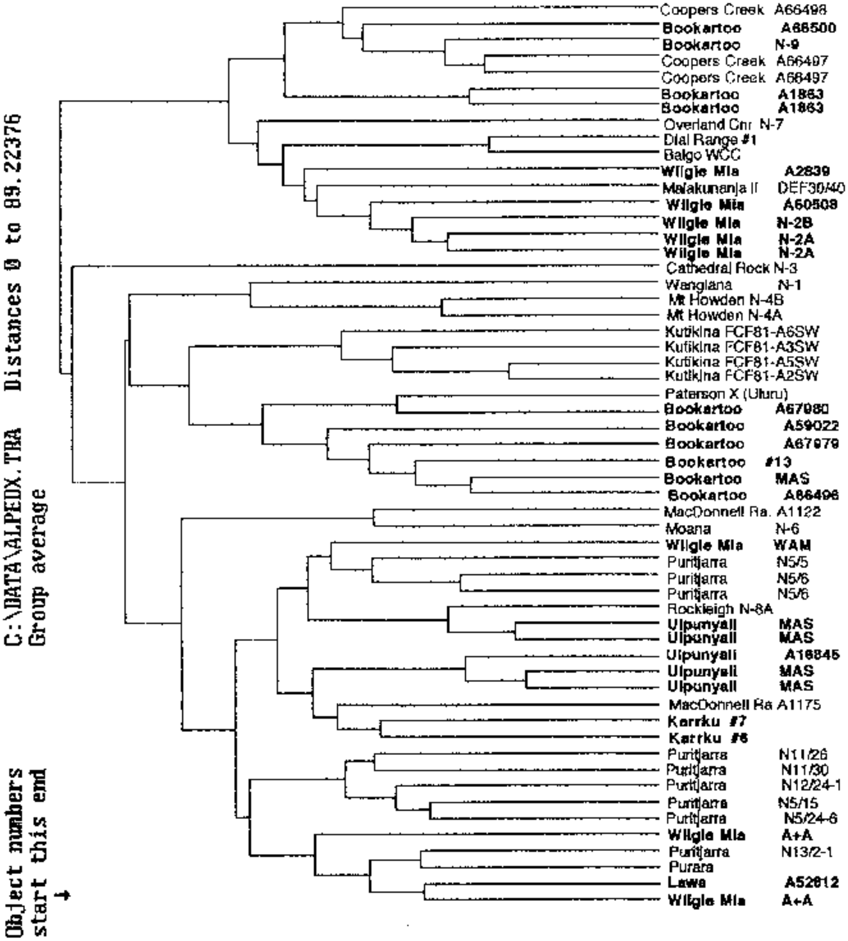

FIGURE IV/2

UPGMA cluster analysis of EDXA data showing clustering on major and minor oxides.

Source file: ALPEDX (All pulverised samples excluding Arkaba and O'Connor specimens) made from ALLEDX.

Transformations: normalised to 100 %, rank order by variable.

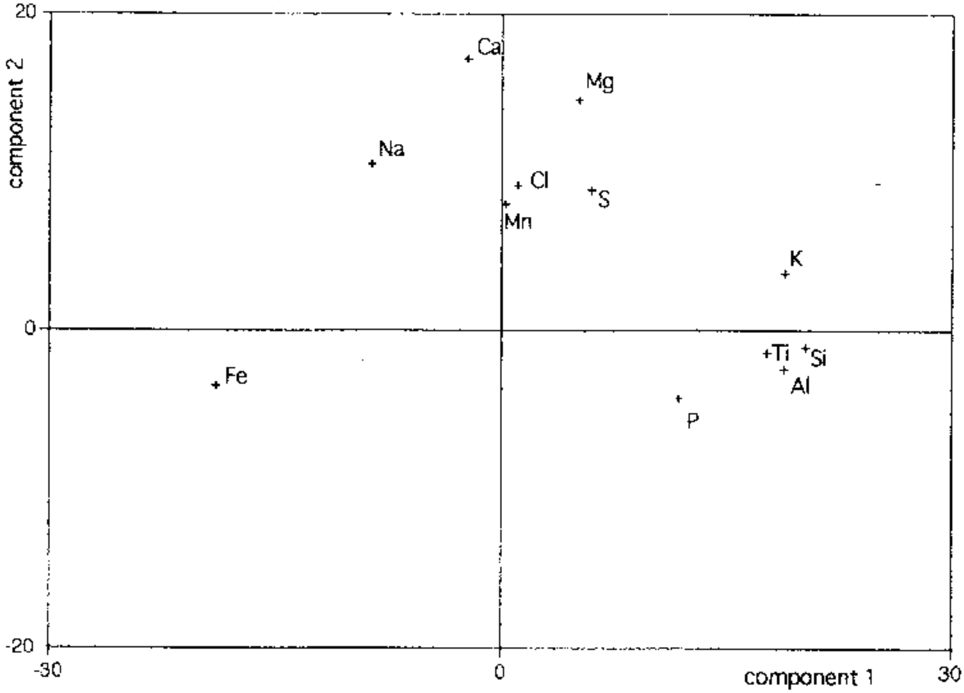

FIGURE IV/3A

PCA on EDXA oxides. Plot showing relationship between oxides (labelled as elements for convenience).

Source file: ALLEDX

Transformations: data normalised to 100%, rank order by variable.

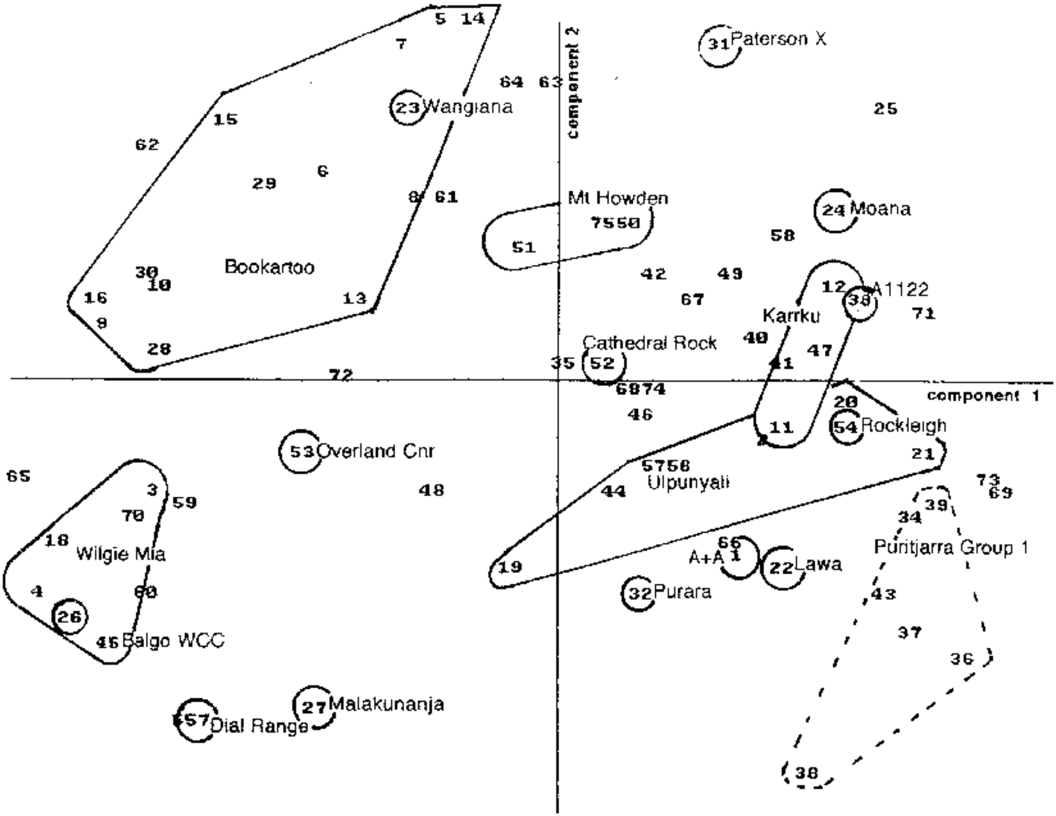

Figure IV/3B

PCA of EDXA data to compare sources. Plots show source variability for pulverised samples only.

Source file: ALLEDX (see Appendices)

Transformations: data normalised to 100%; rank order by variable.

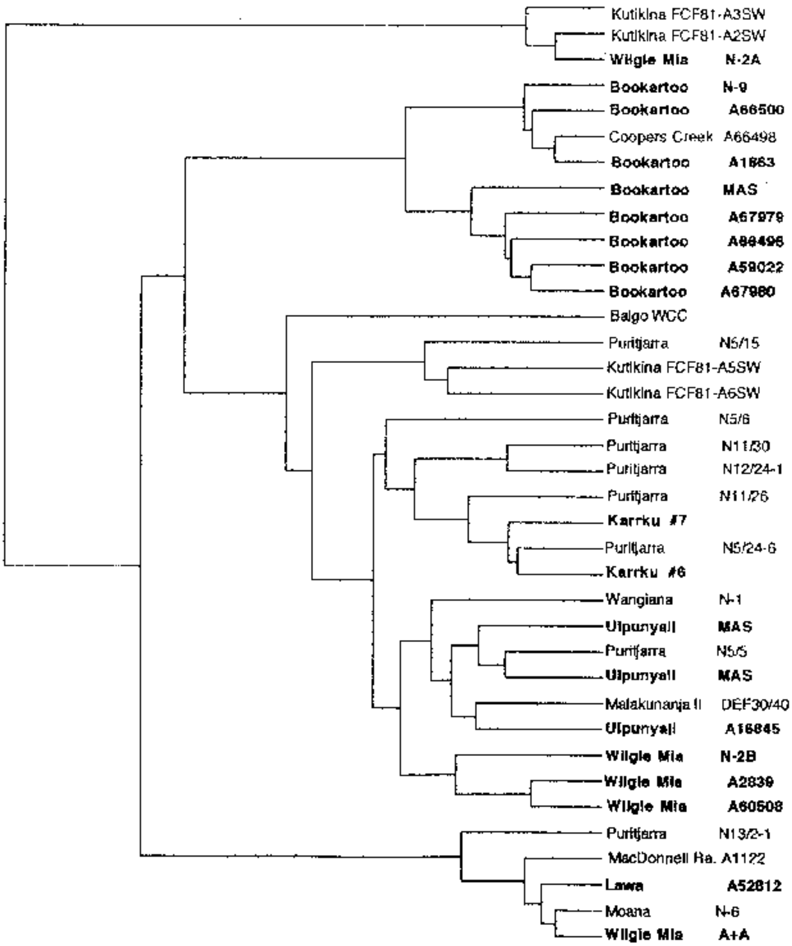

FIGURE IV/4

Cluster analysis on trace element composition of pulverised samples. Clustering algorithm is UPGMA using plain Euclidean distance. Distances 0 to 84.48.

Source file: ALLICPPT

Transformations: records normalised to 100%.

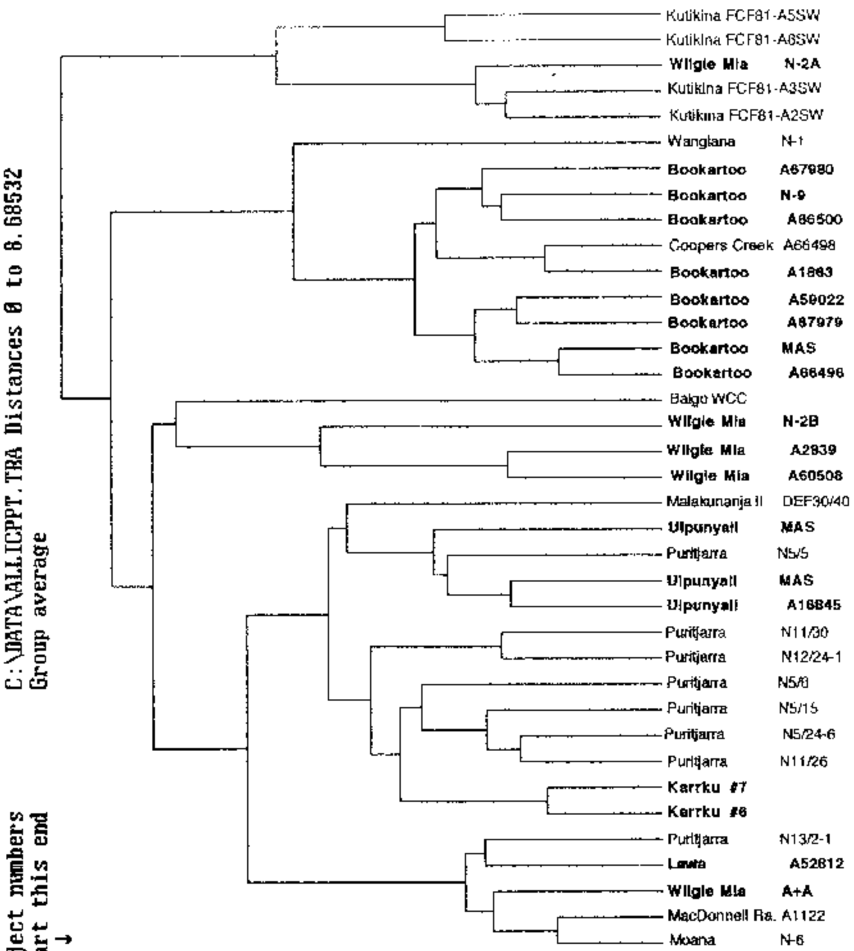

FIGURE IV/5

Cluster analysis on trace element data weighted to reduce the influence of less abundant elements. Distances 0 to 8.68.

Source file: ALLICPPT

Transformations: data normalised to 100 % and then transformed to square roots.

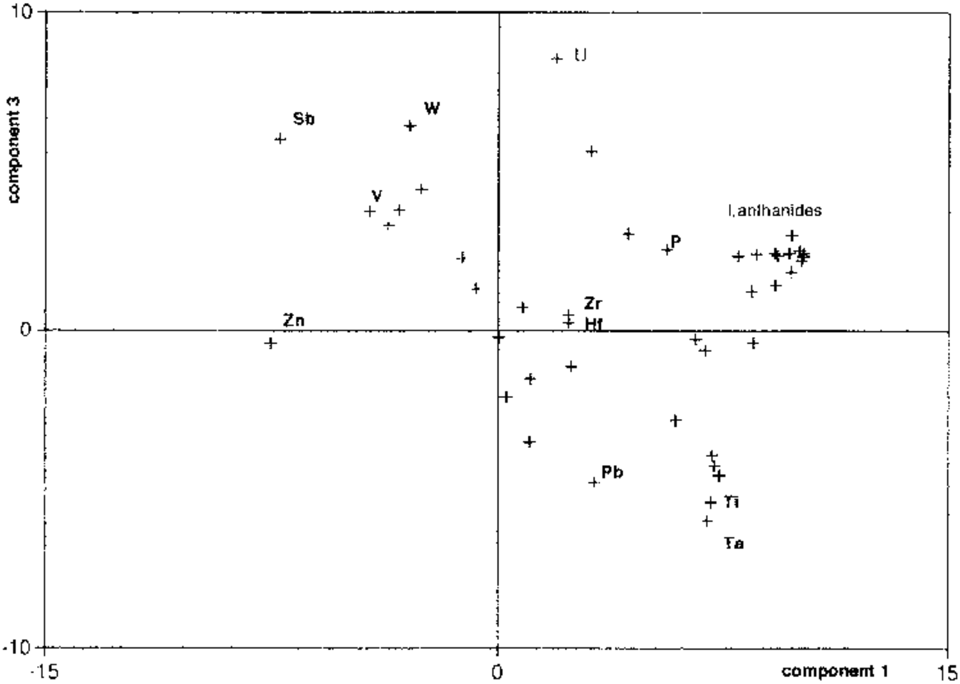

FIGURE IV/6

PCA on trace element composition showing relationship of elements to components 1 and 3.

Source file: ALLICPPT

Transformations: data normalised to 100%; rank order by variable.

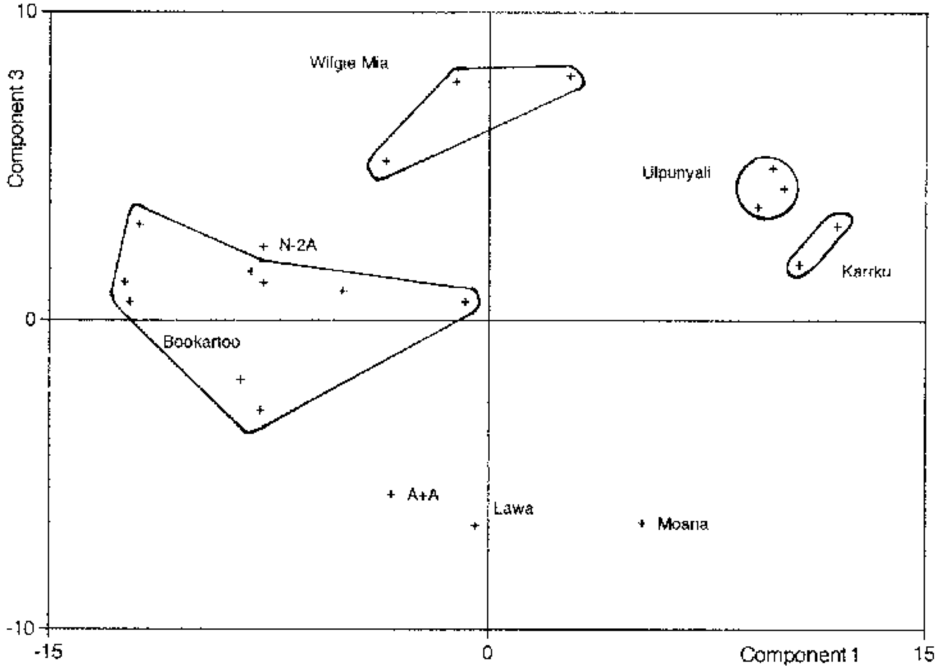

FIGURE IV/7

PCA on trace element composition showing variability within and between selected sources.

Source file: ALLICPPT

Transformations: Data normalised to 100%; rank order by variable.

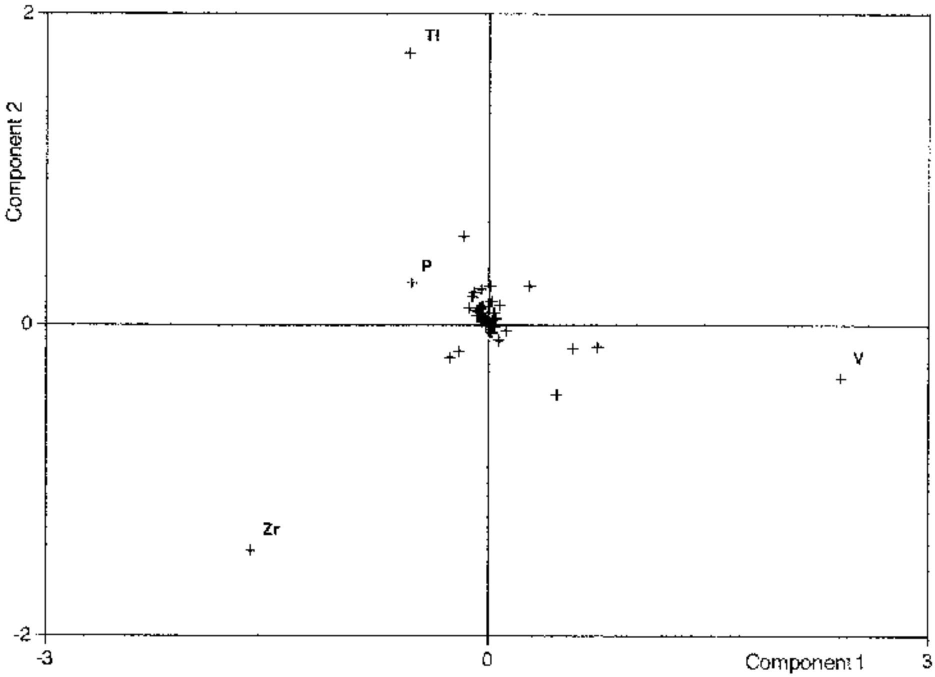

FIGURE IV/8 A

PCA plot of trace element data weighted to reduce influence of less abundant elements. Graph shows the strong influence of Ti, V and Zr. P forms the third component (not shown).

Source file: ALLICPPT

Transformations: data normalised to 100%; transformed to square roots.

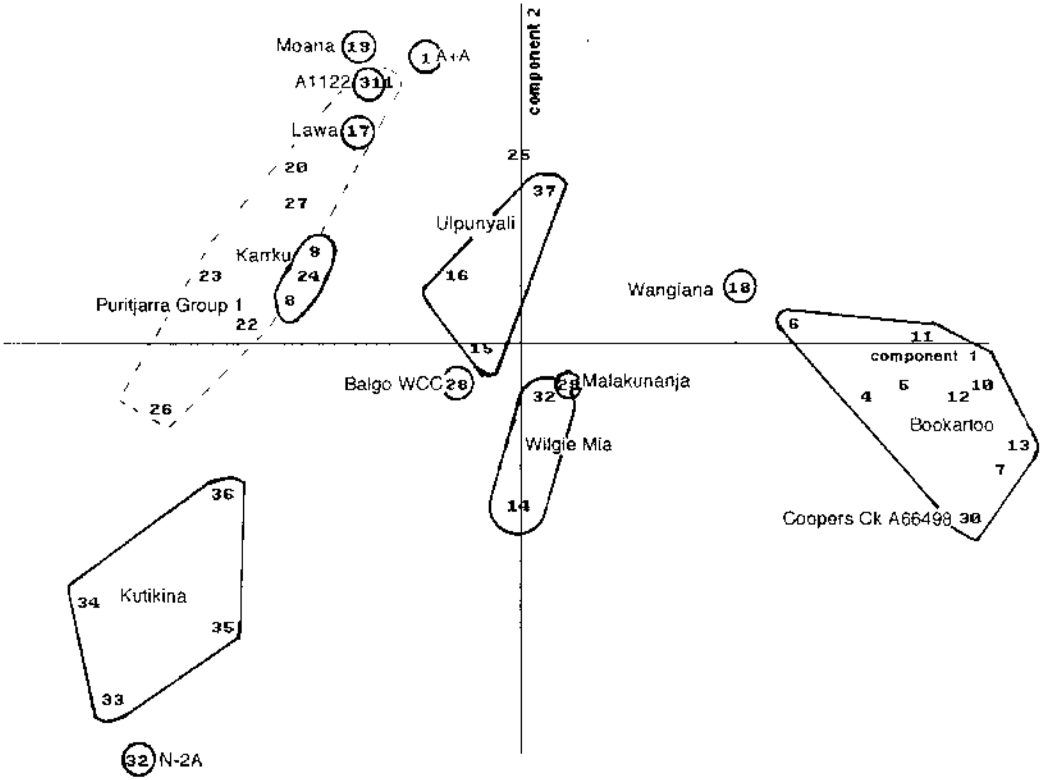

Figure IV/8B

PCA of ICP/MS data to compare sources. Plots show source variability for pulverised samples only.

Source file: ALLICPPT (see Appendices)

Transformations: data normalised to 100%; square root transformation.

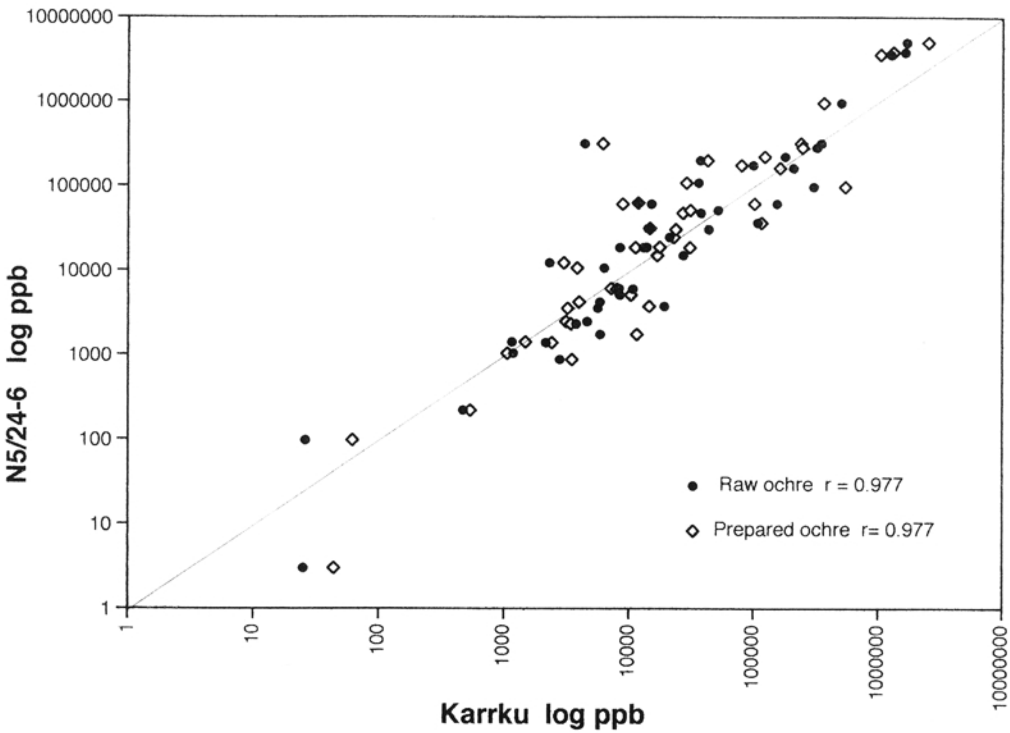

FIGURE IV/9

Comparison of trace element composition of N5/24-6 (Puritjarra-Group 1) and ochre from Karrku.

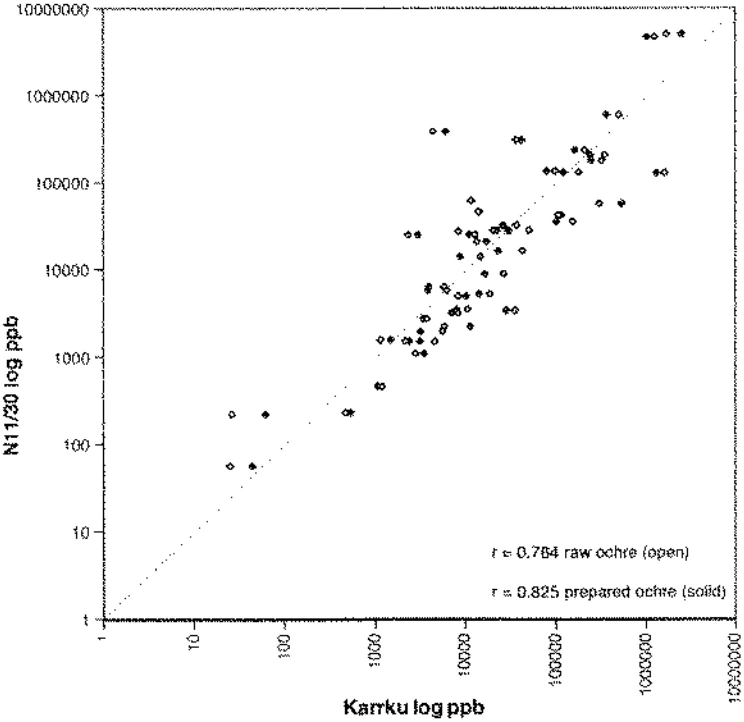

FIGURE IV/10

Comparison of trace element composition of N11/30 (Puritjarra - Group 1) and ochre from Karrku (solid symbols show raw ochre; open symbols show prepared ochre).

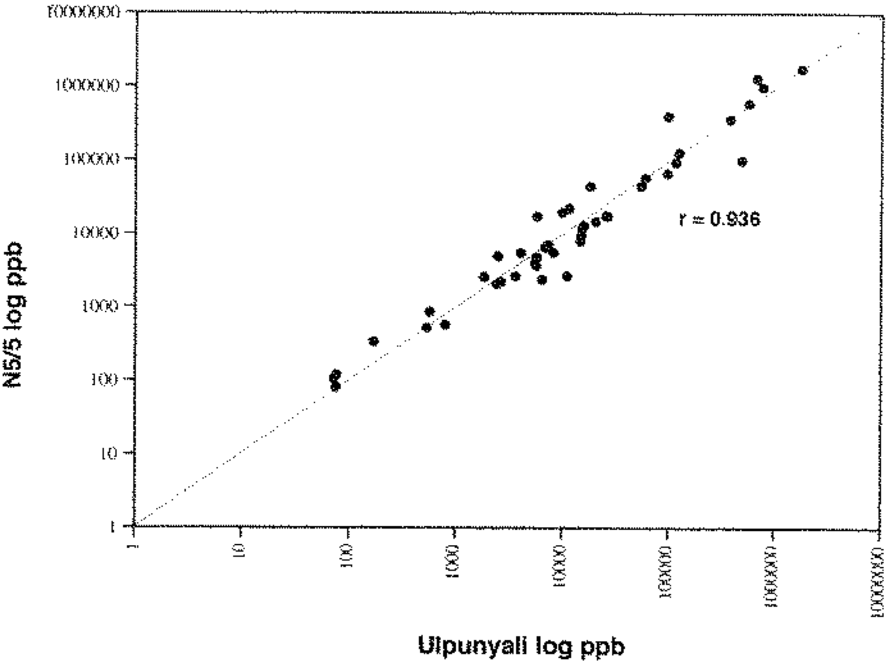

FIGURE IV/11

Comparison of trace element composition of N5/5 (Puritjarra - Group 2) and raw Ulpunyali ochre.

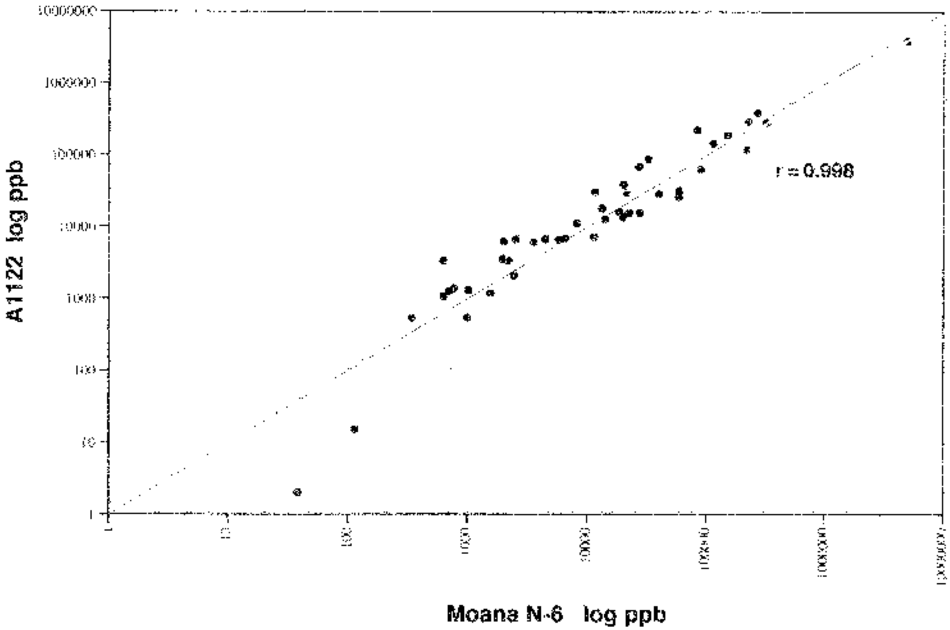

FIGURE IV/12

Comparison of trace element composition for A1122
and raw ochre from Moana (Sample N-6)

Part V - Concluding comments

Diagenesis of ochre deposits

Although little is known about the diagenesis of red ochre deposits the review of major sources presented in Part II of this report indicates that they are often discrete deposits eminently suitable for the sort of geochemical sourcing methods used in archaeology. Sagona and Webb (1994) distinguish three types of red ochre in Tasmania on petrology:- specular vein haematite, beds of ferruginised sandstone, and ochres that originate in laterite. This is in line with our own thinking on the matter. We suggest the following types of deposit:

1. Ochre in veins or lodes
   a) vein haematite of hydro-thermal origin
   b) sedimentary infill in joints and fractures (Bookartoo; Karrku)

2. Beds of ferruginised sandstone (often formed by weathering of iron sulphides in marine sediments) (eg. Toolumbunner; Ulpunyali).

3. Weathering products
   a) lateritic ochres (formed by concentration of metal oxides after other minerals have been leached out).
   b) super gene enrichment (eg. gossans - where an existing deposit of metal oxides is enriched by material leached from elsewhere) (eg. Wilgie Mia).

Cross-cutting this classification is a division of ochres into Fe-rich, carbonate-rich or silicate-rich deposits (set out in Part IV above).

Vein haematite appears to be comparatively rare - though the Mt Housetop source in Tasmania is specular vein haematite (Sagona and Webb 1994) and the ground haematite pieces excavated from the lower levels of Malakunanja II rock shelter in western Arnhem Land and from Kutikina Cave in Tasmania are almost certainly of vein haematite. None of the major sources appear to be of lateritic origin, perhaps because this type of ochre is often hard and lacks the sheen associated with the better quality red ochres. Many of the major ethnographic ochre sources appear to be sedimentary in origin, either ferruginised beds in marine sandstones of Palaeozoic age or sedimentary infills in joint lines. For instance, Sullivan and Opik (1951) found that the Rumbalara yellow ochre deposit in central Australia was the basal sedimentary unit of a marine Cretaceous formation. They suggest it was originally a bacterial sediment formed by iron-accumulating micro-organisms.

Prospects for sourcing red ochres

Our results show that sourcing red ochres is possible and that small archaeological specimens (<1g) present no particular difficulty. Bookartoo ochre is particularly distinctive and we found little difficulty in recognising samples collected over 80 years apart as well as material from prepared cakes. The central Australian sources also have a distinctive chemical finger-print, particularly in terms of their rare earth content. Although variability within sources did not represent insurmountable difficulties for sourcing we think that variability within the Wilgie Mia deposit requires further attention. Our data may indicate the presence of several beds of ochre at Wilgie Mia - each with a discrete chemical signature - rather than continuous chemical variability within the lode.

Although initially we thought that prepared pigments would present particular difficulties for sourcing, the trace element composition of prepared ochres from Karrku and Bookartoo unambiguously identifies the source of these ochres. Note however that our sample preparation techniques remove any organics likely to have been added to the ochre, and that our choice of trace elements avoids elements likely to be introduced as coarse-grained inclusions (Ca, Mg, Si, K, Al). There is greater variability in the major oxide content of prepared ochres and we suggest that on its own XRD or EDXA analysis of prepared ochres could give misleading results.

Our analysis of archaeological samples from Puritjarra shelter suggests that very small samples of ochre (~0.1 g) may be subject to post-depositional chemical changes, involving leaching of some elements such as U.

Methodology for sourcing ochres

Although we have found that ICP/MS trace element composition gives the best discrimination between sources we argue that it is preferable to use a nested series of methods in conjunction to give greater confidence in the results. In this project we have combined petrological examination, EDXA analysis of major and minor oxide composition with ICP/MS analysis of a wide range of trace elements. In a few cases we have also been able to analyse stable isotope composition of quartz inclusions in the ochres. Use of a single method may give misleading results. For instance on trace element chemistry alone vein haematite from Malakunanja II clusters with ferruginised sandstone from Ulpunyali. EDXA analysis of major oxides and petrology however will show that this can be ruled out.

We recommend preparing all ochre samples in a muffle furnace to remove any organics prior to analysis. However, we found that there was little to recommend working with fines rather than whole pulverised ochres.

Establishment of an archive of analytical results and ochre samples

As this work develops we feel that it will be important to build up consolidated data files of compositional data for Australian ochres. This will allow unknown ochres to be rapidly compared with known sources on file using multivariate methods. In this study compositional data for each sample is stored as a computer data-file. As this file is added to and updated it will provide the basis for identifying unknown ochres. We have also archived a portion of all ochres we analyse to allow samples to be re-run as analytical techniques improve.

Archaeological implications

Our results show that a systematic application of these methods to an archaeological assemblage of ochres can provide a unique perspective on prehistoric land use, as well as basic information about the chronology of major ochre quarries. The results of our Puritjarra case study are remarkable in that they show that Karrku - an ethnographic ochre mine currently exploited by Wailpiri people in central Australia - was in use 30,000 years ago. The results (described in Part IV above) also indicate the presence of a well established population in the region west of the MacDonnell Ranges in the late Pleistocene.

Avenues for further work

Our work opens up several avenues for further work, which we are keen to pursue.

First, we now have the tools to identify Bookartoo ochre on archaeological sites - and probably also on implements in Museum collections. This opens up the possibility of studying the geographical distribution of this ochre and the operation of trade and exchange in the Lake Eyre basin in the nineteenth century. In combination with archaeological investigations at sites in the Flinders ranges and along the red ochre route to the north this will allow the chronology of this exchange system - and of the Bookartoo quarry - to be worked out in some detail.

Secondly, we are now also in the position to investigate the chronology of other major ochre mines - such as Wilgie Mia mine and Toolumbunner - through a systematic study of excavated ochres from sites in adjacent regions. The results will give a fresh perspective on land use and exchange in these regions and will allow the chronology of the mines to be worked out.

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Appendix 1 – Data files

File: ALLEDX

Made from ALLMPT.ED (ALLMPT.ASC) with settled samples from ALLMST.ED (ie. MS2A-MS9B1, FS10A-FS17A) on 10 January 1996

All results are post- June 1995 EDXA results ie. All of the results below were obtained using the same EDXA/SEM configuration.

EDXA SEM results on ochres - <u>all samples</u>

<u>Preparation method:</u> samples pulverised (p) or settled (s) + then fired in muffle furnace

For multivariate analysis these data were imported into MVARCH as ALLEDX.mva. Where appropriate the SUBSET program was used to partion this file into ALPEDX (Records 1-58 pulverised samples) and ALSEDX (Records 59-75 settled samples).

Variables:

1/ P2O5;
2/ SiO2;
3/ TiO2;
4/ Al2O3;
5/ Fe2O3;
6/ MnO;
7/ MgO;
8/ CaO;
9/ Na2O;
10/ K2O;
11/ SO3;
12/ CL

Pulverised samples

1	Wilgi Mia A+A	101A	0.01	48.25	0.62	21.70	27.85	0.00	0.20	0.16	0.54	0.29	0.37	0.01
2	Wilgi Mia A+A	101B	0.10	47.49	0.58	21.24	28.91	0.17	0.17	0.20	0.42	0.29	0.38	0.05
3	Wilgi Mia 60508	102A	0.05	2.74	0.20	1.97	93.43	0.00	0.14	0.14	0.90	0.12	0.13	0.19
4	Wilgi Mia 2839	103A	0.00	2.50	0.03	2.04	94.17	0.01	0.25	0.10	0.86	0.00	0.04	0.00
5	Bookartoo 66496	104A	0.13	10.65	0.36	2.35	51.03	0.19	1.72	32.02	0.95	0.20	0.31	0.09
6	Bookartoo 67979	105A	0.20	9.07	0.19	2.03	67.98	0.32	5.60	13.40	0.86	0.26	0.09	0.00
7	Bookartoo MAS	106A	0.08	11.29	0.14	2.65	53.71	0.43	0.78	28.66	0.69	0.46	1.06	0.07
8	Bookartoo #13	110A	0.16	14.86	0.13	2.87	60.58	0.12	0.97	18.83	0.60	0.48	0.40	0.00
9	Bookartoo 1863	107A	0.01	4.00	0.11	0.85	92.24	0.00	0.14	1.09	0.96	0.10	0.44	0.07
10	Bookartoo 1863	107B	0.07	4.57	0.09	0.85	91.22	0.05	0.21	1.05	0.99	0.15	0.71	0.03
11	Karrku #6	108A	0.37	35.01	0.28	12.79	46.14	0.00	0.52	0.15	0.53	3.62	0.55	0.05
12	Karrku #7	109A	0.36	41.89	0.49	13.81	37.25	0.14	0.55	0.56	0.57	4.02	0.30	0.05
13	Bookartoo 66500	111	0.12	7.56	0.31	1.76	61.67	0.01	0.30	27.50	0.35	0.16	0.13	0.12
14	Bookartoo 67980	112	0.33	17.81	0.31	2.38	67.75	0.23	3.20	4.50	1.51	0.33	0.23	1.41
15	Bookartoo 59022	113	0.07	4.36	0.00	1.22	83.77	0.50	1.77	7.40	0.28	0.08	0.48	0.06
16	Bookartoo N-9	114	0.01	3.27	0.04	0.89	92.64	0.00	1.21	1.25	0.45	0.07	0.00	0.18
17	Wilgi Mia N-2A	115A	0.14	4.46	0.05	3.65	91.13	0.00	0.05	0.08	0.37	0.00	0.00	0.08
18	Wilgi Mia N-2B	115B	0.06	0.91	0.05	0.88	97.09	0.00	0.17	0.44	0.28	0.01	0.02	0.09
19	Ulpanyalli 16845	116	0.25	26.35	0.17	2.77	68.82	0.02	0.34	0.17	0.20	0.70	0.20	0.00
20	Ulpanyalli MAS	117A	0.52	68.33	0.23	7.94	20.48	0.00	0.42	0.24	0.24	0.89	0.57	0.13

21	Ulpanyalli MAS	117B	0.62	64.24	0.41	9.29	22.97	0.00	0.37	0.33	0.09	1.03	0.53	0.13
22	Lawa 52812	118A	0.13	41.81	1.12	20.22	35.64	0.15	0.15	0.29	0.11	0.16	0.20	0.02
23	Wangiana N-1	118B	0.06	4.79	0.00	1.38	13.01	0.35	0.31	33.11	0.13	0.24	46.41	0.21
24	Moana N-6	119	0.01	46.42	0.84	14.88	30.56	0.00	1.16	0.19	1.01	4.19	0.33	0.41
25	Arkaba N-5	120	0.01	60.36	0.70	17.29	5.61	0.00	1.39	1.93	4.72	3.30	4.62	0.07
26	Balgo Hills	121	0.11	2.41	0.06	0.59	95.94	0.28	0.00	0.13	0.33	0.00	0.13	0.01
27	MII'89 DEF30/40	122	0.33	8.61	0.00	3.52	86.61	0.00	0.13	0.22	0.24	0.30	0.05	0.00
28	C'Creek 66497	123A	0.00	7.60	0.12	1.34	88.86	0.00	0.35	0.74	0.57	0.08	0.08	0.28
29	C'Creek 66497	123B	0.00	11.39	0.12	2.17	80.36	0.02	0.63	4.08	0.58	0.14	0.18	0.33
30	C'Creek 66498	124	0.02	10.46	0.00	1.34	86.09	0.27	0.34	0.56	0.59	0.01	0.11	0.22
31	Paterson X (Uluru)	125	0.28	26.56	0.36	9.80	53.06	0.84	1.91	1.98	0.77	3.69	0.26	0.50
32	Purara	126	0.03	29.61	0.64	9.54	58.65	0.11	0.03	0.20	0.23	0.57	0.37	0.00
33	MacD Ra 1122	127	0.05	47.41	0.62	13.25	29.80	0.11	2.03	0.13	0.46	5.91	0.10	0.13
34	MacD Ra 1175	128	0.20	46.91	0.65	15.78	31.36	0.00	1.15	0.12	0.23	3.40	0.17	0.03
35	Sue O'C Yellow	129	0.39	24.06	0.03	1.76	5.35	0.00	0.66	67.01	0.13	0.53	0.05	0.03
36	PJ#21 N12/24-1	130	0.76	51.53	1.05	21.02	23.76	0.17	0.29	0.05	0.13	1.19	0.00	0.06
37	PJ#25 N11/30	131	1.53	31.99	1.10	22.11	41.17	0.03	0.21	0.11	0.25	1.14	0.35	0.01
38	PJ#28 M 11/26	132	1.21	50.65	0.59	9.33	37.25	0.00	0.10	0.12	0.09	0.49	0.16	0.01
39	PJ#32 N5/24-6	133	1.11	63.66	0.96	14.86	17.32	0.02	0.22	0.21	0.43	0.99	0.16	0.05
40	PJ#42 N5/6	134A	2.01	44.50	0.47	4.24	43.30	0.07	0.39	3.44	0.34	0.92	0.12	0.21
41	PJ#42 N5/6	134B	2.12	42.95	0.45	4.30	44.80	0.13	0.29	3.62	0.10	0.77	0.27	0.21
42	PJ#43 N5/5	135	0.56	25.13	0.39	6.79	60.41	0.00	0.69	4.23	0.42	0.70	0.21	0.47
43	PJ#31 N5/15	136	2.19	59.30	0.89	10.92	25.21	0.02	0.16	0.27	0.18	0.74	0.00	0.10
44	PJ#47 N13/2-1	137	0.01	21.78	0.49	14.55	61.04	0.09	0.20	0.40	0.25	1.02	0.13	0.03
45	Wilgi Mia N-2A	138A	0.39	1.69	0.00	0.97	96.18	0.00	0.12	0.16	0.35	0.02	0.02	0.10
46	Kutikina A2 SW	139	1.65	23.87	0.25	6.87	63.90	0.16	0.92	0.79	0.30	1.27	0.00	0.02
47	Kutikina A3 SW	140	0.56	29.49	0.74	8.48	35.79	0.15	1.82	20.72	0.10	2.13	0.00	0.00
48	Kutikina A6 SW	141	1.28	11.97	0.09	3.18	81.49	0.24	0.61	0.66	0.15	0.32	0.00	0.01
49	Kutikina A5 SW	142	6.02	25.00	0.32	9.21	47.85	0.28	1.19	7.47	0.35	2.22	0.04	0.03
50	Mt Howden N-4A	143	0.07	18.51	0.30	3.47	22.90	0.01	0.14	17.98	0.49	1.50	34.56	0.08
51	Mt Howden N-4B	144	0.27	17.41	0.13	1.86	34.27	0.06	0.04	14.96	0.44	0.81	29.64	0.11
52	C"dral Rock N-3	145	0.30	15.89	0.91	0.24	45.45	0.13	0.09	0.05	3.30	2.93	30.55	0.16
53	Overland Cnr N-7	146	0.69	22.87	0.00	0.78	74.25	0.01	0.36	0.17	0.50	0.06	0.21	0.09
54	Rockleigh N-8A	147	0.48	32.53	0.21	29.86	30.76	0.00	0.31	0.30	0.14	1.21	4.06	0.14
55	Dial Ra #1	148	0.15	3.30	0.23	1.10	94.58	0.15	0.05	0.08	0.22	0.01	0.13	0.01
56	Ulpanyalli MAS #1149A		0.26	39.23	0.30	5.50	52.67	0.02	0.48	0.34	0.10	0.66	0.42	0.02
57	Ulpanyalli MAS #1149B		0.31	41.61	0.22	4.75	51.16	0.03	0.45	0.32	0.25	0.58	0.31	0.01
58	Wilgi Mia WAM	150	0.69	31.54	0.21	32.69	30.81	0.04	0.58	0.61	0.54	0.80	0.42	1.08

Settled samples

59	Wilgie Mia 60508	MS2a	0.29	3.67	0.01	3.05	91.33	0.00	0.15	0.12	0.87	0.00	0.43	0.10
60	Wilgie Mia 2839	MS3A	0.18	2.62	0.16	2.22	93.52	0.00	0.26	0.09	0.80	0.00	0.11	0.03
61	Bookartoo 66496	MS4A	0.19	9.21	0.60	3.10	69.61	0.07	2.10	13.79	0.82	0.35	0.14	0.01
62	Bookartoo 67979	MS5A	0.04	4.58	0.00	1.49	84.04	0.39	3.31	5.22	0.78	0.08	0.04	0.03
63	Bookartoo MAS	MS6A	0.19	14.31	0.35	5.22	53.14	0.15	1.72	20.93	0.64	0.52	2.80	0.04
64	Bookartoo MAS	MS6B	0.26	11.76	0.19	4.43	51.57	0.12	1.09	26.39	0.68	0.56	2.90	0.06
65	Bookartoo 1863	MS7A	0.00	2.91	0.00	1.18	94.31	0.00	0.38	0.42	0.73	0.00	0.07	0.00
66	Karrku #6	MS8A	0.54	21.27	0.35	14.95	57.79	0.00	0.67	0.10	0.54	3.65	0.12	0.02
67	Karrku #7	MS9A1	0.46	18.12	0.56	10.56	65.00	0.00	0.41	0.42	0.78	2.50	1.08	0.11
68	Karrku #7	MS9B1	0.29	15.84	0.38	9.59	69.39	0.00	0.37	0.26	0.67	2.13	1.03	0.04
69	Moana N-6	FS10A	0.13	54.38	1.10	17.29	21.33	0.06	1.15	0.06	0.13	4.17	0.14	0.06
70	Balgo WCC	FS11A	0.10	3.36	0.03	1.04	94.19	0.39	0.19	0.09	0.37	0.02	0.17	0.05
71	Ulpunyali MAS	FS12A	0.96	31.54	0.77	18.66	42.72	0.10	1.02	0.53	0.14	2.10	1.36	0.08
72	C'Creek 66498	FS13A	0.01	6.32	0.48	3.12	86.40	0.00	0.65	2.39	0.35	0.08	0.15	0.04
73	MacD Ra 1175	FS14A	0.51	39.21	0.60	24.72	27.88	0.11	1.69	0.14	0.10	4.86	0.16	0.01
74	Ulpunyali MAS	FS16A	0.35	15.37	0.30	6.61	73.90	0.00	0.85	0.43	0.09	1.45	0.55	0.09
75	C'Creek 66498	FS17A	0.11	29.37	0.26	12.11	52.29	0.12	3.11	1.64	0.39	0.40	0.15	0.07

ALLICPPT

Data are ICP/MS analyses of red ochres.

August 1995

Converted from file: ALLICPPT.ASC (All pulverised samples)

All samples pulverised in Retsch mill and fired to remove organics.

Variables:

1/Lithium 2/Beryllium 3/Phosphorus 4/Scandium 5/Titantium
6/Vanadium 7/Chromium 8/Cobalt 9/Nickel 10/Copper
11/Zinc 12/Gallium 13/Rubidium 14/Strontium
15/Yttrium 16/Zirconium 17/Niobium 18/Molybdenum
19/Silver 20/Cadmium 21/Tin 22/Antimony
23/Caesium 24/Barium 25/Lanthanum 26/Cerium
27/Praeseodymium 28/Neodymium 29/Samarium
30/Europium 31/Terbium 32/Gadolinium 33/Dysprosium
34/Holmium 35/Erbium 36/Ytterbium 37/Lutetium
38/Hafnium 39/Tantalum 40/Tungsten 41/Thallium
42/Lead 43/Thorium 44/Uranium

1/**Wilgi Mia** A+A FP101 21588 1088 247893 42251 5139280 253451 125863 4716 154375 34506 71879 27097 14680 21479 10754 165412 3658 421 30 5 10479 2000 637 302533 9664 15551 1968 7456 1545 376 266 1555 1631 348 984 1044 163 3975 307 1383 462 44473 3440 3072

2/**Wilgi Mia** 60508 FP102 332 1333 876813 24563 613296 342829 311171 4781 35502 17372 13945 7376 552 36624 24624 348848 6507 1722 36 158 10922 600326 101 39873 35271 61015 8761 32978 7504 3292 943 6221 5094 938 2389 2351 351 7529 57 59921 8 601159 1683 42499

3/**Wilgi Mia** 2839 FP103 246 750 436259 6743 212395 116641 204568 7761 20134 12311 16049 4373 515 18448 3355 101040 616 4771 17426 197 12047 250667 124 34711 6848 21831 3107 16105 4190 1381 243 2233 1010 152 336 311 49 2152 43 84053 6 141302 291 27194

4/**Bookartoo** 66496 FP104 5725 1387 315954 1649 508736 1654577 23979 4204 10079 3909 200484 2700 6727 116427 5971 192430 1754 6311 26 1057 12079 65565 536 56117 26095 31262 2685 8169 1138 213 146 987 840 174 483 488 78 4321 142 2275 76 405585 2165 2382

5/**Bookartoo** 67979 FP105 4777 890 386046 1392 385292 1484807 20675 3105 7830 3539 604443 2710 4472 271566 4049 91398 1574 6792 18 1901 10340 81836 524 51445 9267 16214 1587 5671 932 166 109 772 606 121 328 316 50 2100 123 3513 115 360400 1801 2968

6/**Bookartoo** MS FP106 4722 1362 208310 2065 661118 1002746 17975 4843 10433 5080 161582 3132 12470 82310 8021 160704 2090 3904 35 451 11529 56001 829 73022 11811 19694 2152 7992 1484 288 209 1369 1222 254 706 702 112 3673 167 1195 109 273756 2489 1959

7/**Bookartoo** 1863 FP107 1830 2085 80281 188 233996 2417913 38841 2008 13237 1943 88034 3172 2173 16598 1111 107281 902 18473 21 55 8849 134388 515 27563 22014 23700 1605 3745 255 36 24 163 155 34 105 127 23 2406 89 9368 28 325975 1229 4466

8/**Karrku** #6 FP108 8358 3771 1255027 12854 1689473 209193 36909 2315 14898 4388 8398 14084 107666 348391 154116 1631909 13698 5828 26 25 11631 2788 2156 503293 99491 321180 37400 179810 51412 6329 5611 43386 26909 4625 10702 8268 1183 35701 1154 5880 471 303807 20830 19049

9/**Karrku** #7 FP109 10269 3416 1037494 11164 2513891 162715 42489 3001 8831 6119 30491 14526 115950 240605 101784 1309697 17395 3973 62 44 11747 3502 2407 363441 80038 246790 26769 122885 30694 3845 3215 23439 16672 3124 7986 7188 1055 28650 1477 11468 536 541812 22668 14347

10/**Bookartoo** 66500 FP111 2103 782 157686 448 497665 2779706 11647 13692 8059 88464 122698 2647 2539 55536 3826 91290 2412 2774 27 193 21240 65696 303 28289 25475 29572 2398 5952 612 114 83 553 497 103 291 293 48 2090 149 1135 42 65950 2519 1323

11/**Bookartoo** 67980 FP112 8422 1425 697994 633 991924 3651194 27104 11360 6174 252045 760751 4176 9742 194891 4609 111761 3706 5814 71 145 29537 84036 1021 47255 61864 85225 6254 14524 884 134 109 685 597 128 364 398 68 2675 312 1954 108 134420 4669 3247

12/**Bookartoo** 59022 FP113 3056 1109 207488 485 299882 1827639 25163 12974 17551 69716 529479 3074 3445 186798 2575 80240 1773 7802 29 275 12136 118818 545 128454 34708 47440 3423 8725 713 115 76 520 394 76 199 192 32 1814 88 4512 316 211437 1903 3076

13/**Bookartoo** N-9 FP114 2401 909 114329 531 153317 1920006 25485 10804 9217 115629 200199 2924 1595 115170 842 61223 1049 10752 22 17 23385 131773 418 68957 3299 4633 351 1131 163 31 21 148 129 27 75 86 16 1446 54 5138 47 91694 1027 3152

14/**Wilgi Mia** N-2B FP115B 411 902 200845 10720 22972 88653 48721 16989 65865 59120 5667 2410 648 5806 948 127833 223 11377 9 12 4932 100079 59 25076 2619 5057 592 2622 532 163 38 251 215 43 126 175 31 2821 16 31991 5 3310 652 24379

15/**Ulpunyali** 16845 FP116 1792 5282 907010 5240 536679 716157 34588 13790 5620 106537 2924 12156 9201 192724 47140 722865 3204 3714 26 9 19475 760 404 456723 27455 88983 10561 48656 12358 2552 1776 11884 8947 1611 4391 4898 751 15770 200 3220 45 8965 5596 8610

16/**Ulpunyali** MAS(Bag A) FP117 4052 6395 1768808 6849 672597 568237 18200 15183 8234 98080 5753 14666 9863 378706 60240 489968 2460 2621 72 75 115499 535 565 766388 54950

123462 20554 96344 25495 5667 3592 26527 15783 2417 5691 5530 802 11012 170 1831 76 11563 14852 7342

17/**Lawa** 52812 FP118A 4641 1415 248725 8894 5056751 242331 37817 20861 29364 168090 52322 53512 6739 22736 9825 659003 81340 11789 88 31 40490 940 80 72919 29906 80957 4117 12541 2242 487 342 1850 2068 422 1195 1426 228 17913 4751 1929 155 21404 40234 1952

18/**Wangiana** N-1 FP118B 20856 6674 814893 3564 473153 945263 5028 18069 77659 123432 141607 2026 7409 426489 20274 88845 1039 2709 1 7 14271 695 1021 31862 7695 14001 2079 8772 1872 550 401 2475 2457 525 1312 1021 149 1864 68 362 152 7776 884 2749

19/**Moana** N-6 FP119 11656 2521 320028 14043 4877838 113505 83171 13311 21422 216537 27117 22298 148783 32600 20070 224170 20051 625 114 38 58441 999 8241 268872 58671 88297 11434 39645 6557 1013 626 4451 3571 695 1959 2189 341 5758 1554 2449 769 18600 27545 2009

20/**Puritjarra** #21 N12/24-1 FP130 5970 1871 2646677 18326 4102492 193753 197398 15982 15630 541101 18020 34460 41575 155000 29973 899962 16573 4341 117 32 78107 703 1765 457840 99676 119129 21310 84719 18582 3814 1351 11084 6489 1158 2869 2957 444 19960 1174 1668 254 43126 18505 3699

21/**Puritjarra** #25 N11/30 FP131 4941 2731 4634869 25295 5034805 231992 305313 24813 13929 382228 27473 45363 42179 203619 35269 126788 21053 6319 221 56 61175 1093 1513 586797 133785 176692 31784 128812 27996 5746 1943 16298 8862 1497 3497 3178 463 3388 1569 2212 228 56425 27999 5254

22/**Puritjarra** #28 M11/26 FP132 3099 2250 3817532 48895 2545892 280948 431494 9881 8125 602806 10844 53909 19179 151427 33569 2700964 9933 5000 1486 104 87915 925 769 574149 83317 162866 20202 81463 18181 3700 1421 11304 6934 1290 3437 3819 655 83314 778 1145 120 57780 21881 7606

23/**Puritjarra** #32 N5/24-6 FP133 5101 2312 3553799 18543 4981216 162115 198700 12192 60408 312008 18448 31242 36397 314876 61465 3817113 18618 4190 97 3 62459 875 1380 954343 173417 282689 47580 219730 50915 10664 3528 30362 14990 2451 5955 6065 1037 107878 1414 1739 219 96807 24311 3712

24/**Puritjarra** #42 N5/6 FP134 5462 2480 5788273 8381 2461467 412077 25120 5300 11086 103176 14860 7780 25666 295254 93805 1560412 7305 2921 149 157 22289 355 1126 401327 38670 128054 15187 72121 19083 3922 2865 19432 15753 3049 7858 7431 1133 45650 489 1780 169 12661 8379 9759

25/**Puritjarra** #43 N5/5 FP135 5432 2372 1704468 6466 1301921 586838 43455 11598 5503 392633 17019 7854 19256 357363 56901 98526 4880 2178 105 81 92137 516 852 975275 43671 126312 14509 65610 17498 3617 2600 17129 12799 2063 4709 3930 575 2660 337 2556 118 21808 9357 6954

26/**Puritjarra** #31 N5/15 FP136 4106 2897 4169263 34037 4616560 335998 297342 16249 22287 285820 21096 31116 27278 532659 77882 10119257 15590 5963 375 41 57954 1297 952 1169253 172740 294176 51392 229558 52639 11114 3756 32207 16848 2954 7953 9646 1840 290788 1168 1655 167 99985 25921 6739

27/**Puritjarra** #47 N13/2-1 FP137 5057 1757 428005 10478 3699947 216957 233936 19811 7584 80101 16066 21501 51745 86394 7578 1120210 14022 459 25 43 25842 729 3879 256236 39827 61913 5928 19526 2859 437 189 1474 1085 259 833 1199 224 25946 1219 2492 275 32815 37137 4366

28/**Balgo?** World Council of Churches FP121 1159 425 403393 760 256921 63148 929778 24021 138924 673649 429011 5133 551 9134 6919 245228 4681 70171 144 1 95706 19537 56 123621 3459 6917 746 2822 549 155 103 654 662 172 519 565 102 5267 125 7024 49 23210 649 849

29/**Malakunanja II** DEF30/40 FP122 1860 1000 1501238 4275 474616 987613 115084 2111 3716 123535 12152 8373 9636 143991 6511 486370 2588 13948 53 1 203829 58390 320 30771 97440 144765 13918 43776 4878 663 206 1918 1058 214 629 714 125 10453 249 81178 68 4780 14369 2587

30/**Coopers Creek** 66498 FP124 3352 2543 134162 430 340095 4605163 205334 1021 6757 27533 123510 3730 1612 28930 2708 428502 1507 15299 26 13 27350 148939 454 23126 13085 14732 1293 3676 437 77 58 378 350 81 254 312 62 9220 101 6581 47 334126 2272 4511

31/**MacDonnell Ranges** 1122 FP127 30667 6627 283688 12815 3985952 143781 224418 18314 30046 118715 69280 15724 187093 87826 39072 290038 13611 3320 15 2 25868 541 11240 386394 31380 64039 7253 28643 6894 1319 1062 6754 6099 1274 3524 3339 528 6564 1195 2127 1390 16218 15776 6336

32/**Wilgi Mia** N-2A FP138 177 1258 612217 28778 590087 411417 1072029 6271 24092 66670 8758 7787 597 5356 69134 28642279 8108 1674 1056 108 15548 789700 90 13828 5159 10082 1308 5507 2442 993 817 3470 6962 2148 8650 14891 3200 650579 156 53400 5 6873 5377 50771

33/**Kutikina** FCF81/A2SW FP139 8447 1290 3068803 30786 1540259 348646 741715 2996 13779 58579 429160 10460 40628 29106 83597 37348400 9490 2391 898 262 7760 8607 2377 108037 17123 41510 4383 17725 5204 1044 1181 6007 8668 2637 10811 18067 4067 867074 564 2457 355 164653 38904 14453

34/**Kutikina** FCF81/A3SW FP140 5820 1413 641690 16438 3269850 109263 290389 35711 22397 35842 50628 10038 58054 139744 113141 22793447 15233 2032 91 77 4312 5861 1655 221654 55436 177738 16869 71779 14347 2210 1750 10667 12469 3367 12025 16953 3195 498321 1012 1749 276 31301 15718 9837

35/**Kutikina** FCF81/A6SW FP141 11177 2681 3374720 5777 318851 339909 974814 2901 175019 13881 112311 6575 27989 60882

49110 5976823 7217 1383 221 82 3776 90017 2325 109392 7603 16351 1886 7853 1981 455 574 2735 4445 1274 4489 5817 1074 144015 108 9549 27 94120 3834 10255

36/**Kutikina** FCF681/A5SW FP142 21029 3952 11330286 11517 2506792 138758 876559 19827 68133 442429 661314 11750 60176 51813 76501 9560806 10261 2207 370 521 5606 517644 2455 151538 44340 51735 12385 49512 10073 1870 1582 10184 9796 2220 7043 8556 1664 228349 727 4485 382 971765 12965 5654

37/**Ulpunyali** MAS#1 FP149 3102 7733 864643 3624 1140879 665199 178705 4878 15632 16427 5988 7944 8519 238943 183678 164082 4566 3239 57 42 3632 930 504 553068 34850 107329 12644 58386 16357 3590 3802 20296 24748 5502 15900 14822 2036 4282 280 3320 75 31819 9186 7023

Appendix 2 – PCA output files

```
C:\DATA\OUT167.DOC   Analysis by MV-ARCH program BIGPCA3
Data file name C:\DATA\ALLEDX.TRA
Date 15/Feb/95   Time 16:07

C:\DATA\ALLEDX.TRA    Made from file C:\DATA\ALLEDX.DOC into MV-ARCH
file by program CSPACESV
 COVARIANCE MATRIX

Sum of PCA eigenvalues = 5600

Eigenvalues
    %2064.56889.67658.04

%
     36.87 15.89 11.75
CUM %
     36.87 52.75 64.50

PCA variable loadings
   1: 11.76 -4.28 -6.48
   2: 20.24 -1.07  0.74
   3: 17.65 -1.42  1.48
   4: 18.81 -2.46  0.82
   5:-18.87 -3.48 -1.38
   6:  0.23  7.93-12.69
   7:  5.11 14.51 -8.61
   8: -2.26 17.14 -5.93
   9: -8.59 10.43  8.52
  10: 18.83  3.59  0.93
  11:  5.90  8.85 12.11
  12:  1.06  9.11 10.96

PCA object scores
   1:  3.72 -3.10  3.62
   2:  4.10 -1.17  1.29
   3: -6.95 -2.06  4.87
   4: -9.04 -3.90  0.09
   5: -1.81  6.78 -1.02
   6: -3.79  3.88 -5.91
   7: -2.45  6.43 -0.74
   8: -2.12  3.47 -2.51
   9: -7.86  1.06  4.97
  10: -6.85  1.80  2.19
  11:  4.33 -0.86  2.81
  12:  5.41  1.92 -0.50
  13: -3.44  1.53  0.09
  14: -1.23  6.72 -0.45
  15: -5.60  4.85 -3.13
  16: -7.96  1.66 -0.06
  17: -6.10 -6.32  1.60
  18: -8.67 -2.89  0.42
  19: -0.42 -3.44 -1.74
  20:  5.65 -0.28  3.13
```

21:	6.93	-1.34	2.10
22:	4.32	-3.47	-1.35
23:	-2.31	5.15	0.33
24:	5.48	3.20	5.96
25:	6.37	5.25	5.14
26:	-8.56	-4.39	-2.07
27:	-4.13	-6.12	-1.64
28:	-6.87	0.69	2.66
29:	-4.96	3.65	2.20
30:	-7.17	1.96	-0.26
31:	3.34	6.33	-0.73
32:	1.72	-3.91	0.46
33:	5.89	1.51	0.29
34:	6.78	-2.58	0.24
35:	0.39	0.48	-3.57
36:	7.80	-5.22	-2.97
37:	6.73	-4.55	-0.08
38:	4.93	-7.37	-0.26
39:	7.25	-2.29	0.70
40:	3.88	0.93	-1.34
41:	4.39	0.37	-1.26
42:	2.04	2.13	1.62
43:	6.41	-3.96	-1.16
44:	1.40	-1.97	-0.30
45:	-7.92	-4.90	0.61
46:	1.79	-0.51	-6.20
47:	5.21	0.62	-8.07
48:	-1.91	-1.92	-7.29
49:	3.55	2.09	-6.14
50:	1.65	2.88	4.26
51:	-0.37	2.41	3.13
52:	1.08	0.37	5.77
53:	-4.24	-1.25	0.73
54:	5.69	-0.81	3.59
55:	-6.44	-6.25	-2.22
56:	2.63	-1.55	-0.94
57:	2.00	-1.54	-1.53
58:	4.46	2.63	2.07
59:	-6.30	-2.23	5.05
60:	-7.01	-4.03	1.63
61:	-1.59	3.51	-2.87
62:	-7.02	4.31	-5.10
63:	0.15	5.57	-1.00
64:	-0.49	5.56	-0.04
65:	-9.60	-1.68	-0.43
66:	3.40	-3.01	-0.04
67:	2.85	1.52	4.41
68:	1.58	-0.20	3.37
69:	8.38	-1.93	-0.57
70:	-7.38	-2.56	-0.96
71:	7.12	1.32	-0.43
72:	-3.52	0.08	0.17
73:	8.14	-1.84	-3.49
74:	1.98	-0.14	0.97
75:	1.13	2.93	-2.21

C:\DATA\OUT127.DOC   Analysis by MV-ARCH program BIGPCA3
Data file name C:\DATA\ALLICPPT.TRA
Date 09/Feb/95   Time 17:03

C:\DATA\ALLICPPT.TRA   Made from file C:\DATA\ALLICPPT.ED into MV-ARCH file by program CSPACESV
COVARIANCE MATRIX

Sum of PCA eigenvalues = 5016

Eigenvalues
%1872.47822.11502.51

%
37.33 16.39 10.02

CUM %
37.33 53.72 63.74

PCA variable loadings

1	0.29	6.86	-2.11
2	3.08	6.63	5.62
3	5.61	-0.48	2.54
4	6.90	-0.35	-0.63
5	7.10	3.37	-5.40
6	-4.24	7.33	3.75
7	-0.73	-3.80	1.31
8	0.03	5.55	-0.22
9	-1.17	4.10	2.27
10	1.05	2.44	-3.52
11	-7.50	5.26	-0.40
12	5.91	3.65	-2.83
13	7.12	2.17	-3.94
14	4.33	6.27	3.04
15	9.20	-2.22	2.42
16	2.36	-8.67	0.47
17	7.21	1.97	-4.25
18	-3.26	6.57	3.79
19	0.82	-4.08	0.71
20	-2.54	3.06	4.43
21	1.08	5.22	-1.53
22	-7.21	1.90	6.00
23	2.43	6.51	-1.14
24	8.48	3.10	-0.39
25	6.59	4.48	-0.28
26	8.44	3.30	1.24
27	9.22	2.66	1.43
28	9.73	1.96	1.84
29	10.11	0.73	2.20
30	9.77	0.04	2.99
31	10.16	-0.48	2.33
32	10.17	0.14	2.42
33	10.03	-0.99	2.50
34	9.68	-2.05	2.41
35	9.29	-2.85	2.35
36	8.60	-4.39	2.40
37	7.98	-5.31	2.34
38	2.35	-8.78	0.24

39	6.95	3.41	-5.98
40	-2.92	3.36	6.43
41	3.21	6.86	-4.78
42	-3.63	4.07	3.31
43	7.36	2.08	-4.57
44	1.94	2.23	8.55

PCA object scores

1	-3.32	0.92	-5.64
2	2.76	-2.21	7.94
3	-1.15	1.08	7.74
4	-5.00	4.68	0.95
5	-8.13	4.77	1.57
6	-0.82	4.73	0.61
7	-11.92	3.09	3.11
8	11.94	1.58	3.07
9	10.66	1.92	1.83
10	-8.48	3.00	-1.92
11	-7.81	4.93	-2.91
12	-7.69	7.20	1.22
13	-12.25	5.47	0.60
14	-3.54	0.83	5.17
15	9.23	-0.00	3.70
16	10.13	1.08	4.28
17	-0.46	0.73	-6.63
18	0.35	4.50	1.32
19	5.27	3.39	-6.56
20	6.24	0.81	-4.84
21	6.43	2.38	-3.52
22	4.93	-3.86	-2.64
23	8.14	-2.84	-3.24
24	5.70	-4.44	0.53
25	8.47	3.21	0.90
26	5.69	-6.49	-1.87
27	0.49	1.65	-6.11
28	-7.12	-1.50	-1.81
29	0.35	1.20	-0.73
30	-12.43	-0.61	1.24
31	6.60	3.70	-3.26
32	-7.70	-12.70	2.39
33	-6.99	-11.34	-2.23
34	-0.31	-9.29	-1.79
35	-3.88	-6.33	3.21
36	-4.12	-6.57	-0.63
37	9.75	1.34	4.95

C:\DATA\OUT128.DOC   Analysis by MV-ARCH program BIGPCA3
Data file name C:\DATA\ALLICPPT.TRA
Date 09/Feb/95   Time 17:53

C:\DATA\ALLICPPT.TRA   Made from file C:\DATA\ALLICPPT.ED into MV-ARCH file by program CSPACESV
COVARIANCE MATRIX

Sum of PCA eigenvalues = 26

Eigenvalues
10.37 6.38 3.34

%
39.57 24.36 12.73

CUM %
39.57 63.93 76.65

PCA variable loadings

```
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 13:  0.96 -0.23 -0.06
 14:  0.03 -0.40  0.48
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 21: -0.24  0.64  0.30
 22: -0.48  0.06  0.24
 23: -0.55  0.17  0.04
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 25:  0.03  0.48  0.39
 26: -0.63 -0.16 -0.03
 27: -0.38  0.36 -0.39
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 29:  0.12 -0.08  0.38
 30:  0.87 -0.42 -0.27
 31: -0.25  0.65 -0.37
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 33: -0.73 -0.87 -0.30
 34: -0.79 -0.64 -0.50
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 36: -0.53 -0.37  0.29
 37:  0.06  0.37  0.18
```

G96/5222 - Further characterisation and sourcing of archaeological ochres

Report to AIATSIS (2003)

M.A. Smith and B.L. Fankhauser

Introduction

The prospect of being able to examine prehistoric trade, customary exchange systems, social boundaries and regional inter-connections has attracted some notable studies of the distribution and petrology of ground-edge axes and grindstones (Binns and McBryde 1972; McBryde 1987) and of pearl shell and baler shell (Akerman and Stanton 1994; Mulvaney 1976). Although prehistorians have long recognised the potential for similar work on red ochre (Clarke 1976; Mulvaney 1976) it attracted little sustained interest until the mid 1990s.

The major barrier to geochemical sourcing of ochres appears to have been instrumental. Standard XRD or XRF techniques either require too large a sample to be practical for many archaeological specimens, or are not sufficiently sensitive to measure minor and trace components, or are too labour intensive to analyse for the number of elements initially required to determine the best means of characterising individual sources. The ready availability of quantitative analytical techniques such as Rietveld XRD QPA, NAA, PIXE/PIGME, FTIR, ICP/MS and SEM/EDXA has transformed this situation, as recent studies by several research groups show (David et al 1993, 1995; Ford et al 1994; Goodall et al 1996; Smith et al 1998; Smith and Fankhauser 1996; Smith and Pell 1997). Most importantly this work shows that the major ochre deposits can be distinguished from one another on their geochemical and mineralogical signatures (see especially Smith and Fankhauser 1996 - G94/4879).

The current project

The current project builds on a previous study by Smith and Fankhauser, G94/4879 *'An archaeological perspective on the geochemistry of Australian red ochre deposits: Prospects for finger-printing major sources'*. In particular it set out to:

- extend the database of geochemical data on Australian ochre sources
- further investigate the variability of selected sources (eg. Wilgie Mia)
- extend the study to include a range of archaeological case studies document the history of the major ochre quarries (eg. Wilgie Mia, Bookartoo and Toolumbunner).

Results from our first phase of research into the characterization and sourcing of red ochres (reported in G94/4879) showed that geochemical provenancing red ochres is both possible and useful in archaeological contexts. Small archaeological specimens (<lg) present no particular difficulty for analysis. However, the utility of any sourcing project depends on the number of potential sources included in the database. Ideally, all major ethnographic ochre sources would be included as well as a wide range of other potential sources. Also, in ideal circumstances, each source would be characterized by multiple samples (to give a measure of internal variability in each source) and by multiple analyses (to test instrumental replicability). Phase II of the ochre project (G96/5222) therefore focussed on extending the ochres database to ensure that it included the major Australian red ochre quarries and a range of regional sources.

Our previous research had shown that an assemblage of archaeological ochres from known-age contexts (eg from Puritjarra rockshelter in central Australia) could be used to investigate the history of particular ochre mines (in this case, the Karrku and Ulpanyali mines). In the current study we aimed to extend this work to the Wilgie Mia, Bookatoo and Toolumbunner mines by analysing assemblages of ochres excavated from archaeological sites within the potentail distribution area of these quarries. The aim was to see if we could identify any of these ochres in dated archaeological context.

The samples.

The ochres analysed in phase II of the ochres project are listed in below.

Table 1 - Ochres analysed in Stage II

Wilgie Mia	Two samples from I.M. Crawford's excavations at Wilgie Mia ochre quarry, Weld Range, WA. (Additional samples to determine intra-source variability).
Gara Widgie	Gara Widgie may be Little Wilgie Mia, an important ochre source, adjacent the main Wilgie Mia ochre body.
Tirnu	Two samples: one from a lateritic ochre outcrop and the other a ground/utilised piece found near the ochre outcrop in the Great Sandy Desert.
Karrku	Two samples from different parts of ochre seam at this major central Australian ochre mine. (Additional samples to determine intra-source variability).
Bloodstone Pt	Sample from lateritic outcrop on Maria Island, Tasmania. To be compared with other lateritic sources.
Dial Range	Sample from an ochre source in western Tasmania (To be compared with previously analysed sample).
Toolumbunner	A major ethnographic ochre mine in the Gog Range, northern Tasmania.
Sisters Creek	An archaeological specimen attributed to the Mt Housetop quarry, Tasmania.
Northdown	An archaeological specimen attributed to the Mt Housetop quarry, Tasmania.
Moana	Ochre quarry on coast, south of Adelaide, South Australia. (To be compared with previously analysed samples).
Overland Corner	An ethnographic ochre source along the Murray River, South Australia. (Additional samples to characterise quarry).
Puntutjarpa	Archaeological ochres dated <400 - 3000 years BP from Puntutjarpa rock shelter, excavated by R. A. Gould. (To test for presence of ochre from Wilgie Mia).
Serpent's Glen	Archaeological ochres from the excavation by S. O'Connor and Peter Veth (To test for presence of ochre from Wilgie Mia).
Kaalpi	Archaeological ochres excavated at a rockshelter in the Calvert Range by P. Veth and M. Smith. (To test for possible match with Tirnu and Wilgie Mia ochres).
Kirriwiri	Ochre samples from an archaeological site in the Great Sandy Desert. Attributed to a source south of Percival Lakes. (Test for match with archaeological ochres at Puntutjarpa and Kaalpi).
Kurtararra	Ochre from an archaeological site in the Great Sandy Desert. (Test attribution to Tirnu source).
Arkaroo Rock	Archaeological ochres dating from 6000 BP to present. Site is closest excavated site to Bookartoo ochre quarry in the Flinders Ranges, South Australia. (To test for presence of ochre from Bookartoo).

Carpenters Gap	Ochre samples from an archaeological site in the Napier Ranges, Kimberly, Western Australia, excavated by Dr S O'Connor. These samples are for comparison with pigment on a rock surface and in-situ analysis of rock paintings.
Djibitgun	An ochre source near Jinmium, in the Keep River region, NT.
Jinmium	Archaeological ochres from the Jinmium site.
Hunter Valley	High quality archaeological ochres from sites in the Hunter valley.

Ochre sources: Additional samples were analysed as a check on intra-source variability in elemental composition of several ochre formations: eg Dial Range, Karrku, Moana, Overland Corner and Wilgie Mia. Other samples represent new sources added to the ochre database: eg. Bloodstone Point, Mt Housetop, Toolumbunner, Tirnu, Gara Widgie and Djibitgun.

- Toolumbunner: The Toolumbunner ochre mine in the Gog Range, Tasmania, is described by Sagona in *Bruising the Red Earth: Ochre mining and ritual in Aboriginal Tasmania.* The two samples analysed were supplied by Dr John Webb (Latrobe University). Both are from Sagona's Excavation Site B at Toolumbunner.

- Bloodstone Point: This is a lateritic ochre source on Maria Island, Tasmania.

- Mt Housetop: This is a high-grade source of specular haematite in northern Tasmania. The actual source no longer exists. The samples analysed are from archaeological sites nearby (Sisters Creek, and Northdown) and were supplied courtesy of Dr John Webb.

- Tirnu: During fieldwork in the Great Sandy Desert in 1996, one of us (MAS - in collaboration with Dr Peter Veth) collected red ochre samples from an ethnographic ochre source at Tirnu - essentially a lateritic surface where ochre was obtained by Martujarra people.

- Gara Widgie: This is an otherwise unidentified Western Australia ochre deposit. The sample analysed was supplied by Dr John Webb from museum samples held in Tasmania and Victoria. The WA Aboriginal Sites department has no record of Gara Widgie but our working assumption was that it was associated with the Wilgie Mia deposit (possibly the 'Little Wilgie Mia' deposit, given that *gara* = little).

- Djibitgun: This is an outcrop of red ochre in the vicinity of the Jinmium site in the Keep River. Samples were provided by Dr R. Fullagar.

Archaeological ochres: In stage 2 of the ochre project we attempted to expand our analysis to look at archaeological sequences which might give an indication of the history of major ethnographic ochre mines, in particular Wilgie Mia in the Weld Range WA, Bookartoo in the Flinders Ranges SA, Toolumbunner in the Gog Range, Tasmania, and Mt Housetop in the same region. In each case, we examined assemblages of archaeological ochres from excavated sites within the likely distribtion area of each quarry.

- For Wilgie Mia, we analysed archaeological ochres from Kaalpi, Kirriwiri, Kurtarrara, Puntutjarpa, and Serpent's Glen.

- For Bookartoo, we analysed ochres from Arkaroo Rock.

- For Toolumbunner and Mt Housetop, we analysed ochres from Kuitkina Cave.

Methods

The methods used in Stage II were consistent with those in our earlier Stage I report. A wide range of samples were analysed by energy dispersive x-ray analysis (EDXA) to determine major and minor elements. A smaller but representative series of ochres were analysed in more detail using inductively coupled plasma with mass spectrometry (ICP/MS) analysis to determine trace element composition.

Standards for inter-laboratory comparison were prepared. In this case, we selected two ochre source samples (#67979 from Bookartoo and #6 from Karrku) which have quite different elemental compositions. Multiple aliquots from the ~20 g batches have been analysed by EDXA and ICP/MS. These standards are included in all our analytical runs and can be made available to other laboratories undertaking ochre analyses – to ensure comparability between analyses.

ICP/MS is a very sensetive analytical technique (determining trace elements in ppb) and we took the precaution of testing to see if sample preparation using conventional Retsch Milling to finely pulverise samples actually contaminated the samples. Samples of acid-washed sand which pulverised in either a mortar and pestle (the control) or a Retsch MW were submitted for trace element analysis by IMMS to determine to what extent zirconium oxide from the Retsch MW might contaminate ochre samples. We established that processing in a Retsch MW does lead to artificially elevated trace levels of zirconium and have taken this into account in subsequent multivariate analysis of ochre composition.

Table 2 provides a breakdown of the analyses carried out in stage II of the project.

Table 2 - Number of ochre samples by analytical method (EDXA and ICP/MS)

Ochre samples	EDXA #analyses	ICP/MS #analyses
<u>Ochre sources</u>		
Bloodstone Pt TAS	2	1
Dial Range TAS	3	1
Gara Widgie WA	2	1
Hunter Valley NSW	14	0
Karrku NT	3	2
Moana SA	4	0
Northdown TAS	2	1
Overland Corner SA	5	2
Tirnu WA	12	2
Toolumbunner TAS	4	2
Sisters Creek TAS	2	1
Wilgie Mia WA	4	2
Djibitgun NT	5	1
<u>Archaeological ochres</u>		
Arkaroo Rock SA	14	3
Carpenters Gap WA	31	0
Jinmium NT	4	1
Kaalpi WA	4	2
Kirriwiri WA	10	0
Kurtararra.WA	3	1

Serpent's Glen WA	22	4
Puntutjarpa WA	10	3
Total	**160**	**30**

Results

Although little is known about the diagenesis of red ochre deposits a review of major sources suggests a broad division as shown here in Table 3. Sagona and Webb (1994) distinguish three types of red ochre in Tasmania on petrology:- specular vein haematite, beds of ferruginised sandstone, and ochres that originate in laterite. This is in line with our own thinking on the matter. EDXA results generally provide a good breakdown by type of ochre, but rarely allow individual sources to be identified.

In Table 3 we also show how the ochres sources in our database are classified by diagenesis.

Table 3 Types and diagenesis of red ochre deposits

Ochre in veins or lodes	a) vein haematite of hydro-thermal origin	Mt Housetop
	b) sedimentary infill in joints and fractures	Bookartoo Karrku
Beds of ferruginised sandstone (often formed by weathering of iron sulphides in marine sediments)		Toolumbunner; Ulpunyali Dial Range Moana Lawa
Weathering products	a) lateritic ochres (formed by concentration of metal oxides after other minerals have been leached out).	Tirnu Bloodstone Point Gara Widgie
	b) super gene enrichment (eg. gossans - where an existing deposit of metal oxides is enriched by material leached from elsewhere)	Wilgie Mia

Vein haematite appears to be comparatively rare - though the Mt Housetop source in Tasmania is specular vein haematite (Sagona and Webb 1994) and several of the ground haematite pieces excavated from Kutikina Cave in Tasmania are almost certainly of vein haematite. Several of the regional sources appear to be of lateritic origin, perhaps because this type of ochre is widespread and readily available. Many of the major ethnographic ochre sources appear to be sedimentary in origin, either ferruginised beds in marine sandstones of Palaeozoic age or sedimentary infills in joint lines.

- <u>Bookartoo</u>: Our analyses confirm that this ochre is very distinctive as it has unusually high concentrations of V (>1,002,700 ppb) and of Zn (>122,600 ppb). The latter is presumably from the sphalerite (ZnS) formed during diagenesis of this deposit (see Keeling 1984). Any haematite rich, fine-grained dark pink or purple ochre with major carbonate content (either calcite or dolomite) and very high trace levels of vanadium could be from Bookartoo and further analyses should be undertaken with this possibility in mind.

- Wilgie Mia: Most Wilgie Mia samples analysed here have moderate Zr/Ti and high U/Ti ratios. Some samples have anomalously high Ti (A+A) (5,139,280 ppb) or high Zr (N-2A) (28,642,279 ppb). Wilgie Mia however is very variable across the deposit and it appears that that discrete beds within banded iron formations may represent separate physical and chemical facies. This obviously complicates the task of characterising Wilgie Mia ochre and requires further attention.

- Karrku and Ulpunyali: The two Central Australian quarries west of the MacDonnell ranges both have a high proportion of Lanthanide elements. These are most likely a weathering product and may be characteristic of sources in the interior.

Archaeological case studies

Arid zone sites and Wilgie Mia. We analysed ochres from several archaeological sites a) where ochre ochre was stratified within a dated cultural sequence and b) where the site might be expected to have received ochre from Wilgie Mia as part of 'down-the-line' exchange in the past. None of assemblages examined provided any definite evidence of Wilgie Mia ochre – and hence no indications of the antiquity of this mine. Further work should focus on Walga Rock the nearest excavated site to the Weld Range (which we were not able to examine).

- Kaalpi (see attached publication). Kaalpi rockshelter was excavated by Peter Veth and Mike Smith in 1996. Analysis of the ochres showed that all are derived from lateritic sources. The chemistry rules out a close match with a known source at Tirnu – to the north near the Percival Lakes - but other possibilities lie to the east of the Calvert Ranges. The age of the major horizon containing ochre in the shelter deposits was established by a series of 14C dates (obtained under this grant) as ranging from 1300 BP.

- Puntutjarpa The Western Australian Museum loaned us 8 ochre samples excavated from the Puntutjarpa site by RA Gould between 1968-70. On hand examination, 4 types of ochre appeared to be present. (A19523 - bright red lateritic ochre; A19300- dark red ochre with some geothite clots; A19801 - fine-grained friable red ochre; A19636 and A20839 - dark red fine-grained ochre, representing the most common type of ochre in the Puntutjarpa samples). EDXA and ICP/MS analyses indicated that all of these ochres were lateritic ochre, and most were from from one source (not represented in our database). None of the Puntutjarpa ochres are from Wilgie Mia.

- Kurtararra This is an open site near a spring on the northern side of the Percival Lakes. Radiocarbon dating of associated baler shell (this grant) indicates the site has been used intermittently for at least 2 millennia. Surface remains include fragments of red ochre. One specimen of high-grade red ochre was submitted for analysis. This appears to be from a deeply weathered sedimentary source, with a similar diagenetic history to Karrku. There was no definite match with any of the sources in our database. However, the sample is not a lateritic ochre like Tirnu, nor a supergene ochre from Wilgi Mia.

- Serpents Glen Serpents Glen is an important late Pleistocene site in the Carnarvon Range in the Western Desert. Several archaeological specimens of red ochre were supplied by Dr Sue O'Connor. Analysis showed that none of these closely matched material from Wilgie Mia. Three speciments were from the same source of high-grade red ochre – probably from a sedimentary lode. The closest match in our sample was with the archaeological specimen from Kurtarrarra. One specimen (SG219) is quite different to any other ochre in our database and we were unable to suggest a diagenetic classification.

Sites near Bookartoo

- Arkaroo Rock. Excavations at Arkaroo Rock in the Flinder Ranges by Dr Neale Draper provided an excellent opportunity to look for Bookartoo ochre in dated context. This site has occupation deposits spanning the last 6000 years and the excavations have recovered a large assemblage of ochre pieces. Also, local Aboriginal people are said to have identified some archaeological ochres during excavation as Bookartoo ochre. Hand examination suggested that there several different groups of ochres represented in the assemblage. None seemed a good match to Bookartoo ochre but for ICP/MS analysis we chose those specimens we felt *most likely* to provide a match.
  1. H5/4/6 and I6/4/7a. These samples superficially resembled Bookartoo ochre
  2. I6/4/7 and H6/1/7/2. These were identified by Aboriginal people as Bookartoo ochre (but bore little resemblance even on hand examination)
  3. I6/4/8. This is the oldest sample of high-grade red ochre at the site and the only specimen of this quality in the assemblage.

  Our analysis indicated that none of these specimens are Bookartoo ochre. One of the specimens (#49 a purple ochre, I6/4/7a) is clearly from an unidentified lateritic source. Another (#48, H6/1/7/2) is not definitely an ochre. The oldest excavated ochre this site (#50, I6/4/8) is a high-grade red ochre from a sedimentary source. This could could not be matched with any in our database – but the closest match (because of the rare earth content) was with red ochre from Karrku.

Tasmanian sites

- Kutikina We compared excavated ochres from the late Pleistocene site of Kutikina (supplied by the Late Rhys Jones) with several Tasmanian ochre sources in our database: Toolumbunner, Mt Housetop; Bloodstone Point and Dial Range. Our results indicate that the excavated ochres in the Kutikina assemblage form two groups. Three specimens are a ferruginised sandstone, matching the control samples from the Toolumbunner mine and are likely to have been derived from this or a similar source (To confirm this possibility, more information on regional geology, and on the mineralogy of these ochres would be necessary). The fourth sample is a high-grade red ochre from a sedimentary lode or vein haematite – but not closely matching the Mt Housetop source.

Jinmium

- Jinmium. We compared an archaeological specimen excavated from Jinmium by R. Fullagar and compared it with samples that he provided from Djibitgun a nearby ochre source. Both samples are vein haematite but their chemistry is not consistent with the same source, even allowing for some degree of intra-source variabilty.

Radiocarbon dating

As a supplementary grant to G96/5222, AIATSIS provided funds for a series of radiocarbon dates for sites in the Great Sandy Desert. These provide chronological context for our analysis of archaeological ochres from this region (see tables 4 and 5).

- From sites in the *Warla*-salt lake country around the Percival Lakes (*Kiriwirri*; *Yurlpu* and *Kutararra*), P. Veth and M. Smith collected 5 samples of baler shell, which must have originated either on the Pilbara or Kimberley coast and have been traded into the heart of the desert. Dating of these samples provides not only the first series of dates for sites in the *Warla* country and some indication of the antiquity of currently visible evidence of site use but also provides a) significant first order dating of regional exchange of baler shell between the coast and desert interior and b) an indication of the age of the ochres collected from these sites.

- From a small archaeological excavation at *Kaalpi*, a rock shelter site in the Calvert Range (south of Lake Disappointment) P. Veth and M. Smith collected a series of charcoal samples to date critical points of change in the archaeological sequence at this site. The excavation at *Kaalpi* recovered an assemblage of red ochre most of which dates after 1300 BP

Table 4 – Radiocarbon dates on baler shell for sites in the Percival lakes area

Site/Sample	Laboratory code	Sample size (g.)	Radiocarbon age (yrs BP)	Age with Oceanic reservoir correction
Kiriwirri #1	Wk5638	**9.0**	**500±70**	**50 BP**
Kiriwirri #2	Wk5639	**3.0**	**660±150**	**210 BP**
Kurtararra Well #1	Wk5640	**1.0**	**2710±280**	**2260 BP**
Kurtararra Well #2	Wk5641	**8.0**	**1220±90**	**770 BP**
Yurlpu	Wk5642	**16.0**	**2270±60**	**1820 BP**

All samples are marine shell, identified as Melo sp . All samples were analysed by XRD and found to be aragonite.

Table 1: Radiocarbon age determinations (uncalibrated) from *Kaalpi* excavation.

Wk No.	Square	Spit	Years BP	Unit	Depth bsl
Wk-5643	W5	4	210±50	1	8-9 cm
Wk-5644	W6	8	970±60	2	23-25 cm
Wk-5645	W6	10	1,310±60	2	28-30 cm
Wk-5646	W5	14	2,175±78	3	34-39 cm
Wk-4966	W6	14	2,270±80	3	42-46 cm

Conclusions

Our results show that a systematic program of provenancing archaeological ochres has great potential in Australia. Major ochre sources often have distinctive chemical fingerprints, particularly if a range of analytical techniques are used in conjunction to characterise ochres. Ochre is frequently found in both late Pleistocene and Holocene contexts, often in sufficient quantity to permit systematic study of temporal changes in prehistoric systems. As this work develops we feel that it will be important to build up consolidated data files of compositional data for Australian ochres. This will allow unknown ochres to be rapidly compared with known sources on file using multivariate methods. In this study compositional data for each sample is stored as a computer data-file. As this file is added to and updated it will provide the basis for identifying unknown ochres. We have also archived a portion of all ochres we analyse to allow samples to be re-run as analytical techniques improve. Our work-to-date also suggests some cautions:

- To characterise individual sources it will be safest to use more than one analytical method in conjunction. Data on major element or oxide composition is useful for confirming that a sample is actually an ochre but otherwise will only give information on the geological environment of the ochre rather than identify specific sources.

- For most archaeolgical applications, a program of characterising regional sources will be necessary to provide the basis for positively matching archaeological ochres to sources.

Appendices

Appendices 1 and 2 are files of compositional data for the ochres analysed in this project.

Appendix 1 Major and minor oxides (%). This tabulates the results of all EDXA analyses carried out in 1997. Samples from Smith and Fankhauser (1996) were reanalysed for comparison.

Appendix 2 Trace elements (ppb) This tabulates all ICP/MS results (including our 1996 data).

Appendix 1: Major and minor oxides (%) determined by EDXA

	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Mn	Fe
104	0.48	0.84	0.95	3.68	0.01	0.10	0.11	0.13	16.54	0.04	0.09	24.93
4	0.52	0.78	0.93	3.73	0.04	0.09	0.07	0.12	17.14	0.16	0.11	26.75
105	0.48	2.81	0.88	3.53	0.05	0.06	0.00	0.14	7.40	0.05	0.20	36.95
5	0.51	2.73	0.87	3.42	0.07	0.03	0.00	0.17	7.73	0.09	0.20	38.36
6	0.39	0.36	1.07	4.05	0.03	0.33	0.05	0.29	15.72	0.07	0.25	28.82
106	0.21	0.37	1.11	3.92	0.00	0.00	0.00	0.21	14.83	0.05	0.05	29.60
107	0.63	0.10	0.40	2.07	0.03	0.15	0.12	0.02	0.70	0.01	0.00	57.95
7A	0.65	0.08	0.41	1.71	0.00	0.16	0.06	0.07	0.72	0.06	0.00	59.19
7B	0.69	0.12	0.42	2.01	0.03	0.27	0.03	0.12	0.70	0.05	0.04	60.02
110A1	0.42	0.46	1.12	5.96	0.04	0.11	0.04	0.29	10.39	0.00	0.03	33.27
110A2	0.42	0.44	1.27	5.43	0.06	0.13	0.03	0.25	10.22	0.08	0.00	35.45
110B1	0.40	0.49	1.26	6.00	0.00	0.09	0.07	0.28	10.57	0.00	0.15	33.68
10	0.36	0.48	1.24	5.67	0.06	0.13	0.00	0.32	10.98	0.07	0.08	34.59
111	0.19	0.13	0.69	2.63	0.04	0.04	0.09	0.10	14.63	0.14	0.01	32.11
112	1.01	1.73	1.13	7.50	0.13	0.08	1.27	0.25	2.89	0.17	0.16	42.66
113	0.18	0.92	0.56	1.75	0.03	0.16	0.05	0.06	4.53	0.00	0.33	50.22
114	0.30	0.67	0.43	1.40	0.00	0.00	0.16	0.05	0.81	0.02	0.00	59.22
101	0.31	0.12	9.31	19.17	0.00	0.18	0.05	0.24	0.27	0.32	0.00	15.86
1A	0.34	0.10	9.87	19.38	0.00	0.13	0.01	0.21	0.10	0.32	0.00	16.74
1B	0.27	0.09	9.72	19.20	0.04	0.13	0.04	0.20	0.12	0.30	0.11	17.48
102A	0.78	0.11	0.87	1.16	0.07	0.03	0.16	0.01	0.08	0.07	0.05	59.75
102B	0.65	0.02	0.79	1.04	0.10	0.05	0.22	0.05	0.12	0.07	0.00	61.15
2	0.63	0.08	0.98	1.21	0.02	0.05	0.18	0.09	0.10	0.12	0.00	61.76
103	0.49	0.13	0.90	1.04	0.06	0.05	0.08	0.00	0.07	0.02	0.02	59.78
3	0.58	0.14	1.00	1.08	0.00	0.02	0.00	0.00	0.07	0.02	0.01	60.71
115A	0.25	0.03	1.79	1.93	0.06	0.00	0.07	0.00	0.05	0.03	0.00	59.07
115B	0.19	0.10	0.44	0.40	0.03	0.01	0.08	0.01	0.29	0.03	0.00	63.69
138	0.23	0.07	0.45	0.70	0.15	0.01	0.09	0.02	0.10	0.00	0.00	59.92
150	0.34	0.30	14.74	12.56	0.26	0.14	0.92	0.56	0.37	0.11	0.02	18.38
8	0.37	0.30	6.43	15.55	0.15	0.21	0.05	2.86	0.10	0.16	0.00	30.67
108	0.42	0.33	6.57	15.08	0.13	0.15	0.07	2.76	0.10	0.21	0.00	28.87
9	0.40	0.31	6.75	18.10	0.14	0.11	0.05	3.09	0.37	0.27	0.10	24.08
109	0.26	0.26	6.13	17.91	0.11	0.14	0.04	2.86	0.28	0.11	0.04	21.16
116	0.14	0.19	1.38	11.60	0.10	0.08	0.00	0.55	0.11	0.10	0.02	45.32
117A	0.16	0.23	3.78	28.72	0.21	0.20	0.12	0.67	0.16	0.13	0.00	12.88
117B	0.06	0.19	4.29	26.21	0.24	0.18	0.11	0.75	0.21	0.22	0.00	14.03
149A	0.07	0.27	2.72	17.14	0.10	0.16	0.02	0.52	0.23	0.17	0.01	34.47
149B	0.18	0.27	2.43	18.85	0.13	0.12	0.01	0.46	0.22	0.13	0.03	34.71
118A	0.07	0.08	9.32	17.03	0.05	0.07	0.02	0.12	0.18	0.59	0.10	21.72
118B	0.09	0.17	0.68	2.09	0.03	17.36	0.20	0.18	22.12	0.00	0.26	8.51
119	0.70	0.65	7.35	20.24	0.00	0.12	0.38	3.26	0.13	0.47	0.00	19.94
120	2.98	0.71	7.79	24.03	0.00	1.58	0.06	2.34	1.17	0.36	0.00	3.34
121	0.22	0.00	0.28	1.01	0.04	0.05	0.01	0.00	0.09	0.03	0.19	60.29
122	0.16	0.07	1.73	3.74	0.14	0.02	0.00	0.23	0.14	0.00	0.00	56.30
123A	0.39	0.19	0.66	3.29	0.00	0.03	0.26	0.06	0.49	0.07	0.00	57.48
123B	0.39	0.34	1.03	4.79	0.00	0.06	0.30	0.11	2.62	0.07	0.02	50.58
124	0.41	0.19	0.66	4.57	0.01	0.04	0.21	0.01	0.37	0.00	0.19	56.36
125	0.51	1.03	4.66	11.14	0.11	0.09	0.45	2.76	1.27	0.19	0.58	33.31
126	0.15	0.02	4.48	12.29	0.01	0.13	0.00	0.43	0.13	0.34	0.08	36.43
127	0.31	1.13	6.45	20.38	0.02	0.04	0.12	4.53	0.09	0.34	0.08	19.17
128	0.16	0.64	7.69	20.20	0.08	0.06	0.03	2.61	0.08	0.36	0.00	20.21
129	0.06	0.24	0.57	6.83	0.10	0.01	0.02	0.27	29.09	0.01	0.00	2.27
130	0.08	0.15	9.61	20.82	0.29	0.00	0.05	0.86	0.03	0.54	0.12	14.36
131	0.16	0.11	10.35	13.22	0.59	0.12	0.01	0.84	0.07	0.58	0.02	25.47
132	0.06	0.05	4.42	21.19	0.47	0.06	0.01	0.37	0.08	0.32	0.00	23.32
133	0.27	0.11	6.72	25.45	0.41	0.06	0.04	0.71	0.13	0.49	0.02	10.36
134A	0.24	0.22	2.11	19.58	0.83	0.04	0.20	0.73	2.31	0.26	0.05	28.52
134B	0.07	0.16	2.13	18.81	0.87	0.10	0.20	0.60	2.42	0.25	0.09	29.36
135	0.29	0.39	3.32	10.86	0.23	0.08	0.43	0.54	2.79	0.22	0.00	39.06
136	0.12	0.08	5.06	24.26	0.84	0.00	0.09	0.54	0.17	0.47	0.02	15.43
137	0.16	0.11	6.88	9.09	0.00	0.05	0.03	0.76	0.26	0.26	0.06	38.13
139	0.20	0.50	3.27	10.01	0.64	0.00	0.02	0.95	0.51	0.13	0.11	40.16
140	0.06	0.86	3.50	10.76	0.19	0.00	0.00	1.38	11.56	0.34	0.09	19.55
141	0.10	0.33	1.53	5.08	0.51	0.00	0.01	0.24	0.43	0.05	0.17	51.81
142	0.23	0.65	4.42	10.59	2.38	0.02	0.03	1.67	4.84	0.17	0.19	30.37
143	0.33	0.08	1.69	7.96	0.03	12.73	0.07	1.15	11.82	0.17	0.01	14.76
144	0.30	0.02	0.92	7.63	0.11	11.12	0.10	0.63	10.02	0.07	0.05	22.49
145	2.27	0.05	0.12	6.89	0.12	11.34	0.15	2.26	0.04	0.50	0.10	29.52
146	0.32	0.18	0.36	9.27	0.26	0.07	0.08	0.04	0.11	0.00	0.01	45.06
147	0.09	0.15	13.23	12.73	0.17	1.36	0.12	0.84	0.18	0.11	0.00	18.03
148	0.14	0.02	0.51	1.35	0.06	0.04	0.01	0.01	0.05	0.12	0.10	57.85
FP143	0.45	0.10	1.47	7.31	0.13	13.21	0.08	0.79	11.80	0.06	0.00	16.20
FP140	0.07	0.87	3.30	9.96	0.23	0.03	0.02	1.18	9.27	0.23	0.06	15.16
FP142	0.19	0.67	4.61	11.41	1.59	0.04	0.02	1.76	2.95	0.21	0.19	32.75
OCH A47	0.17	0.54	1.44	2.49	0.07	0.13	0.13	0.67	19.37	0.07	0.02	22.91
OCH #6	0.18	0.28	6.32	14.66	0.25	0.10	0.10	2.61	0.19	0.17	0.03	30.19
OCH 67..	0.14	2.50	0.91	3.52	0.09	0.05	0.04	0.18	7.29	0.02	0.18	39.19
S140	0.13	0.37	1.51	1.74	0.09	0.16	0.16	0.57	15.90	0.12	0.04	32.19

S141	0.12	0.38	2.12	4.70	0.21	0.11	0.27	0.86	0.34	0.12	1.64	48.94
S142A	0.10	0.29	1.28	3.98	0.02	0.06	0.20	0.72	28.74	0.11	0.04	7.55
S143A	0.03	0.62	0.83	1.70	0.06	0.04	0.07	0.55	33.36	0.12	0.16	1.88
S144	0.13	0.73	2.93	7.93	0.14	0.06	0.04	1.27	20.44	0.13	0.13	12.12
S145	0.21	0.25	3.00	5.80	0.45	0.10	0.22	1.48	0.37	0.14	0.29	47.47
S146A	0.13	0.60	10.14	24.74	0.06	0.07	0.16	2.63	1.01	0.58	0.03	5.73
S147	0.14	0.36	1.71	1.73	0.08	0.09	0.12	0.35	9.48	0.10	0.06	42.15
S148A	0.77	0.49	15.96	19.47	0.03	0.05	0.05	5.83	0.11	0.23	0.03	4.12
S149	0.11	0.63	1.24	2.22	0.15	0.11	0.14	0.45	21.97	0.05	0.05	20.84
F153	0.00	3.89	0.65	2.32	0.02	0.02	0.07	0.09	8.39	0.04	0.14	28.67
F156	0.10	0.32	3.84	13.52	0.26	0.20	0.14	0.87	0.25	0.19	0.03	29.28
F178	0.11	0.81	4.08	18.07	3.47	0.00	0.05	1.69	0.17	0.29	0.05	9.39
F179	0.06	0.18	0.35	18.68	0.31	0.07	0.05	0.08	0.26	0.08	0.29	28.52
F180	0.08	0.78	0.20	0.51	0.02	0.25	0.12	0.14	7.17	0.01	0.01	0.39
F181	0.57	1.70	8.21	23.61	0.06	0.06	0.06	4.25	0.16	0.45	0.00	6.21
F182A	0.04	0.32	3.10	8.89	0.30	0.00	0.09	0.94	0.06	0.16	0.25	41.31
F182B	0.06	0.64	4.00	10.00	0.18	0.04	0.05	1.83	0.12	0.13	0.20	38.75
F183	0.13	0.11	12.01	12.78	0.06	0.02	0.08	0.08	0.13	0.15	0.03	21.44
F184	0.02	0.30	3.14	15.88	2.11	0.00	0.09	0.82	0.12	0.95	0.05	22.33
F185	0.00	0.28	3.02	25.31	2.93	0.00	0.08	0.51	0.21	0.19	0.03	6.00
F186	0.01	0.06	2.13	24.96	1.16	0.00	0.08	0.20	0.24	0.20	0.03	18.09
F187	0.00	0.14	1.98	26.67	2.72	0.00	0.10	0.23	0.10	0.31	0.04	11.72
F188	0.03	0.12	6.62	23.28	0.98	0.00	0.03	1.26	0.11	1.11	0.07	11.07
F189	0.70	0.22	9.86	11.11	0.05	0.15	1.06	0.10	0.08	0.31	0.03	25.96
F190	0.06	0.01	0.38	0.62	0.01	0.00	0.03	0.01	0.01	0.00	0.06	60.95
F191	0.04	0.05	0.18	0.31	0.01	0.01	0.04	0.02	0.00	0.00	0.01	60.67
F192	0.02	0.38	6.56	25.38	0.06	0.04	0.12	3.25	0.00	0.38	0.02	10.94
F193	0.11	0.15	3.67	8.35	0.32	0.05	0.09	0.85	0.02	0.11	0.09	43.08
F194	0.02	0.06	6.75	13.84	0.63	0.00	0.07	0.30	0.10	0.29	0.03	23.66
F195	0.00	0.35	1.39	25.65	5.24	0.00	0.06	0.21	0.02	0.20	0.01	4.52
F196	0.23	0.11	14.38	17.32	0.13	0.02	0.13	0.13	0.07	0.79	0.04	8.16
F201	0.04	0.09	1.00	3.94	0.75	0.00	0.04	0.11	0.04	0.06	0.04	53.20
F202	0.07	0.02	0.33	2.99	0.23	0.00	0.05	0.00	0.03	0.01	0.08	56.80
F203	0.12	0.85	1.20	1.80	0.16	0.03	0.18	0.08	2.32	0.02	0.03	52.92
F204	0.08	0.23	4.55	3.21	0.20	0.13	0.06	0.03	0.63	0.14	0.03	49.47
F208	0.07	0.06	2.69	20.62	0.07	0.03	0.00	0.58	0.04	0.11	0.01	22.51
F209	0.06	0.12	6.20	19.80	0.33	0.04	0.03	1.59	0.37	0.34	0.04	20.30
F210	0.01	0.41	10.01	15.35	0.25	0.02	0.06	4.05	0.49	0.31	0.05	18.59
F211	0.02	0.31	7.00	9.82	0.18	0.01	0.02	2.38	0.17	0.16	0.07	32.68
F212	0.00	0.28	7.80	18.77	0.22	0.04	0.05	2.31	0.16	0.18	0.07	21.13
F213	0.03	0.12	0.71	2.17	0.58	0.02	0.07	0.05	0.32	0.02	0.13	53.24
F214	0.02	0.28	7.78	20.30	0.16	0.02	0.06	3.18	0.10	0.17	0.01	13.43
F215	0.08	0.24	3.83	19.59	0.13	0.05	0.09	1.55	0.16	0.18	0.01	28.68
F216	0.05	0.09	1.67	10.98	0.12	0.10	0.04	0.57	0.07	0.13	0.03	44.66
F217	0.07	0.37	11.07	14.35	0.21	0.04	0.02	3.77	0.11	0.32	0.01	21.09
F218	0.05	0.30	8.45	23.83	0.26	0.06	0.02	3.87	0.04	0.28	0.02	7.87
F219	0.04	0.33	7.26	11.82	0.20	0.02	0.05	2.97	0.02	0.25	0.04	28.22
F220	0.17	0.17	10.32	23.58	0.11	0.05	0.05	3.71	0.02	0.40	0.03	7.04
F221	0.01	0.00	17.71	18.89	0.79	0.05	0.09	0.01	0.11	0.00	0.03	1.10
F222	0.08	0.08	0.01	6.12	2.00	0.30	0.23	0.05	0.02	0.28	0.46	39.60
F223	0.20	0.16	4.15	7.12	0.10	0.14	0.02	0.56	0.02	0.11	0.17	45.63
Kirriwir /1	0.10	0.05	1.48	10.79	0.22	0.03	0.04	0.12	0.11	0.27	0.03	45.49
Kirriwir /2	0.07	0.02	2.37	13.37	0.11	0.04	0.07	0.13	0.07	0.25	0.03	40.57
67979N	0.06	4.28	0.74	2.59	0.04	0.04	0.06	0.11	9.07	0.05	0.16	33.38
Dial #1	0.05	0.01	0.47	7.57	0.17	0.02	0.02	0.03	0.01	0.01	0.00	53.96
O'land A	0.32	0.23	0.97	27.83	0.09	0.06	0.13	0.21	0.17	0.19	0.03	17.43
Karrku	0.09	0.30	4.22	14.94	0.27	0.23	0.16	0.87	0.25	0.16	0.03	32.56
Moana C	0.24	0.26	2.73	35.02	0.18	0.05	0.09	1.07	0.01	0.16	0.00	2.88
Djibitg/1	0.23	0.09	0.53	7.38	0.11	0.02	0.01	0.09	0.04	0.04	0.01	53.70
Tirnu 96/1	0.10	0.01	4.64	7.87	0.02	0.04	0.02	0.12	0.03	0.28	0.00	42.83
Tirnu /2a	0.08	0.01	4.82	21.68	0.06	0.06	0.05	0.06	0.03	0.23	0.10	23.38
Tirnu /2b	0.10	0.00	5.21	23.96	0.14	0.05	0.01	0.15	0.01	0.25	0.36	17.82
Tirnu /2c	0.09	0.00	4.80	13.35	0.04	0.14	0.03	0.10	0.12	0.18	0.04	31.33
Karrku /1	0.08	0.41	10.97	21.03	0.14	0.00	0.04	5.26	0.05	0.28	0.00	11.94
Karrku /2	0.05	0.05	3.37	34.91	0.16	0.06	0.06	1.42	0.05	0.12	0.00	5.10
Moana B	0.20	0.62	9.01	23.02	0.06	0.05	0.16	3.32	0.08	0.42	0.05	13.16
K'ararra/1	0.10	0.04	1.99	7.28	0.06	0.07	0.05	0.23	0.10	0.15	0.02	46.85
O'land B	0.64	0.27	1.93	30.17	0.03	0.09	0.10	0.31	0.15	0.20	0.05	14.90
O'land C	0.16	0.09	0.34	31.11	0.08	0.13	0.08	0.06	0.03	0.07	0.02	15.56
N5/24-6	0.11	0.05	6.86	26.17	0.48	0.08	0.06	0.59	0.13	0.50	0.05	10.62
Book 105	0.13	2.45	0.88	3.45	0.05	0.05	0.04	0.15	7.23	0.07	0.16	40.62

Appendix 2: Trace elements (ppb) determined using ICP/MS

	Na	Mg	Al	Si	S	Cl	K	Ca	Mn	Fe	Li	Be
	P	Sc	Ti	V	Cr	Co	Ni	Cu	Zn	Ga	Rb	Sr
	Y	Zr	Nb	Mo	Cd	Sb	Cs	Ba	La	Ce	Pr	Nd
	Sm	Eu	Tb	Gd	Dy	Ho	Er	Yb	Lu	Hf	Ta	W
	Tl	Pb	Th	U								
A&A 101	2000000	200000	86700000	179000000		1600000	400000	1900000	1500000	400000	172000000	
	21588	1088	247893	42251	5139280	253451	125863	4716	154375	34506	71879	27097
	14680	21479	10754	165412	3658	421	5	2000	637	302533	9664	15551
	1968	7456	1545	376	266	1555	1631	348	984	1044	163	3975
	307	1383	462	44473	3440	3072						
Wlgie 102	1600000	0	7900000	10400000	900000	800000	200000	1100000	600000	574000000		332
	1333	876813	24563	613296	342829	311171	4781	35502	17372	13945	7376	552
	36624	24624	348848	6507	1722	158	600326	101	39873	35271	61015	8761
	32978	7504	3292	943	6221	5094	938	2389	2351	351	7529	57
	59921	8	601159	1683	42499							
Wilgie 103	1400000	600000	9200000	10200000	200000	200000	300000	300000	0	580000000		246
	750	436259	6743	212395	116641	204568	7761	20134	12311	16049	4373	515
	18448	3355	101040	616	4771	197	250667	124	34711	6848	21831	3107
	16105	4190	1381	243	2233	1010	152	336	311	49	2152	43
	84053	6	141302	291	27194							
Wilg 115B	1400000	700000	4800000	3700000	100000	1300000	500000	2100000	200000	621000000		411
	902	200845	10720	22972	88653	48721	16989	65865	59120	5667	2410	648
	5806	948	127833	223	11377	12	100079	59	25076	2619	5057	592
	2622	532	163	38	251	215	43	126	175	31	2821	16
	31991	5	3310	652	24379							
Wilg 138	1600000	1000000	4400000	7500000	0	1000000	300000	700000	300000	609000000		177
	1258	612217	28778	590087	411417	1072029	6271	24092	66670	8758	7787	597
	5356	69134	28642279	8108	1674	108	789700	90	13828	5159	10082	1308
	5507	2442	993	817	3470	6962	2148	8650	14891	3200	650579	156
	53400	5	6873	5377	50771							
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