Chapter one

"Archaeology increasingly and very properly adapts and adopts the methods of natural science and unblushingly seeks its aid. It is not on that account itself a science in the classroom meaning of the term. At its best it is a very inexact science".

Sir Mortimer Wheeler (1956:229-30).

Rock engravings and microdebitage

Contemporary archaeology has increasingly focused on items of material culture in the investigation of cultural processes. This has led to a rising interest in determining the age of rock art by both archaeologists and Aboriginal people. For years rock art has been at the fringe of archaeological investigations due to difficulties in obtaining Quaternary dates without destroying the art and the associated archaeological deposit in the process (Susino, 1996).

Many Aboriginal people and archaeologists believe that archaeological investigations should be the least invasive possible to the material and location of sites. Many archaeological investigations employ methods that involve the physical destruction of the site investigated. Aboriginal people reject many of the non-Aboriginal cultural interpretation given to archaeological sites by archaeologists, and they oppose the destruction of their cultural sites on the basis of non-Aboriginal interpretations. The wishes of Aboriginal people relating to archaeological investigators are that only non-invasive methods and techniques be used for extracting information, and that no interpretation will be placed upon Aboriginal material by non-Aboriginal people without prior consent or co-operation. This is compatible with Aboriginal ideas on the revival of their own culture (Susino, 1996).

1.1 Introduction

Most of Australia's *Panaramitee* style (Maynard, 1976; 1977; 1979) rock engravings, or petroglyphs, are pecked on stone with a stone tool. According to Flood (1995; 1997), most of Australia's rock engravings have been chipped or pecked on rock outcrops by percussion with a pointed tool. This method may be used either directly with a hand-held tool or indirectly with hammer and chisel percussion

(Flood, 1997). The aim of this research is to identify the microdebitage resulting from the direct pounding of experimental rock engravings, and to identify its features. The understanding that microdebitage produced by manufacturing rock engravings is similar (if not identical) to microdebitage produced during stone tool manufacturing, is central to this research.

1.2 Background

Archaeology aims to discover, reconstruct and inform on the human past. As a discipline, it encompasses a variety of skills and methods devoted to the pursuit of knowledge. Ranging from anthropology to geosciences, the methods used for archaeological investigations may vary enormously according to the research at hand, from the purely theoretical and experimental to the practicalities of cultural resource management (CRM). The aims of archaeology described by Renfrew and Bahn (1991) are:

> "... to learn about the human past... Traditional approaches tended to regard the objective of archaeology mainly as reconstruction: piecing together the jigsaw. But today, it is not enough simply to re-create the material culture of remote periods, or to complete the picture of more recent ones. A further objective has been termed *the reconstruction of the lifestyles of the people responsible for the archaeological remains.* We [archaeologists] are certainly interested in having a clear picture of how people lived, and how they exploited their environment. But we also seek to understand *why* they lived that way: why they had those patterns of behaviour, and how their lifestyles and material culture came to take the form they did. We are interested, in short, in *explaining* change" (Renfrew and Bahn, 1991: 11,14).

It is the endless variety of archaeological questioning and investigation that leads to the development of applications from other disciplines, and to more refined techniques. The archaeological hypotheses dealt with in this research are designed to increase the knowledge of human globalisation [*Out of Africa theory*] (Gamble, 1993) and human behaviour (Mithen, 1996), by applying new

methodologies for the refining of investigative techniques. In so doing, this will add to the already existing body of knowledge concerning the human past. The presence of humans in all continents has been described as species adaptation to all environmental conditions existing on the globe. It is in the Upper Palaeolithic, from between 35,000-40,000yrs BP, that modern *Homo sapiens* have, according to Gamble (1993), displaced, incorporated, surpassed, and/or eliminated the *Ancient* from the human landscape. At the same time, behavioural differences between the ancient and the modern became apparent in all facets of survival technologies, exchange patterns and expansion into new habitats (Gamble, 1993; Mithen, 1996).

1.3 Human presence in Australia

The minimum dating of the first human presence in Australia is based upon a radiocarbon chronology associated with a large number of archaeological sites. These sites have been dated, in their earliest occupational levels, between 35,000 and 40,000yrs BP (O'Connell and Allen, 1998; Allen, 1989; Chappell, 1993). These archaeological sites include *Devil's Lair*, the *Upper Swan River* and the *Huon Peninsula* (Allen, 1989; O'Connell and Allen, 1998). These sites fit into the hypothesis for the arrival of the first humans in Australia, following the pattern (and chronology) of world occupation by modern *Homo sapiens sapiens* (Gamble, 1993; O'Connell and Allen, 1998).

A route, based on dated cultural sites and modern human remains, has been proposed, delineating migration through southern China and across the dry lands of the Sunda shelf at approximately 50,000 yrs. BP. This migration continued through the Philippine-Malay Peninsula to Borneo or Java, and finally across 65km of open water to the western extremity of Wallacaea (Bellwood, 1997; Allen, 1993; Schuster, 1998; O'Connell and Allen, 1998). However, the earliest evidence of occupation recorded for an Australian site is *Lake Mungo*. Dated with electron spin resonance (ESR) and uranium-thorium techniques, a date of 62,000 ± 6,000 years, was achieved for a buried skeleton (Simpson and Grün, 1998), and 61,000± 2,000 years for the associated sediment dated with optically stimulated

luminescence (OSL) (Thorne *et al*., 1999). These dates seem to invalidate claims of migration across Sunda at around 50,000 years.

The migration to Australia is considered to be a component of a global movement, whereby groups of modern *Homo sapiens* may have displaced existing populations of hominids and colonised extensive regions devoid of hominid occupation (O'Connell and Allen, 1998). This colonisation has attributed to modern *Homo sapiens* the behavioural and cognitive abilities (Mithen, 1996) necessary for migrating into new territories. This includes the construction and operation of adequate watercraft and the colonisation of glacial Eurasia (O'Connell and Allen, 1998).

A recent theory has been developed involving at least two movements of *Homo sapiens* out of Africa. These are associated with the behavioural and cognitive ability developed by humans in preparation for adaptation to Wallacaea and higher latitudes (O'Connell and Allen, 1998). The interpretation of several sources of evidence has suggested the possibility that humans were present in Australia prior to 40,000yr BP. It has also been suggested that archaeological sites with Pleistocene sedimentary deposits do not often contain dateable materials (Allen and Holdaway, 1994; Jones, 1993). Several sites have utilised relative dating techniques, such as the rate of soil formation, accretion and sedimentation and other geomorphological analyses to date human presence (Allen, 1989; O'Connell and Allen, 1998).

Microdebitage can be found in sedimentary deposits and can be used for spatial and chronological analyses. This research used microdebitage replicated by manufacturing rock engravings, and simulated its depositional existence by adding sedimentary material to the microdebitage samples. The microdebitage and its location in sedimentary deposits can be used to further the research into Quaternary dating and spatial patterning within archaeological sites, extending the understanding of lithic material *in situ*. This research also has the potential for furthering research into the early occupation of Australia by *Homo sapiens*.

Two main scholarly works have been important to this research, namely, Fladmark (1982) and Krinsley and Doornkamp (1973). Fladmark designed the use of microdebitage as an indicator of human cultural activity. The present research continues his work, expanding it in some new directions. Fladmark's research was concerned with the recognition of microdebitage (the microscopic by-products of stone tool manufacture), as an alternative to more conventional macroscopic markers for evidence of human activity, such as the production of lithic artefacts. Krinsley and Doornkamp (1973) catalogued microscopic features on quartz grains according to the environment in which quartz grains are located. Their work was based on the use of scanning electron microscopy. This method has proven to be very useful and more reliable than light microscopy for the optical recognition of features on quartz grains and diagnostic features on microdebitage.

The works of Fladmark (1982) and Krinsley and Doornkamp (1973) were designed for different purposes and adopted different but not totally incompatible approaches and methods. Fladmark (1982) developed the use of microdebitage for spatial analysis based on the utilisation of space for knapping and sharpening tools. Krinsley and Doornkamp (1973) concentrated on the study of the environmental origin of quartz grains.

The microdebitage used in this research originated from a series of experiments undertaken in 1996 at Broken Hill (New South Wales, Australia) by John Clegg, Dan Witter and William (Badger) Bates. In those experiments a series of engravings were pounded by Bates on sandstone slabs resting on a polythene sheet as part of an ongoing investigation by Mr Clegg of rock engravings found at Mutawintji National Park and Sturts Meadows (near Broken Hill, NSW) (Gunn *et al*., 1997). During an archaeological field survey at Sturts Meadows, Mr Clegg recognised two modified cobblestones that have now been identified as quartzite pounding tools (Clegg, pers. comm.). Features on the pounding tools were similar to tools made by Dr Witter for hand-held direct percussion on sandstone slabs.

The debitage resulting from pounding was collected for further analysis in Sydney (Clegg, 1997a). In 1997, Dr Dan Witter (NSW National Parks and

Wildlife Service, Western Region's archaeologist, Broken Hill) collected three soil samples from the same hill from which the sandstone slabs were collected and sent the material to Sydney. The debitage from the experimental rock engravings and the soil samples are the basic materials analysed in this research.

Three sandstone slabs were used as base material for the engravings. Quartz and quartzite cobbles for direct percussion tools. This material is abundantly available at Sturts Meadows and Mutawintji (formerly known as Mootwingee). The quartz and quartzite cobbles were skilfully knapped by Dr Dan Witter into pointed fist-size tools for the direct percussion method. William (Badger) Bates, a local Aboriginal artist, used these tools for the making of engravings on Mutawintji sandstone slabs. The art produced was to closely resemble the *Panaramittee* style rock engravings observed at Mutawintji, Sturts Meadows (Clegg, 1993), and in several other sites in Australia (figure 1.3.1).

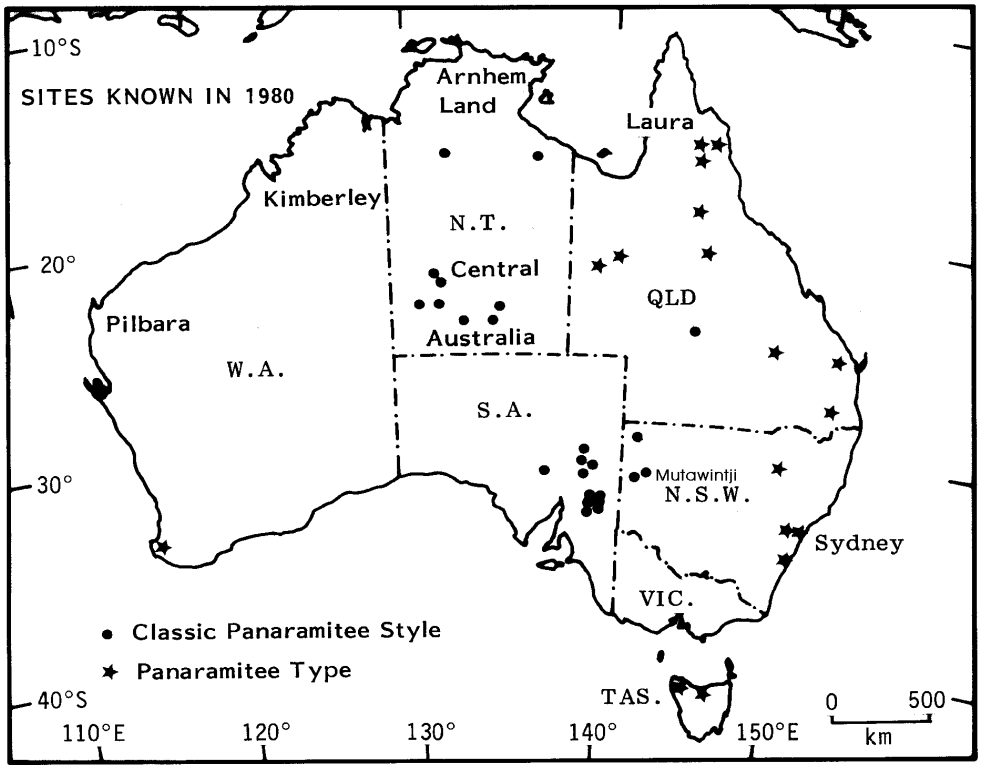


Figure 1.3.1. Distribution of the Panaramitee Style and Type in relation to Mutawintji, the origin of the experimental microdebitage (map courtesy of John Clegg).

The experiments yielded information concerning engraving methods. In particular it was discovered that engravings done by direct percussion were manufactured more quickly and accurately than those made by hammer-and-chisel indirect percussion (Flood, 1997). Further, the experiments have revealed that to make rock engravings with a fist-sized quartzite tool (within the size range of the *Panaramittee* style) took between 24-36 blows per 10 seconds or about 150-200 blows per minute. One engraved figure can take between 14 minutes, if small, to 21 minutes. According to Clegg (1997a), who undertook experiments to find out how long it takes to make engravings of the style available at Sturts Meadows (Broken Hill, NSW):

> "The replication suggests... with 6 engravings made in one morning, 12 could be possible in one day. One engraver working an eight-hour day, 5 days a week, could have produced the 18,152 recorded engravings [at Sturts Meadows] in four years. Only 1/20th of the engravings on the site have been recorded, so the complete assemblage would require 80 person years." (Clegg, 1997a: 17).

The material recovered from the experiments yielded about 100g of microdebitage from three engraved sandstone slabs. The microdebitage from the experiments can be of value for the identification of microdebitage at rock engraving sites, as there may be such material available in the archaeological deposit. If only three small engravings yielded 100g of microdebitage (33.3g average per engraving), the amount of microdebitage in the environment and deposits of the engraving site at Sturts Meadows, with over 18,000 engravings in one square kilometre, would have (potentially) at least 600kg of microdebitage in its deposits. However, the amount of microdebitage available in the deposits would be much lower, as the microdebitage would have been spread in an area of several square kilometres aided by rain, wind and bioturbation effects prior to and after incorporation in the sediments. Even if a small fraction of the potential 600kg of material remained in the sediments, there should be enough material available in the deposits for analysis.

1.4 Aims of this research

The two main areas of research investigated in this thesis are the recognition of quartz microdebitage by its shape and surface features, and the difference between microdebitage and natural quartz grains from soil under scanning electron microscopy and optical microscopy. The two experimental stages of this research are aimed at the recognition of microdebitage as a possible marker for ancient human activity at rock engraving sites.

An outline will be presented of the literature on lithic technology and remnant ancient debris. This primarily involves a review of Fladmark's contribution in identifying microdebitage. An outline of the works of Krinsley and Doornkamp on the identification of features on quartz grains. An outline of the experimental rock engravings studies undertaken by Mr. Clegg at Broken Hill. And notes on the possibility of employing this method to assist in the Quaternary dating of rock art.

This thesis aims to investigate three main questions.

1. *What features occur on "non cultural " quartz grains?*

   Observations will be made on the characteristics of quartz grains from different environments. These characteristics will assist in distinguishing between naturally occurring grains in sediments, and microdebitage from rock engravings.

2. *What features occur on quartz grains derived from the rock engraving process? Are they different from other quartz grains?*

   Observations will be made on characteristics of quartz grains from sedimentary origin and quartz microdebitage from rock engravings. This part of the research is based on two series of experiments, identifying broad differences between quartz grains from differing environments and microdebitage based on shape (degree of roundness). Statistical work was done to quantify the variation of features on quartz grains from differing environments as opposed to experimental microdebitage.

3. *Can quartz grains derived from the rock engraving process be identified under natural conditions?*

Tests will be undertaken for the recognition of quartz microdebitage from sandstone experimental rock engravings. Visual recognition of microdebitage will been conducted on the material, which is a mix of experimental microdebitage and sediment from the same area of origin as the sandstone slabs used for the manufacture of experimental rock engravings.

These tests are designed to expand and explain further the differences between naturally occurring quartz grains in deposits and microdebitage. Although experimental, the outcomes of this research may have the potential to assist in dating archaeological deposits, in conjunction with spatial site investigations. The results of this thesis will include the outcome of analyses, and suggested future directions, and archaeological implications.

Chapter two

> *"Microdebitage is defined as all stone flaking residue less than 1mm in maximum dimensions. Experimental replications indicate that it is produced in great quantities by stone tool manufacture and can permeate site matrices as a permanent signature of past cultural activity. Initial sampling studies suggest that microdebitage analysis may have considerable utility as a means of lithic site surveying."*
>
> *Knut Fladmark (1982:205).*

Microdebitage, archaeological deposits, and dating

The term *microdebitage* was proposed by Fladmark (1982) to describe lithic debris smaller than 1mm in size, which resulted from the manufacture of stone tools. For this research, the term microdebitage is used for lithic debris resulting from the making of rock engravings.

This chapter outlines previous research on lithic technology, microdebitage analysis, the recognition of quartz grain features, replication of rock engraving techniques, and rock art dating techniques. This whole thesis bases its research on several seemingly unrelated analyses undertaken in archaeology, geology and geomorphology. These analyses are directed towards understanding the nature of microdebitage and investigating its potential for elucidating rock engraving chronologies.

The study of lithic assemblages has been confined predominantly to the analysis of lithic materials and associated technology available in archaeological deposits. No studies have recognised rock engraving manufacturing as part of lithic technology and identified its by-product as microdebitage. The study of lithic technology and tool assemblages can be useful to the assessment and analysis of debitage and microdebitage related to the manufacture of rock engravings.

This research on microdebitage is based upon the similarities of lithic tool reduction debitage, seen at microscopic level. The microdebitage resulted from the production of rock engravings. Microdebitage can also be categorised by reference to general environmental features (Krinsley and Doornkamp, 1973). For the purpose of this research, the terms used to describe the features will be those used in the geoscience disciplines.

Other studies have been useful for the identification of quartz grain features, beyond the environmental (Fladmark, 1982; Hull, 1983). The features on microdebitage outlined by Fladmark (1982) and Hull (1983) for lithic activity related to spatial analysis at archaeological sites.

Lithic microdebitage and spatial analysis have been applied, according to Vance (1987), to the analysis of archaeological sites:

> "The analysis of activity location in archaeology is based on one or more of several assumptions. A traditional assumption often used in interpreting archaeological sites is that the place where an artefact is found archaeologically corresponds where it was used: as if raw materials, tools, and garbage were used and then dropped and left there until the site was abandoned". (Vance, 1987: 59).

The following discussion will investigate a possible connection between the use of microdebitage for spatial analysis and its potential for age determination. Quartz microdebitage, if treated as sedimentary quartz, can be dated and calibrated by some of the methods described in this chapter. A new technique, optically stimulated luminescence (OSL), may be applied to single grains of quartz.

2.1 Lithic technology

The methods employed in this research for the understanding and analysis of microdebitage from rock engravings are largely based on the analysis of lithic assemblages. Rock-on-rock shattering produces microdebitage. Visually, the material appears as a white dust released by the percussion of rocks against each other.

Tool assemblages and their analysis are based on the observation of remnant lithic debitage *in situ*. These observations can potentially provide clues on the nature of the materials used, techniques employed, and the age of the material. Within this framework of lithic tool fabrication, some of the debris may remain in the environment, near the place of manufacture. The debris may also have been incorporated into sedimentary deposits. If this is so, it may be possible to find some microscopic remnants of the tool manufacturing process.

Evidence for ancient lithic technology has been discovered in Australia. According to Sullivan (1973), quartz tool industries have been most important for the survival of humans in early Australian occupation. Quartz has been a common raw material for lithic implement manufacture. Fashioning and using stone tools was common in Australia before European settlement. However, in later years stone was slowly substituted with European materials (eg. glass, ceramics, and metals).

The microscopic debris derived from this action is similar to that of tool-making remnants. Literature concerning lithic tool assemblages is used as a starting point for research on the dynamics of tool production and the understanding of debitage and microdebitage.

Original research undertaken on lithic tool assemblages for the purpose of archaeological investigation has led to further analysis and interpretation of remnant lithic debitage. The study of lithic technology, according to Church (1994), was originally coupled with the study of the manufacture of stone tools, core reduction (Binford, 1986; Newman, 1994; Septh, 1975; Stahle and Dunn, 1982), and lithic technology analysis (Kuhn, 1994; Jahren *et al., 1997*). Other methods are taken in consideration, such as archaeological interpretation (Amick and Mauldin, 1989); petrographic analyses (Hutchinson, 1974; Shipley and Graham, 1987); soil and sedimentary analyses (Dean, 1993; Farrand, 1985; Stein, 1985); microwear analysis (Balmforth *et al.*, 1990; Moss, 1983; Nance, 1971; Young and Balmforth, 1990); cultural studies (Vierra, 1995); and stylistic approaches (Sackett, 1977).

Lithic technology studies have not been applied to the analysis of rock engravings. The work of Clegg (1997a, 1997b; and reported by Flood, 1997) has illustrated the feasibility of using stone tools for the replication of engravings. This may aid in understanding the lithic technology employed in their production.

According to Sullivan and Rozen (1985: 755), debitage analysis is "...the systematic study of chipped stone artefacts that are not cores or tools".

This classification sets the premise for the study of debitage, which can be used to reconstruct lithic technology and past cultural behaviour. Debitage from rock engravings can be identified within the meaning and categorisation devised by Sullivan and Rozen (1985), however it is not yet subject to typological classification. Microdebitage is the micro-component of that by-product.

2.2 Quartz grains: environmental features

According to Fladmark (1982), microdebitage is composed of lithic a by-product from the manufacture of tools. For the purpose of this research, the use of the word *microdebitage* includes the by-product of rock engraving manufacture. Microdebitage can result from a varied range of materials such as obsidian, chert, flint, chalcedony, basalt, jasper, petrified wood, silcrete, quartzite and quartz among others. This thesis is restricted to quartz grains that have been shattered and released from sandstone in the process of making rock engravings, and from the lithic tools employed in the manufacturing.

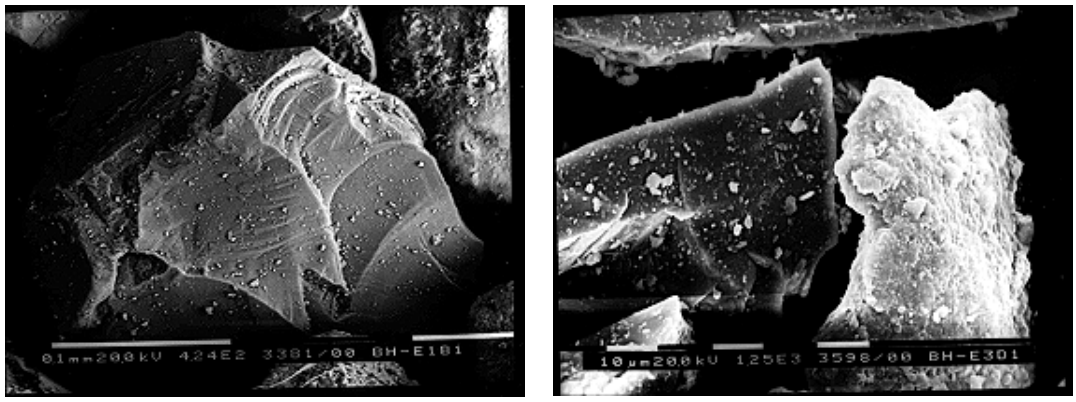
The search for microdebitage by Fladmark (1982) and Hull (1983) was generally confined to material other than quartz. These two studies did not resolve the problem of identification beyond a general description and nor did it take into consideration, or overlooked, at least in the search for quartz microdebitage, the works of Krinsley and Doornkamp (1973). The studies by Krinsley and Doornkamp (1973) allow the recognition of environmental features or textures on quartz grains. The analyses undertaken in this thesis take into consideration both the archaeological (Fladmark) and the geological (Krinsley and Doornkamp) research into quartz.

The abundance of quartz in the environment may be adding to the difficulty of searching for lithic microdebitage. Previous research into microdebitage may have been hindered by this abundance, but this study has found that quartz can be a valuable identifier of human activity. The durability and longevity of quartz grain features can be retained for several thousand years

(Krinsley and Doornkamp, 1973). The retention of features, coupled with the nature of quartz, can make microdebitage a likely candidate for direct Quaternary dating of evidence for ancient human activity (with optically stimulated luminescence, thermoluminescence, or other dating methods). Quartz grains are the most abundant materials available in sandstone and sedimentary deposits. Rock engravings on sandstone have been pounded or abraded in many occurrences in the Australian archaeological record (Flood, 1997).

Krinsley and Doornkamp (1973) catalogued and interpreted quartz grain surface features according to characteristics derived from their weathering environment. They noted that it is not possible to determine the environmental origin of quartz grains by taking into account only a single feature, as each environment produces several distinctive features or combination of features. Krinsley and Doornkamp (1973) based their observations on the provenance of quartz grains on the presence or absence of feature types on the grains themselves. Their observations relied upon the assessment of modifications specific to particular environments (Krinsley and Donahue, 1968; Krinsley and Doornkamp, 1973).

Of the surface characteristics described by Krinsley and Doornkamp (1973), microdebitage presents features that are consistent with freshly broken quartz and quartz from glacial environments. Microdebitage has a high angularity and exhibits conchoidal fractures and flat cleavage surface planes under magnification using a scanning electron microscope (figures 2.2.1a and b, from Mutawintji sandstone).



(a) (b)

Figure 2.2.1. (a) Cleavage planes with conchoidal fractures, (b) High angularity of quartz microdebitage.

Krinsley and Donahue (1968) made general observations (table 2.2.1) on quartz grain features produced by different environments and those subjected to diagenesis. These definitions are used to analyse the features on material from experimental rock engravings. Observations by Krinsley and Doornkamp (1973) determined that fresh quartz sand grains from a glacial environment are extremely angular, even at large magnification (30,000x). Surface textures on quartz grains from glacial environments have been described by Krinsley and Margolis (1971) as having at least four of the following seven textures:

1. Large variation in size of conchoidal breakage-patterns probably related to the large variation in size of particles in glacial sediments.
2. Very high relief (compared with grains from littoral and aeolian environments), probably related to the large size of particles and the large amount of energy available for grinding.
3. Semi-parallel steps probably caused by shear stress.
4. Arc-shaped steps, probably representing percussion fracture.
5. Parallel striations of varying length, probably caused by the movement of sharp edges against the grains involved.
6. Imbricated breakage blocks that look like a series of steeply dipping hogback ridges.
7. Irregular small-scale indentations that are commonly associated with conchoidal breakage-patterns probably caused by grinding.

(Krinsley and Margolis, 1971: 160-163)

The above textures (features) on quartz grains were originally observed and catalogued by Krinsley and Donahue (1968) according to the environment in which they were produced. Table 2.2.1 below illustrates the various textures on quartz grains catalogued by their environment of origin.

Table 2.2.1. Quartz grain surface features characteristics (Krinsley and Donahue, 1968).

LITTORAL		**AEOLIAN**	
High Energy (surf)	**Medium and Low-Energy Beach**	**Tropical Desert**	**Coastal**
I. V-shape patterns of irregular orientation. a. 0.1μm average depth. b. 2 V-shapes per square micron density. II. Straight or slightly curved grooves. III. Blocky conchoidal breakage patterns.	I. *En echelon* V-shaped indentations at low energy. As energy increases, randomly oriented V-shapes replace the *en echelon* features. Continuous gradation is present between high- and low- energy features.	I. Meandering ridges. II. Graded arcs. III. Chemical or mechanical action - regular pitted surfaces replacing the above features in many cases.	I. Meandering ridges. II. Graded arcs.
GLACIAL		**DIAGENETIC**	
Normal	**Glacio-Fluvial**	**Wavy-Patterns**	**Worn (solution)**
I. Large variation in size of conchoidal breakage patterns. II. Very high relief (compared with grains from littoral and aeolian environments). III. Semiparallel steps. IV. Arc-shaped steps. V. Parallel striations of varying length. VI. Imbricated breakage blocks, which look like a series of steeply dipping hogback ridges. VII. Irregular small-scale indentations, which are commonly associated with conchoidal breakage patterns. VIII. Prismatic patterns, consisting of a series of elongated prisms and including a very fine background.	I. Rounding of glacial patterns I-VIII.	I. Curved branching irregular lines developed to varying degrees.	I. Relatively flat and featureless surfaces.

According to Krinsley and Doornkamp (1973), quartz grains from glacial environments can retain features for an extended period. This retention depends on the subsequent depositional environment and diagenetic processes. Some of the features characteristic of glacial environments was found in Pleistocene and Early Tertiary sediments. Experimental investigations undertaken by Krinsley and Doornkamp (1973) compared quartz grains that were released naturally and quartz grains which were broken with a power-driven hammer. All presented the same type of features, however the experimental quartz grains were more irregular in shape than the natural ones. Quartz grains released by mechanical crushing presented a variety of features also present on grains in natural glacial deposits. The most common features on the mechanically fractured quartz grains were high angularity, large cleavage and conchoidal fractures, imbricated cleavage, and irregular fractures with adhering fine quartz

particles (Krinsley and Doornkamp, 1973). Helland and Holmes (1997) also catalogued quartz grain surface textures. Based on Krinsley and Donahue's (1968) work, they have expanded and further defined the list of environmental features. The research by Helland and Holmes (1997) on a glacial deposit off the southeastern coast of Greenland, illustrated that the quartz grains were glacial in origin and dated from the Late Miocene. They identified three groups of quartz grain surface textures as outlined in table 2.2.2 below.

Table 2.2.2. Quartz grain surface features observed by Helland and Holmes (1997: 121).

Morphological	**Mechanical**	**Chemical**
1. angular outline	6. small conchoidal fracture	21. solution pits
2. rounded outline	7 large conchoidal fracture	22. chemical V-shaped pits
3. low relief	8. straight steps	23. adhering particles
4. medium relief	9. arcuate steps	24. limited silica precipitation
5. high relief	10. imbricated blocks	25. extensive silica precipitation
	11. large breakage blocks	26. oriented solution/precipitation
	12. fractured plates	27. euhedral crystal overgrowth
	13. striations	
	14. edge abrasions	
	15. mechanical V-shaped pits	
	16. straight grooves	
	17. curved grooves	
	18. meandering ridges	
	19. irregular depressions	
	20. upturned plates	

Helland and Holmes (1997) applied the twenty-seven surface texture types listed in table 2.2.2, to establish that textures in the morphological and mechanical columns are consistent with a glacial environment and mechanically broken grains of glacial origin. They also concluded that the sediments were Late Miocene in age (11Ma), based on paleontological identification of nanofossils (relative dating) and calibration of Sr-isotope analysis (absolute dating) from planktonic foraminifera.

The origin and provenance of quartz grains in the southwest of Spain was determined by a list of ten features developed by Moral-Cardona *et al.* (1996) (table 2.2.3). Quartz grains from fluvial deposits were related to the parent sandstone by associating remnant features on the transported grains.

Table 2.2.3. Quartz grain surface features analysis by Moral-Cardona *et al.* (1996: 161).

Surface features			
A.	Conchoidal fractures	F.	Chattermark trails
B.	Arcuate steps	G.	Chemical etch pits
C.	Mechanical V-shapes	H.	Silica globules
D.	Linear or curved grooves	I.	Silica pellicles
E.	Upturned plates	J.	Solution pits and hollows

The work of Moral-Cardona *et al.* (1996) relied upon features listed in Table 2.2.3, to relate parent material to sedimentary deposits. Thin sections of sandstone were cut, and comparisons made between the grain features from the original rock and features on the sedimentary quartz grains in sediments. By eliminating the environmental features associated with diagenesis in a fluvial environment, and the use of trace minerals, Moral-Cardona *et al.* (1996) identified the sandstone from which the quartz grains were derived.

To understand aeolian abrasion on quartz grains, experiments were undertaken by Smith *et al.* (1991) and Whalley *et al.* (1982, 1987). They developed a technique that could reduce angular quartz grains into rounded and sub-rounded fragments in less than 128 hours using an experimental electrostatic precipitator that simulates aeolian erosion. In the environmental conditions experienced in semi-arid areas of Australia, aeolian activity coupled with rapid flooding may be highly erosive. If, however, microdebitage is rapidly incorporated into sedimentary deposits it may retain its angularity, retaining differences from the 'background' sedimentary material.

2.3 Microdebitage in relation to archaeological deposits

Based on studies in lithic technology, Fladmark (1982) proposed that microdebitage could be used as an indicator of human cultural activity. With this, he initiated much of what is recognised as micro-archaeology. Fladmark's work focussed on the recognition of cultural microdebitage as an alternative to more conventional archaeological techniques. This development led Fladmark to relate and analyse spatial patterns of activity, which were not obvious from the standard recording of archaeological sites.

Fladmark suggested general procedures on how to isolate and analyse microflakes from lithic debitage present in sediment of archaeological sites. His original study presented evidence of spatial patterning from an experimental flaking area.

On the recognition of microdebitage, Fladmark (1982) indicates that there are several features common to microdebitage regardless of material type. He identified six criteria for the recognition of microdebitage from soil *background*:

> 1. High angular forms,
> 2. transparent or translucent under transmitted light,
> 3. often larger than the mean particle in any screened sample
> 4. usually regular geometric shapes
> 5. usually some aspects of conchoidal fracture,
> 6. often lies close to the surface plane of the microscope
>
> (Fladmark, 1982: 208-209).

The protocols developed by Fladmark were based on standard procedures for the analysis of sediments used in soil science studies. Laboratory procedures devised by Fladmark were adapted from Shackley's methodology for the analysis of archaeological sediments (Fladmark, 1982; Shackley, 1975). To recognise microdebitage from other sedimentary material Fladmark (1982), employed the use of light microscopy to identify quartz grains from quartz microdebitage.

According to Fladmark (1982), a quartz crystal under light microscopy has the following characteristics:

> "...transparent to highly translucent; has regular straight fracture edges; no inherent cleavage pattern and usually shows good conchoidal fracture characteristics, with occasional crystal facet remnants sometimes marked by right-angled striae. Under polarised light quartz shows bright birefringence colours, up to the fourth order... depending on thickness. Ridges, flake-scars and other surface relief features will be picked out by marked angular unconformities in the trend of the birefringence colours. The bright multi-order interference colours of quartz crystal under crossed nicols is its most distinctive feature, easily distinguishing it from obsidian from which it might some times otherwise be visually mistaken. Although other silica minerals such as feldspars have some of the same characteristics, they can usually be distinguished by other features such as crystal twinning, cleavage, hardness and weathering patterns"(Fladmark, 1982: 219).

The study by Fladmark (1982) refers to raw material used for lithic technology, the most common raw materials in Canada being chert, obsidian, quartz, quartzite and basalt. Fladmark (1982) suggests that microdebitage can be identified at least as far back as 6,000 years. However, geological work suggests that sedimentary quartz grain angularity and features associated with glaciations can be retained for periods of millions of years (Moral-Cardona *et al.*, 1996).

Angular microdebitage, if subjected to erosion, will develop features consistent with the environment in which the grain is released (original bedrock). The time required for angular microdebitage to develop features in an aeolian environment is not known at this stage. Erosion and deposition of grains is highly variable, and the estimation of time needed for modification of the features may vary considerably according to environmental conditions.

In his studies on the field applications of microdebitage analysis, Nicholson (1983), evaluated different techniques (including Fladmark, 1982) on the use of microdebitage and spatial analysis, for the assessment of cultural resources within specific geographical areas. Nicholson's (1983) study did not take in consideration quartz microdebitage, since deposits at the site contained only a low concentration of angular quartz grains, which could have been naturally occurring in the soil matrix. The study by Nicholson is based on material other than quartz (flint, chert, obsidian and chalcedony); however, he observed that these materials exhibited similar impact features to quartz. The research by Nicholson (1983) is based on the roundness and angularity of the material extracted from core samples at the archaeological site. He concluded that the lithic micro-material identified as microdebitage was angular in nature, and had been imported to the area.

Following on from the work of Fladmark (1982), Hull (1983) analysed several sites in Canada by applying spatial patterning analyses to microdebitage from stone tool manufacture. Hull identified microdebitage by adopting Fladmark's (1982) methodology with six attributes that form the basis for identification of microdebitage from natural sedimentary material.

The methodology developed by Fladmark (1982) was evaluated and expanded by Hull (1983). She noted that microdebitage analysis is extremely time consuming, but that simplified methods would result in loss of data. Light microscopy was used by Hull to analyse microdebitage, applying Fladmark's (1982) methods and protocols. Included in her study, Hull (1983) detailed differences and similarities in microdebitage features originated from different lithic materials. Hull's contribution to the identification of differences in the origin of microdebitage has revealed that features on quartz microdebitage exhibit great similarity with obsidian microdebitage. The use of light microscopy in Hull's (1983) study limited the identification of lithic material type to materials other than quartz.

2.4 Interpretation of sediments at archaeological sites

Understanding sedimentary deposits is a major concern for archaeological investigations, since naturally occurring material and microdebitage will be ultimately incorporated into a single deposit. The work of Krinsley and Doornkamp (1973) has direct bearing on the interpretation of sandy sediments, and microdebitage in particular, by identifying the provenance of such sedimentary material.

Several methods were outlined by Stein (1985) that is relevant for the assessment of sediments for cultural content. According to Stein (1985):

> "...A careful examination of the sediments and chemical residues is required to identify the cultural component of the site matrix. Interpretation begins with a consideration of sedimentation. A sediment's history is a function of four factors: 1) source; 2) transportation mechanism; 3) environment of deposition; 4) post-deposition environment. The study of the chemical and physical properties of sediments can identify the nature of each of those factors as well as the natural or cultural agents responsible. The history of sediment is reconstructed by comparing the subject sediment with one of known history... If the characteristics cannot be ascribed to natural agents, cultural impact on one or more of the four factors [is] indicated" (Stein, 1985: 5).

Archaeological investigations usually attempt to reconstruct the natural environment of sites. The importance of sediments in this process has not been exploited fully. The analysis and interpretation of culturally modified sediments, according to Stein (1985), should permit the identification of formation and deposition processes of archaeological deposits. The interpretation of sediments should be able to determine if natural or cultural processes were responsible for the deposition. Based on the assessment of sediments collected from a study area and a control area, the differences between the two should allow for an interpretation of such a formation process.

It is often stated in the literature that the analysis of sedimentary material is the key to understanding the formation of sedimentary deposits (eg. Stein, 1986; Ferrand, 1985; Dean, 1993; Holiday *et al.*, 1993; Ripley, 1998). These types of analyses lead to greater understanding of the material's origin (cultural or natural). Microdebitage from quartz and other lithic materials thus increases the interpretative value of sediments, where the difficulty of discerning between natural and cultural deposits is at their greatest. The analysis of sediments and microdebitage can greatly enhance the retrieval of information from archaeological deposits.

The identification of cultural site formation processes using spatial analysis of microdebitage and macrodebitage, was outlined by Hull (1987), in her study for the recognition of areas of use and disposal of lithic tool manufacturing. In Hull's (1987) findings, the use of microdebitage to identify cultural deposits has been a valued method in the assessment of spatial activity within a site (Janes, 1989). Microdebitage analysis is employed for the identification of lithic activity areas. The outcome of the analysis was based upon site characteristics that reflect cultural behaviour; in this case, the analysis reflected the use of space within and outside a Native American Tipi.

Janes (1989), has commented on the use of models for microdebitage distribution. Although not doubting the effectiveness of microdebitage recognition, Janes discussed the difficulty of taking into consideration all aspects of human

occupation and habitation on the land, and especially their impact on sedimentation processes. He believes that processes like bioturbation, animal burrows, and human trampling on the soil help obscure the stratigraphy. Ultimately, Janes (1989) is supportive of the use of microdebitage in spatial analyses of ancient occupational sites.

Applegate (1993) also applied microdebitage analysis to lithic assemblages. As with Hull (1987), the outcome of the microdebitage analysis focussed on lithic assemblage systems, composition, and formation processes. Applegate (1993) identified several site formation processes using micro- and macrodebitage. These processes have direct bearing on the soil and sedimentary deposition of culturally derived microdebitage. Gravity, frost heaving, bioturbation, creep, trampling and clearing at the site are factors which must be investigated prior to the taking of samples for microdebitage analysis. The incorporation of microdebitage into a sedimentary deposit allows the possibility for retrieval of spatial and temporal information regarding site use. To retrieve the material, Stein (1986) suggested coring or augering. Stein (1986) recommends that:

> "Systematic coring and augering of a site can provide a variety of data not otherwise available. This technique facilitates the definition of subsurface units, provides a clear view of the buried surfaces on which occupation took place, enables the estimation of volumes of site components, and determines the real extent of the site. The technique is inexpensive, is adaptable to any site with distinct soil-colour or texture variations, and is minimally destructive. Most importantly, coring and augering can expand the number of significant hypotheses that can be addressed concerning site stratigraphy and deposition processes" (Stein, 1986: 523).

Schuldenrein (1991) supported the methods employed by Stein (1986), since coring methodologies can be of great help in cultural resources management (CRM), as they are cost-effective and less invasive than large-scale trench excavations. In addition, Schuldenrein (1991) argues that coring and augering techniques can be of major benefit to archaeology in their utility for detecting sites "rapidly, accurately, efficiently, and cost-effectively". This has particular relevance for CRM, where non-archaeological concerns of a political and

administrative nature are balanced against the archaeological necessities of research and discovery (Lambert, 1993; 1992). However, there are problems of interpretation and terminology between archaeologists and geologists, as outlined by Stein (1993); these have not yet been resolved.

Sediments in and around rockshelter archaeological sites may be a source of microdebitage. Farrand (1985) investigated the factors that influence depositional processes in rockshelter sediments. In many instances, rockshelters are identified with prehistoric habitation, and can function as sediment traps for any cultural material.

Represented in an archaeological context, sediments from rockshelters can be studied with a variety of methods, of which sedimentary analysis is but one (Hughes and Sullivan, 1986; Sullivan and Hughes, 1983; Hughes and Lampert, 1977). Hughes and Sullivan (1986) believe that geoarchaeological and geomorphological studies should concentrate in areas adjacent to archaeological deposits to include the relationship between occupational deposits and the landscape. They argue that:

> "Detailed comparison of the sedimentary and archaeological record may allow an even finer resolution of geomorphic events and of the relationships between these events and Aboriginal use of sites and their surrounds" (Hughes and Sullivan, 1986: 131).

Sedimentary analysis in archaeological sites is not confined to rockshelters but is applicable to all sites. Sediments are the result of natural geological processes and human and animal activity. They contain a record of habitation and abandonment, and other human ancillary activity, artefacts, remains of plants and animals used as food, hearths, and fossils. The interpretation of sedimentary processes and modifications (by human activity, weathering and erosion) must be organised and follow a logical sequence.

The aims and achievements of sedimentary analysis are outlined by Ferrand (1985) as follows:

> 1. Detailed description of archaeological strata, i.e., something more than "brown cave earth";
> 2. reconstruction of the physical environment during and between the occupation of the site;
> 3. (From 2) interpretation of past climate of the area;
> 4. (From 2 and 3) means of correlation between sites in the same climatic region.
>
> (Ferrand, 1985: 22).

Sediments must be seen and collected in a manner by which they are *in situ*, or at least be seen prior to disturbance and bagging for analysis. This aids the definition and understanding of the natural structure of the sedimentary unit, and allows further investigations of the features. Outlined below are some of the relationships between materials, which should be taken into consideration during investigations of archaeological sediments:

> 1. *Sedimentary structures*: stratification, especially thin lamination, crossbedding, ripples, mud cracks, etc.;
> 2. *contact relations*: sharp, clear, or completely gradational, including possible unconformities (gaps);
> 3. *colour relation*: uniform, mottled, banded;
> 4. *Lateral relations*: facies changes, proximity to walls, hearths, roof, collapse, etc.
>
> (Ferrand, 1985: 22).

It is thought by Ferrand (1985) that the use of a geologist on site is essential for the correct evaluation of stratigraphic and chronological evidence, not only for the collection of samples.

The analysis of sedimentary deposits in archaeological sites has been instrumental in the investigation of human activity. Finding microdebitage in deposits can be extremely useful for the investigation of rock art sites.

Occupational archaeological sites are usually excavated and analysed for artefactual contents (eg. middens, rock shelters, and open sites). This research proposes that rock engraving sites may be analysied spatially and chronologically by using microdebitage (treated as microscopic artefacts). The study of sediments for archaeological investigations entails the use of geomorphological and pedological methods. As archaeologists increase their understanding of sedimentary processes, determining the formation of archaeological deposits becomes an important component of the investigative process.

The sub-discipline of geoarchaeology deals with geographical and geological processes affecting archaeological sites and deposits. The understanding of sediments and depositional material has become increasingly useful in identifying human presence and activity at archaeological sites. Both microscopic and macroscopic remains in depositional stratigraphic levels have proven capable of enriching and elucidating human activity in sites not immediately recognised as important. Human activity can now be mapped in both spatial and temporal models, giving a fuller picture of site usage in time, through the understanding of sediments, archaeological deposits and site formation processes.

M.A. Smith (1987; 1993), Rosenfeld (1993) and C. Smith (1992) have undertaken studies on sediments in archaeology. These studies revealed the nature of sediments and archaeological value of understanding them. The temporal structures of Australian sites have inherent problems stemming from difficulties in applying dating methods to archaeological deposits. In addition, understanding the sedimentation processes and the morphology of archaeological deposits is incomplete, giving rise to obstacles for the successful application of existing dating methods. Quartz grain features may provide further information that could have benefits for archaeological interpretation.

Several studies on the sediments of large sites, rock art sites and rockshelters (Shackley, 1978; Smith, 1993; Veth, 1989; Pell and Chivas, 1995) have produced models for the occupation of Australia based on archaeological and sedimentary

depositional evidence. Sediments thus become an important medium for the establishment, evaluation and investigation of archaeological sites.

Sediments are not static in time: depositional material can be reworked within the sediment by bioturbation, animal activity, earthworms (Stein, 1983), frost and other environmental actions. Bioturbation within the sediments may well invalidate their dating, as seen with the problems encountered in dating the Jinmium excavated site, where bioturbation may have been the cause of mixed-age quartz. Sediment mixing may provide a possible explanation for the very old dates obtained with thermoluminescence dating (TL) (Spooner, 1998; Goldie, 1998). According to Roberts *et al.* (1998), the explanation for the older dates is based on the choice of dating technique, and:

> "Using conventional (multiple-grain) optical dating methods, we estimate that the base deposit is 22 Kyr. However, dating of individual grains shows that some have been buried more recently. The single-grain optical ages indicate that the Jinmium deposit is younger than 10 Kyr. The result is in agreement with the late-Holocene ages obtained for the upper two-thirds of the deposit from radiocarbon measurements. We suggest that some grains have older optical ages because they received insufficient exposure to sunlight before burial. The presence of such grains in a sample will cause age overestimates using multiple-grain methods, whether using thermoluminescence or optical dating" (Roberts *et al.,* 1998: 393).

The process of bioturbation is a source for many of the problems associated with the identification of strata within archaeological or sedimentary deposits. A source of frustration for the researcher, bioturbation in deposits has many forms and is endemic to all sediments. Caused mainly by organisms, plants, and humans, these processes have profound impact on the understanding of archaeological and geological process of investigation (Hughes and Lampert, 1977).

Research undertaken by Humphries and Mitchell (1983) and Williams (1978) investigated the role of bioturbation in soil movement processes. Humphries and Mitchell (1983) address the role of bioturbation and rainwash on sandstone in the Sydney Basin, as being very important, as shallow bioturbation

and rainwash allow the reworking of finer particles from the surface into the sediment. Other sediment formation processes are outlined by Williams (1978), in the Northern Territory of Australia, which must be identified for better understanding of the nature of a site. These include soil creep, slopewash, slope retreat, and seasonal expansion of clays. Williams (1978) also elaborates on the relationship between bioturbation and soil accretion and erosion caused by termites building their mounds. Termites bring quartzitic material from lower levels of the sediments up to the surface. Geomorphological, biotic, petrologic, and sedimentary interactions must also be taken in consideration when identifying sites of great antiquity (Entwistle *et al.,* 1997; Hughes, 1978; 1980; 1983; Hughes and Sullivan, 1986; Magee, 1980; Noble and Tongway, 1986; Welton, 1984), together with the site's sedimentary properties (Walker, 1964; Shepard, 1954; Link, 1966).

In describing microdebitage deposits, Vance (1987) has identified the structure of site formation, and the possible cause of at least one type of deposit formation and disturbance:

> "Microdebitage is formed by a specific activity, where that activity takes place, and because of its size it is not likely to be cleaned away or removed. It is probably trampled into the dirt or other floor by normal foot traffic. Therefore... microdebitage is likely to be available for archaeologists to find." (Vance 1987: 59).

To Vance's description (1987), it may be added that site formation and disturbance are cause and effect of the same. Archaeological deposits are formed by the disturbance of sediments (Hughes and Lampert, 1997). This thesis analysed material derived from sandstone in aeolian, semi-arid environments, to assess the possibility of microdebitage being present in deposits at rock engraving sites. This research aims to establish whether in an aeolian, semi-arid environment, with sandstone outcroppings, microdebitage remnants from the making of rock engravings can be recognised in sediments.

The identification of sedimentary processes (post-depositional) is of prime importance to this research if quartz microdebitage is to be used for dating human activity at rock engraving sites.

The identification and analysis of bioturbation is of importance to the understanding of post-depositional activity. It takes many forms, and varies from site to site, based on environmental conditions. Several case studies have been examined; some are related to the Australian continent and are based on the environments to which this research has possible applications. Aeolian environments, arid and semi-arid areas are of interest since the quartz grains there are very different from particles of microdebitage.

It is almost impossible to determine the time it takes to turn an angular quartz grain into a smooth, rounded one. It is therefore impossible to determine how long it has been in the environment or how long it has been enclosed in a sedimentary rock matrix. Once released from the rock, the quartz grain becomes part of local sediments, and is then subjected to local environmental conditions. If the quartz grain has been pounded off, it will exhibit features consistent with both microdebitage and grains crushed naturally by mechanical forces in glacial environments. There could also be problems of identification of microdebitage if quartz grains from the parent rock were angular. If quartz microdebitage was trampled during the making of rock engravings, it may be incorporated quickly into the soil and probably retain the features of mechanically crushed grains.

In many parts of Australia, rock engravings are pecked or abraded on sandstone outcrops. The microdebitage remaining in nearby deposits may be analysed using standard strategies and analytical models utilised in geology, geography and geoarchaeology (Sullivan and Hughes, 1983; Flood, 1997). Research procedures developed for the study of sediments have assisted in the interpretation of sedimentary and archaeological deposits (Quine, 1995; Gale and Hoare, 1991; Shackley, 1972; 1975; Canti, 1995; Macphail and Goldberg, 1995).

Quartz microdebitage, as reported by Fladmark's work, is limited to the visual identification of *microflakes* under light microscopy. As reported by Vance (1987), Fladmark's method made it difficult to distinguish microdebitage from other quartz grains naturally available in sediments (see also Hull, 1983, 1987; Keeley, 1991).

Research conducted for this thesis has assessed and expanded this methodology by applying it to rock engravings. The analysis of microdebitage using environmental features recognition on quartz grains can be applied to material from rock engravings. The research developed by Krinsley and Margolis (1971), Krinsley and Doornkamp (1973), and the statistical work of Krinsley and Donahue (1986) can be applied to the analysis of microdebitage as a marker for human activity in archaeological sites.

2.5 Investigating rock art

As this thesis outlines, microdebitage can be of use in research involving rock art. Research on rock engravings and rock art in general has been undertaken in two distinct manners: scientific and interpretative. This thesis outlines the scientific methodologies and hypotheses involved in the search for microdebitage derived from the making of rock engravings. The research undertaken will be viewed as complementary to investigations of meaning and interpretation of the art depicted in archaeological sites.

The procedures most frequently used for archaeological analysis of rock art sites are outlined by Layton (1992). Investigation begins after the first identification of the assemblage of figures at a site. This proceeds to record their shape and colour, deducing the techniques by which they were made, and examining the distribution of the same motifs between sites. Layton (1992) has devised general strategies for the investigation of Australian rock art sites, which is outlined thus:

1. Locate figures.
2. Record form and colour; measure dimensions; deduce technique.
3. Categorise the figures into motifs.
4. Infer representational quality (sometimes); count motif frequencies; seek correlation between technique, motif, and apparent age; identify the same motif in different sizes, ranges; plot the distribution of figures on the panel at the site.
5. Group motifs according to style.

Between sites, variation in time:

1. Establish age by means of carbon 14, calcrete deposits, and cation ratios.
2. Date start of site occupation, site abandonment.
3. Look for depiction of extinct species.
4. Document relative weathering, superimposition.

Seek correlation between:

1. Change in content (superimposition depicted, technology).
2. Usage in associated habitation debris, change in style.

Between sites, variation in space:

1. Plot distribution of sites in landscape.
2. Distinguish major and minor art sites.
3. Seek correlation with ecology and habitation debris.
4. Map distribution of motifs and styles between sites.

These procedures summarise Layton's (1992) comprehension of the archaeological procedures for a systematic method of investigating rock art sites. The dating of rock art must be part of an all-encompassing investigation, and not just the quick answer to the question of the art's age (Layton, 1992).

To add to the general contextual understanding of rock pictures, Flood (1997) employs the term *rock art* as a general label for deliberate marks or images on a rock surface. Rock art is comprised of two principal classes: pigmented art and rock engravings. Pigmented art is produced by adding pigment to rock surfaces, and rock engravings are the result of extraction or removal of material from the rock surface by hammering, pounding, abrading, drilling or scratching the rock surface (Flood, 1995, 1997).

Two techniques are employed in the manufacture of engravings. *Direct percussion,* whereby a sharp pointed hammerstone of fist-sized proportions is used to peck or hammer directly on the rock surface. *Indirect percussion*, employing a pointed 'chisel' made of stone, which can be hit, with a cobble hammerstone or a wooden hammer. Different methods are employed on softer or harder rock surfaces, depending on the type of rock, the cultural context, or the geographical region of the engraving (Flood, 1997; Clegg and Stanbury, 1990).

Quartz has been used in Australia as a raw material for lithic technology. Implements made of quartz are found in many ancient Australian assemblages, and make up a high proportion of material type usage. Sullivan (1973) outlines the existence of quartz tool industries at Australian archaeological sites. Use of quartz in the manufacture of stone tools is less common than the use of other materials such as chert, chalcedony, siltstone, and other siliceous stone. The problems identified by Sullivan in the analysis of quartz lithic technology stems from the nature of quartz: it produces more flakes per tool than other materials, making the process of identification of the artefact difficult (Sullivan, 1973). The features on the surface of quartz flakes (some of which also appear on microdebitage) can be observed as concavities, convexity of bulbs of percussion, positive and negative bulbs and shatterlines, ripples, striking platform, and small flake scars. Sullivan (1973) observed the presence and absence of these features, and the identification of flakes depends on the presence of any four of these features.

The investigation of rock art has been difficult primarily due to the lack of correlation between style and time. Stylistic chronologies do not always correlate with temporal chronologies, making the process of investigation much more difficult. The need to test stylistic chronologies against a more reliable temporal marker can be undertaken by employing Quaternary dating methods which will help to fix a stylistic form of rock art in time.

2.6 Dating sediments and rock art

Dating rock art has proven particularly difficult because of the nature and processes associated with the art and sedimentary deposits. Dating rock engravings may be done directly by dating the engraved surface, and indirectly by dating the nearby sediments. This thesis investigates the possibility and reliability of using microdebitage as an indicator of the manufacturing of rock engravings and other associated lithic technologies. The experiments undertaken and the evaluation of results may also assist in dating material through stratigraphic association of microdebitage and other instances of human activity.

Diagnostic microdebitage may occur with datable materials, such as charcoal for radiocarbon determination using accelerator mass spectrometry (AMS), or sand-grains that could be dated by optically stimulated luminescence (OSL) or thermoluminescence (TL). Hence, the archaeometric potential of microdebitage is realised in the chronological data gathered for archaeological sites. Microdebitage from rock engravings may occur in the stratigraphy of rock art sites and nearby archaeological deposits. It is envisaged that microdebitage (quartz grains) may be dated directly by employing OSL techniques, or indirectly by dating the stratigraphic unit in which the microdebitage occurs.

Knowing the date of a particular rock engraving or a painting is archaeologically meaningless without the context of which the date is part. Knowledge of age becomes important when related to intrasite comparisons or stylistic region. Intrasite comparison becomes important in providing further evidence of time and distance in the spread of human activity. Dating methods are therefore an important aspect, but not the exclusive methods, by which answers to the questions posed may be acquired.

The least invasive technique to the rock art is to date human activity in archaeological deposits associated with it. For example, the remains of human activity may be found by excavating the stratigraphy in the floor of an overhang on which rock art is depicted (provided the deposits have not been disturbed by erosion/removal, and no recent deposition of unrelated sediments has occurred). Radiometric and other techniques can date discarded tools, fires, and food remains. It may be argued that these events and materials may give a possible *terminus anti* and *post quem* for the rock art that is associated with human activity at archaeological sites. However, the argument is based on the link or possible links of the occupation deposits to the rock art. The possibility exists that those who manufactured the art may not have been the same people who inhabited the area. Minimum ages can be established by means of the association of motifs buried by datable soil deposits: the deposited material covering them must be younger than the motif. Superimposed motifs can give a relative age to specific images within a site. Where there are animal species depicted, these may be linked to the presence or absence of a particular animal or plant species in the

area or be linked to mental schemas of potential food sources, or be simply a teaching device. Minimum ages in rock art can be assessed by known age of the figure content depicted; this can include the depiction of items such as guns, horses, cows and ships, which in Australia are of known European origin and were not depicted prior to European contact. Another manner of estimating minimum age is to use the rates of weathering or fading of paintings or engravings to achieve an appropriate relative age (Frankel, 1991).

Dating can be broadly divided in two categories: relative and absolute. Some of the relative dating methods can be calibrated with absolute dating which may assist in narrowing and refining dates. Relative dating entails the use of deductive reasoning assisted by sequential analyses. Absolute dating methods can be calibrated against each other, to increase accuracy. However, problems exist in the conversion between an uncalibrated and calibrated date (actual calendar date), making the conversion difficult and in many instances unreconcilable. For example, there is a difference between dates achieved from carbon samples taken in the same stratigraphy as quartz grains. Radiocarbon years do not correspond to TL dates, even where samples are taken from the same stratum. The conversion of these to calendar years can be difficult and the calibration may contain large error bands in the estimated age range.

Dating techniques are extremely variable and some need calibration with other methods. Table 2.6.1 and 2.6.2 lists these methods.

Table 2.6.1. Absolute and relative dating methods (after Renfrew and Bahn, 1991:102-139).

Absolute dating methods	**Relative dating methods**
Calendars	Stratigraphy
Glacial varves	Typological sequences
Radiocarbon	Seriation
Thermoluminescence	Linguistic dating
Electron Spin Resonance	
Potassium- Argon	
Uranium Series	
Fission Track	

Table 2.6.2. Calibration of relative dating methods (after Renfrew and Bahn, 1991:102-139).

Calibrated relative methods	Note:
Obsidian Hydration Amino-acid Racemisation Cation-ratio Paleo-magnetism Geomagnetic Reversals Climate and Chronology Deep sea cores Pollen dating Faunal dating	The relative dating methods can be calibrated using radiocarbon or radionucleide dating (eg. Uranium Series, Stable Isotopes ratios, and other isotopes which decay at a steady and known rate)

Calibrated relative dating methods use the association of an absolute dating method to achieve a more reliable date for material that cannot be dated directly. This can be based on the availability of material types in sediments. As an example, quartz grains can be dated directly with OSL or TL. A single grain of quartz can be used if the right conditions for dating apply. This grain can also be quartz microdebitage, allowing the direct dating of an artefact. Other materials can be used to both calibrate and/or directly date sedimentary strata. The material used can consist of quartz, carbon, pollens, bones, teeth, shells, and many others. Each technique is developed for a specific target material (Wintle, 1996). The time span for each method is listed in Table 2.6.3. and 2.6.4.

Table 2.6.3. Range of absolute dating methods (after Renfrew and Bahn, 1991: 112).

Absolute dating methods	Time span (range in years BP)
Calendars	0-5,000
Glacial varves	0-12,000
Radiocarbon (^{14}C and AMS)	100-40,000
Thermoluminescence	0-450,000
Electron Spin Resonance	5,000-2,000,000 and over
Potassium- Argon	40,000-over 5,000,000
Uranium Series	50,000-500,000 and over
Fission Track	200,000-over 5,000,000

Table 2.6.4. Range of calibrated dating methods (after Renfrew and Bahn, 1991: 112).

Calibrated relative methods	Time span (range in years BP)
Obsidian Hydration	0-500,000 and over
Amino-acid Racemisation	200-100,000
Cation-ratio (calibrated with ^{14}C)	100- 40,000
Cation-ratio (calibrated with K-Ar)	40,000-3,000,000 (Dorn, 1983)
Paleo-magnetism	0-6,000
Geomagnetic Reversals	100,000-over 5,000,000

The dating methods discussed below may be useful to establish the age of depositional material from archaeological sites. It is envisaged in this research that optically stimulated luminescence on quartz microdebitage from archaeological deposits may yield an estimated chronometrical date if calibrated with at least one other dating technique.

2.6.1 Radiocarbon dating

Radiocarbon determination, or carbon 14 (^{14}C) dating has been the most widely used Quaternary dating method for the last fifty years (Taylor, 1997). Accelerator Mass Spectrometry (AMS), developed from the conventional ^{14}C dating method, requires smaller amounts of carbon. Radiocarbon determination is an analytical technique that uses an ion accelerator and its beam transport system to measure the decay rate of various radioisotopes. In radiocarbon dating, the AMS technique measures the decay rate of ^{14}C isotopes. The decay rate is then converted and calibrated by mathematical formulae into a date in time. Radiocarbon is produced in the atmosphere and absorbed by plants through carbon dioxide, and by animals through feeding off plants or other animals. Uptake of ^{14}C ceases when the plant or animal dies. After death the ^{14}C remaining in the tissues of plants and animals decays at the rate of 50 per cent after 5730 years (half-life). The measurement of the amount of ^{14}C left in the results in a date (Renfrew and Bahn, 1991).

In several rock art sites, some of the pigments used in paintings contain organic matter and charcoal. It is from this charcoal component that ^{14}C can be extracted for dating. Research undertaken by McDonald *et al*. (1990) on the dating of prehistoric rock art in the Sydney Basin has revealed that:

> "The ability of AMS to handle very small samples of charcoal ... suggests that this technique is suitable for dating what has been a previously undateable artefact. Initial results suggests a Pleistocene antiquity for some of the art which had been assumed was Holocene in age" (McDonald *et al*., 1990: 83).

The AMS technique uses only 0.5mg of carbon, making this system less invasive than the conventional radiocarbon method that uses much larger samples (Heijnis and Tuniz, 1994). Classic Carbon 14 dating and AMS are very useful techniques for producing dates between 300-400 and 40,000 years. This method is widely used in Australia to date Aboriginal sites that pre-date European contact.

In recent years, it has been proposed that there are limits to the successful use of radiocarbon. Firstly, contamination could change a sample of infinite age into one with an apparent age by introducing particles of contemporary carbon (Beck *et al*., 1998) to older samples. Secondly, the maximum age datable is 40,000 years with AMS from the prior age of around 30,000 years (Roberts *et al*., 1993, 1994; O'Connell and Allen, 1998; Allen and Holdaway, 1994; Fullagar *et al*., 1996; Chappell *et al*., 1996).

O'Connell and Allen (1998) questioned the correlation for the existence of a limit at 40,000yr BP on the chronology for Australian sites based on the lack of such a phenomenon in geological dates. Apparently, difference exists between the archaeological and geological chronologies (O'Connell and Allen 1998; Allen and Holdaway, 1994; Jones, 1993), which are dated with radiocarbon methods. Researchers intent upon verifying the existence of the limits for radiocarbon dating in Australia investigated several early sites using thermoluminescence and optically stimulated luminescence as methods, which are not bound by the limits of carbon dating. However, the difference between radiocarbon years and thermoluminescence years is not yet fully understood nor calibrated.

2.6.2 Thermoluminescence and Optically Stimulated Luminescence

These techniques are known as "trapped charge" dating methods (Heijnis and Tuniz, 1994). Thermoluminescence (TL) dating of sediments depends on the electron storage capacity of crystalline minerals. Used originally to date pottery and other inorganic material such as burnt flint, TL can be useful to date archaeological finds in sediments associated with rock art by using the charge trapped in quartz grains. This technique can supply an earliest relative date for the art by dating pottery or flint from the lowest occupation level in the

stratigraphy (Renfrew and Bahn, 1991). The method is based on the notion that crystalline structures contain small amounts of radioactive elements.

Small amounts of uranium, thorium and radioactive potassium decay at a known and steady rate, and emit alpha, beta and gamma radiation. This radiation bombards the crystalline structure and displaces electrons that become trapped in the imperfections in the crystal lattice. When the material is heated rapidly to 500^0C, or above, the trapped electrons escape, resetting the clock to zero. As the electrons escape they emit light, known as thermoluminescence (Renfrew and Bahn, 1991). By measuring the amount of TL emitted when the sample is heated in the laboratory at 500^0C or more, the age of the sample (this example is pottery) can be determined since the original firing (in the case of quartz grains, since the last exposure to sunlight). Age determination is achieved by the application of this simple formula (Bateman and Bragg, 1996; Aitken, 1997), in which the TL date is achieved by the total accumulation of radiation (saturation of the crystal) minus the annual dose (expressed in Grays).

$$\text{TL Age} = \frac{\text{Total Accumulated Palaeodose (Gy).}}{\text{Annual Radiation Dose (Gy/a).}}$$

There are problems with this technique. The most common aspect that can affect the resulting date is the position of the sample in the soil. Ideally, the sample should be at least 30cm from any change in the stratigraphy and from rocks that can interfere with the accumulation of natural radiation. There are also problems of calibration to achieve absolute dates. However, new techniques for calibration are being developed (McFee and Tite, 1998). Another problem is that the sample to be dated should be kept in the same condition as it was in the soil, away from exposure to natural light and packed in the surrounding natural soil. The associated natural soil is used to measure the amount of natural radiation that helps to refine the technique to determine only the radiation of the sample (Heijnis and Tuniz, 1994).

It may be implied that dates resulting from TL are equivalent to the date of human occupation of a site. The date is actually the date of deposition and sedimentation of the quartz grains (Aitken, 1997). It is by associating the

sedimentary stratigraphic unit with human occupation that the date for a site is assumed. In the case of the Jinmium rockshelter site in the Northern Territory, Australia (Fullagar *et al.*, 1996), dates spanning from 16,000 years for the upper sediments, to a TL date of 176,000 years for the lowest level of the sediment which contained artefacts. These dates have been proven to be erroneous probably due to contamination (with an older grain of quartz) of the sedimentary layer or during the taking of the sample. The new dates, calibrated with OSL and ^{14}C methods, gave a maximum date of 22,000 years, well within the range of other human occupational sites in the Northern Territory (Roberts *et al.*, 1998; and reported by Goldie, 1998; and Schuster, 1998). The earliest known human presence on the Australian continent has been documented at Lake Mungo (skeleton LM3) at 62,000 ± 6,000years with ESR and Uranium Series dating (Simpson and Grün, 1998). The sediment in the same stratigraphic unit has been dated with OSL at 61,000 ± 2,000 years (Thorne *et al.*, 1999).

Optically stimulated luminescence (OSL) is a relatively new technique being applied to the problem of chronological dating of mineral grains in sediments (Huntley *et al.*, 1985; Aitken, 1994). It can be used to date quartz- and feldspar-rich sediments where material for radiocarbon determination is unavailable. Quartz and feldspar sediments can be dated absolutely within a range of 100 to 200,000 years, with an error of ±~10%. All sediments contain low concentrations of potassium, thorium and uranium that produce, over a period of geological time, a flux of ionising radiation (Bateman and Bragg, 1996). This radiation is absorbed and stored in the surrounding sediments until it is released by heat stimulation, in a process similar to TL.

The OSL method is similar to the TL method. The different approach, at least for archaeological research, has produced a better understanding of sedimentary deposits and has highlighted problems associated with calibrated/uncalibrated dates and the limits of TL and OSL dating (Roberts *et al.*, 1998). OSL can extract a date from the decay of radiation in quartz grains previously exposed to sunlight and then buried.

As for TL, the sample is taken to a laboratory, but not exposed to heat but exposed to light simulating a solar bombardment of particles. A date is then extracted in the same manner as it is for TL (Spooner *et al*., 1988; Spooner, 1994).

The new OSL technique has an enormous research potential, especially in Australia, where it was developed and applied to a variety of archaeological and geological sites (Huntley *et al.,* 1993). Recently, this technique has been employed for the dating of mud-wasp nests (CSIRO, 1993), since they contain quartz crystals that have been exposed to sunlight and then incorporated (away from sunlight). Roberts *et al.* (1997) and Morwood *et al.* (1994) have explored this technique for dating rock art in the Kimberley region in the northwest of Australia. Mineral encrustation and mud wasp nests are found under and over rock paintings in many sites, and contain minute fragments of carbon for which a maximum and minimum date can be estimated by taking samples from nests which overlap, or is under the pigment. The implications suggest the possibility for the use of AMS, OSL, and TL to date the same site, cross-referencing the dates to produce a sequence for the art within the same site (Watchman *et al*., 1997; Roberts *et al.,* 1997; Morwood *et al.,* 1994).

TL and OSL dating have produced dates greater than 40,000 years for three sites in Australia: Nauwilibila I, Malakanunja II and Jinmium (O'Connell and Allen, 1998; Smith and Sharp, 1993). These sites exhibited similar profiles, consisting of small rock shelters associated with sandy deposits containing flaked lithic material, debitage, and ochre with a sandstone rubble at its base (O'Connell and Allen, 1998). The Malakanunja and Nauwilibila sites produced a maximum date for human presence of 50,000 to 60,000 years using both TL and OSL on sediments bracketing strata containing artefacts (Roberts *et al*., 1990; O'Connell and Allen, 1998).

Revision of the dates reported at Jinmium (Roberts *et al*., 1998; Goldie, 1998) has provided new insights into the problems of contamination occurring with TL dating. Roberts *et al.* (1998) re-dated the site with OSL using single quartz grains from various stratigraphic units at the site, finding it remarkably younger than previously thought, around 10,000 years old (also confirmed by ^{14}C). This

technique has revealed that the larger amount of quartz grains needed for TL dating may be more susceptible to contamination from older grains. Problems associated with OSL single grain dating can be as problematic as with TL. The grain used may not fully reset the signal (Murray and Roberts, 1997), therefore; the grain may yield a date unrelated to the stratum. However, the use of multiples of a single grain can be more accurate than one grain per sample. If one of the grains has not totally reset the signal, the resulting date is not accurate enough to be of use. Presumably, also all grains tested, apart from one, will yield a similar age.

Murray and Roberts (1997) have applied a single quartz grain technique for dating archaeologically significant sediments at Allen's Cave in South Australia. Advances achieved by Murray and Roberts in the technique are based upon the works of Huntley *et al.* (1985) and Wintle and Huntley (1980), among others, on the use of thermoluminescence and optical dating for sediments (Murray *et al.*, 1997). As stated earlier, the problems of contamination for larger samples used with TL dating have proved to be problematic for archaeological deposits due to disturbance in the sediments. Murray and Roberts (1997) dated an aeolian deposit with OSL that was previously dated at 10,000 years old by ^{14}C. The date with OSL reflected the radiocarbon date.

2.6.3 Electron Spin Resonance (ESR)

Electron spin resonance dating has been applied to a variety of materials in archaeology, geography and geology. It allows the dating of materials such as tooth enamel, mollusk shells, corals, volcanic minerals, heated flint and quartz extracted from ceramics. ESR can be grouped with TL and OSL as a *trapped charge* dating method. According to Grün (1997), the use of ESR for dating quartz in ceramics has not been totally successful, as the technique is far less sensitive than TL and OSL. The technique is often used in conjunction with uranium series dating, which has produced good results for dating tooth enamel and shells (Grün, 1997). Deposits from Lake Mungo (skeleton LM3) were dated at 62,000 ± 6,000 years with ESR in conjunction with uranium series dating (Simpson and Grün, 1998). The technique is similar in its basic theory to TL and OSL.

2.6.4 Cation-Ratio dating

Recently, experiments have been conducted in dating rock varnish formations in desert environments, to determine the age of rock engravings by measuring the ratios of potassium, calcium and titanium cations present in varnish. Known as Cation-ratio dating (CR), this technique allows the establishment of minimum ages for rock carvings and engravings exposed to desert conditions. The varnish forms in arid conditions on rock surfaces exposed to desert dust, and is composed of clay minerals, oxides and hydroxides of manganese and iron, with minor trace elements, and minute traces of organic matter (Nobbs and Dorn, 1988; Schneider and Bierman, 1997). This technique is based and reliant on the understanding and unraveling of the layered desert varnish morphology and microchemistry (Dorn, 1983; Dragovich, 1998). Cation-ratio values in desert varnish were initially used as a relative age indicator. Later the CR's were calibrated using AMS radiocarbon dated organic material in the same varnishes (Dorn, 1983; Nobbs and Dorn, 1988, 1993). The dating method is based on the principle that cations of certain elements are more mobile than others. These cations leach out of rock varnish more rapidly than the less soluble elements and their relative concentration decreases with time. The method requires the measurement of the ratio of some more mobile cations, usually potassium and calcium, to the more stable cation of titanium. The ratio is assumed to decrease exponentially with time (Renfrew and Bahn, 1991).

Some controversy is associated with this method, as is explained by Dorn (1992), one of the scholars who developed the method. First and foremost, varnishes are subject to environmental variability. Being a chemical dating method, if dissimilar varnishes or leaching environments are compared, the results will be erroneous. In recent years, the cation-ratio dating method has undergone some changes. The method does not only rely on inorganic rock varnishes, but also on the dating of the varnish's organic matter (Watchman, 1992). Radiocarbon dating methods, such as AMS, are more commonly used to date the organic matter lying underneath the varnish. Since the organic matter has accumulated after the rock art was manufactured, this provides a minimum age for the art.

The dates achieved are therefore younger than the rock art (Dorn, 1983, 1992).

Cation-ratio dating has encouraged the development of a new avenue for carbon extraction techniques. One of the most recent techniques employs lasers to extract carbon and other trace organic matter from some of the rock art. Both rock paintings and rock engravings have a micro-stratigraphy that contains carbon particles. With a laser, it is now possible to extract these particles from the micro-stratigraphy and to achieve a date for each stratum. This innovative technique can extract carbon particles from fatty acids and oxalate minerals contained in pigments or desert varnishes, making it possible to achieve multiple dates from superimposed paintings or retouched rock engravings employing the AMS dating technique. This can only be done with rock engravings if sufficient varnish and organic materials are removed to permit AMS dating (Watchman and Lessard, 1992).

The CR dating method was used to date rock engravings in the Olary region of South Australia, where CR were calibrated and correlated with radiocarbon ages. Correlation with AMS dating has provided dates for twenty-four individual engravings (Nobbs and Dorn, 1988, 1993). Some recent discussions have questioned the CR method. It is however, not currently known if CR dating is in question, or the methods and outcomes used by Dorn (Beck *et al.*, 1998), or Dorn's methods as replicated by Beck *et al.* (Dorn, 1998).

2.6.5 Amino-Acid Racemisation (AAR)

This technique can be used to obtain a relative minimum or maximum age, although indirectly, for the rock art of a site. This method is based on the fact that amino-acids, which are proteins present in all living organisms, can exist in two forms, D and L. After death, the organism's L amino acids are steadily transformed in D amino-acids (they racemise) (Hare *et al.*, 1997). The ratio of D amino-acids and L amino-acids is used to produce a date for the material. Each organism has a different, but steady, rate of transformation, requiring calibration for each species. Dates can be obtained from bones, shells of any species and land snails (Ellis *et al.*, 1996), up to about 100,000 years old (Renfrew and Bahn, 1991).

There are limits to the sampling method for this technique. The samples must be collected from at least a 1m depth below the natural ground level, and the material must not be heavily weathered. Materials that are collected in coastal or fluvial waters and permanently saturated soils are very good for dating. Several specimens from the same deposit must be collected to assess the variability between individuals of the same species in order to find a mean rate of transformation of the amino-acids (Heijnis and Tuniz, 1994). Furthermore, as AAR depends on the presence of albumin binders (blood or egg white) in pigments, these must have being used in the preparation of the pigment to be able to date rock paintings. The technique is limited to dating pigment binders less than 1800 years old. Pigment binders deteriorate, as a result of the number of amino-acids decreasing in time (Thackeray, 1983).

Calibrated with radiocarbon (AMS) the Amino-acid racemisation technique has been used by Murray-Wallace *et al.* (1996) for the production of a chronological sequence for the ocean floor on the Australian southeastern continental shelf. AAR and AMS was used to record the sequential sedimentary structure by using carbonate-rich sands and mollusks, and the recording of evidence for sedimentary reworking, by using two mollusk species to ascertain the D/L ratios. The research concluded that AAR supports and extends the radiocarbon chronology of the shelf, and that AAR may be able to date beyond the limits of radiocarbon (Murray-Wallace *et al.*, 1996). Results using AAR and AMS can be of use in land-based archaeological deposits, especially middens and occupational deposits. This technique can also be successfully used to support other dating methods for sediments.

2.7 Problems associated with dating techniques

All the dating techniques discussed can be employed to achieve a date for rock art. As a cautionary note, it must be highlighted that in recent years, TL dating in Australia has produced dates significantly older than radiocarbon determination (^{14}C). These results may have serious repercussions in the chronological assessment of the Upper Palaeolithic period in Australia and New Guinea (Allen, 1994; O'Connell and Allen, 1998).

The archaeological understanding of human occupation by chronologically relating sites has been greatly enhanced by the use of absolute dating techniques.

All these Quaternary dating techniques have problems related to calibration and derivative absolute or relative dating. Assumptions in the chronological record for archaeological sites, in many instances, are based on the statement of other dates achieved for similar material and comparable sites. Notwithstanding the (some times) lack of reliability or calibration of these dating techniques, these may be used for directly or indirectly date microdebitage.

The incorporation of rock art studies, and new dating techniques, may lead to the use of microdebitage to be used for the spatial and temporal analysis of human occupation sites (Smith and Pell, 1997; Patel *et al*., 1998). Both calibrated and uncalibrated dates have been produced. Sediments yield much information regarding ancient environments, both human and natural. This thesis aims to contribute to distinguishing between natural sediments and deposits derived from human activity.

The analysis of deposits in archaeology needs to be extended to include microdebitage from rock engravings. The work of Shackley (1975) has incorporated the study of sediments for archaeological investigations, and much detail was devoted to sedimentary analysis for archaeology. However, a consideration of microdebitage was not included. The study of rock engraving microdebitage has been made possible following the contribution to the analysis of sediments by both archaeologists and geoscientists. The works of Gale and Hoare (1991), Selly (1988), Briggs (1977), and Powers (1953) in Geosciences has been extremely useful for the development of ideas and techniques used in this thesis. Other research and methodologies were developed and integrated in this thesis for the interpretation of results and possible archaeological applications of new techniques.

Chapter three

> *"More than 4000 quartz sand grains surfaces have been examined by electron microscopy, and it has been established that surface differences exist depending on the environment of transportation and deposition. Littoral, aeolian, glacial, diagenetic, and combinations of these four environments can be distinguished..."*
>
> *David Krinsley and Jack Donahue (1968:743).*

Quartz microdebitage—shapes and surface features

The previous chapter described how microdebitage is related to human lithic activity, including the manufacture of rock engravings. With the recent advances in Quaternary dating technology, one of the outcomes in the discovery of archaeological sites, has been the ability to undertake chronological placement of sites in vast areas of Australia (O'Connell and Allen, 1998).

Quartz and other siliceous material can be used for dating sediments and archaeological deposits with optical dating techniques. Quartz microdebitage may be differentiated from naturally occurring quartz grains in sediments by the breakage features on the surface.

This chapter outlines the research undertaken on quartz grains and microdebitage by comparing samples of differing provenance. This was done to understand how microdebitage differs from sedimentary and other depositional quartz grains. To achieve this, the shape and features of different samples were analysed in two methodologically different settings. The first part deals with shape of grains (roundness-*versus*-angularity); and the second, with quartz grains surface features.

3.1 Samples—choice, source and environment

The analysis of microdebitage as described by Fladmark (1982), was not entirely successful in dealing with quartz microdebitage. In order to distinguish quartz microdebitage from natural occurring grains in sediments, visual comparisons were made.

A two-fold strategy was devised to answer questions related to microdebitage and naturally available quartz grains:

1. *Is quartz microdebitage more rounded or more angular when compared to naturally occurring grains in different environments (or in similar environments of different age)?*
2. *Does microdebitage have different or similar surface characteristics to naturally occurring quartz grains?*

These questions were devised to determine whether quartz microdebitage could be distinguished from other quartz grains in sediments. Important for this part of the research design, is the comparison between microdebitage and naturally occurring quartz grains as a marker for future recognition under field conditions. To analyse natural grains and microdebitage, a series of samples were collected from different sources (table 3.1.1). The known environmental history rather than their archaeological history determined the sample choice. This was applied to better understand the differences between microdebitage and

Table 3.1.1. Sample classification according to environmental provenance and source.

Sample	Environmental provenance	Source
BH-E1	Mootwingee Sandstone (microdebitage)	Mutawintji (Broken Hill NSW)
BH-E2	Mootwingee Sandstone (microdebitage)	Mutawintji (Broken Hill NSW)
BH-E3	Mootwingee Sandstone (microdebitage)	Mutawintji (Broken Hill NSW)
BH-C1	Aeolian sediment (?)	Mutawintji (Broken Hill NSW)
BH-C2	Aeolian sediment (?)	Mutawintji (Broken Hill NSW)
BH-C3	Aeolian sediment (?)	Mutawintji (Broken Hill NSW)
SY-C1	Beach sand	Maroubra (NSW)
SY-C2	Pleistocene sand dune	Pagewood (NSW)
SY-C3	Hawkesbury Sandstone (building block)	University of Sydney (NSW)
SY-G1	Glass (broken ashtray)	Sydney, NSW (unknown source)

Table 3.1.1 lists the type of sample environments. The samples of sediments from Mutawintji (BH-C1-BH-C3) are from trapped sediment in a sandstone outcrop. These could have weathered directly from it without having been transported. The choice of environments and source of the material was based on the material available at the time in the Division of Geography (University of Sydney); this material originated from environments that differed considerably from the Mutawintji environment (semi-arid). The elaboration of comparisons between

the microdebitage samples and the Mutawintji sediment samples was of primary importance, since the microdebitage is derived from the same rock, providing much of the associated sedimentary material. Differences and similarities between the parent rock and the sediment may be the prime detection that microdebitage is different from the sediment. The samples used for analysis were collected from sources devoid of archeological deposits, which could have interfered with the recognition of microdebitage against sedimentary material.

The naturally occurring sediment samples from Sydney (SY-C1 and SY-C2) and Mutawintji (BH-C) were sieved from a standard 100g of material. The other samples were considerably smaller.

3.1.1 Microdebitage samples

Samples of microdebitage were collected at Broken Hill, NSW. The raw material for the rock engravings is sandstone slabs, collected at Five-Mile Creek (Two Mile Tank) in the vicinity of Mutawintji (Broken Hill, NSW). The tool materials vary from quartz to quartzite, and were collected in a dry creek bed by Dr Witter (NPWS archaeologist). Dr Witter prepared the tools, and Badger Bates (Aboriginal artist and member of the Mutawintji LALC, figure 3.1.1.1) manufactured the rock engraving. The material was prepared as part of rock engraving experiments conducted under the direction of Mr John Clegg (Clegg, 1997a, 1997b).

Thin sections of the tools showed that tool T6 is composed of tightly bonded sub-angular to sub-rounded quartz grains, with a size range of 0.1-0.3mm (see Appendix 5 graph A5.4 and figure A5.7). Tool T7 is composed of tightly bonded, sub-angular to angular quartz grains with a size range of 0.1-0.4mm (see Appendix 5 graph A5.5 and figure A5.8). Tool T9 is composed of quartz with large, very angular crystals in the range of 1-3mm in diameter (see Appendix 5 graph A5.6 and figures A5.9 and A5.10). The use of the quartz tool T9 can be seen in Figure 3.1.1.1 during the manufacturing process of experimental engraving E3. Engraving E3 was the smallest of the engraved figures and yielded 11.8g of microdebitage. It was completed in 21 minutes.

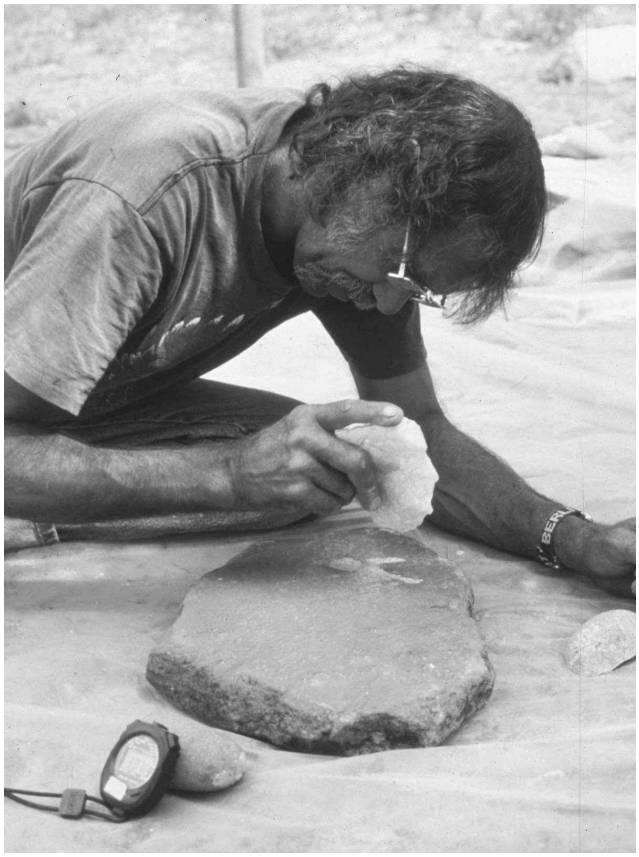


Figure 3.1.1.1. Badger Bates making experimental sandstone engraving E3 with quartz tool T9.

Table 3.1.1.1. Information on the stone tools used to make the experimental rock engravings.

Tool	Stone weight	Discarded flakes	Tool weight	Tool remaining	Tool loss weight	Engraving	Material
T6	710g	328g	382g	321.4g	58.6g	E1	quartzite
T7	886g	378g	508g	368.8g	146.2g	E2	quartzite
T9	838g	168g	670g	642g	28.0g	E3	quartz

Table 3.1.1.1 outlines the weights of all the tools manufactured for the manufacturing of the experimental rock engravings. The tools reflect the possibility that the same materials and techniques may have been used in antiquity. The microdebitage from the manufacturing of experimental rock engravings comprised of broken quartz grains and a matrix derived from pecked sandstone slabs. It was observed that a small portion of the tools used for pecking the engravings also fragmented during production. The likelihood that the microdebitage from the tools may be distinguished from the microdebitage of the sandstone slabs is minute. The material composition of the tools is similar, if not identical to quartz grains, and the breakage patterns are similar to the

material broken from the sandstone. The loss in tool weight was sufficiently high to accept that part of the microdebitage was also composed of micro-flakes from the engraving tools (table 3.1.1.1 and the total microdebitage weight in table 3.1.1.2). Most material lost in the engraving process occurred during re-sharpening of the pecking point by flaking material off the tool. Re-sharpening was conducted outside the microdebitage catching area.

At a microscopic scale, quartz can be distinguished from other materials by the use of an Electron Dispersive X-ray analyser (EDX) which analyses the chemical composition of the materials. The tool and the sandstone blocks are both composed of siliceous material. Under SEM/EDX, all the microdebitage has virtually the same chemical composition (oxygen and silica, with traces of iron oxide and aluminium, with minimal variation in percentage). This gives the possibility of chemically distinguishing between the tool and engraving microdebitage unlikely (see Appendix 5).

Table 3.1.1.2 summerises the microdebitage samples classified by sieved particle size range. The amount of microdebitage produced is related to many factors. Factors to consider may include size of the engraving; the depth of the incisions; the size of the grains in the sandstone; the compaction of the sandstone; the type of matrix of the stone are to be taken in consideration. In addition, the force of the wind while engraving, and if the sandstone was wet or dry during engraving. In this case, the experiments were conducted in dry, windy conditions.

Table 3.1.1.2. Size range and weight of debitage from experimental rock engravings after sieving.

Sample	**> 1000µm**	**1000-500µm**	**500-250µm**	**250-125µm**	**125-63µm**	**Total weight**	**Residue < 63µm**	**Tool type and No.**
BH-E1	10.40 g	6.66 g	20.07 g	9.53 g	4.37 g	52.33 g	1.27 g	Quartzite
%	20%	13%	39%	19%	9%	100%		T6
BH-E2	6.19 g	7.68 g	13.26 g	5.39 g	1.53 g	35.74 g	0.97 g	Quartzite
%	18%	23%	39%	16%	4%	100%		T7
BH-E3	2.50 g	2.61 g	3.77 g	2.19 g	0.44 g	11.80 g	0.73 g	Quartz
%	22%	23%	32%	19%	4%	100%		T9

The second column in Table 3.1.1.2 records the weight and percentage of debitage over 1cm in diameter. It illustrates that the fragmentation of sandstone using this

engraving method is not the largest percentage of the total lithic debitage residual from the manufacturing of the engraving.

The microdebitage was transported from Broken Hill to Sydney for microscopic analysis. The size fractions of the sub-samples were the same as used by Fladmark (1982) and some of his preparation methods were followed. However, Fladmark's (1982) methods were designed for light microscopy while this research followed methods for sample preparation for electron microscopy. After cleaning and sieving, the samples were labelled (Table 3.1.1.3).

Table 3.1.1.3. Size range of the sieved microdebitage from engraving E1.

Microdebitage from experimental engraving E1	
Sample Label	Sample Size range
BH-E1	Entire sample (1000-63µm)
BH-E1A	1000-500µm
BH-E1B	500-250µm
BH-E1C	250-125µm
BH-E1D	125-63µm

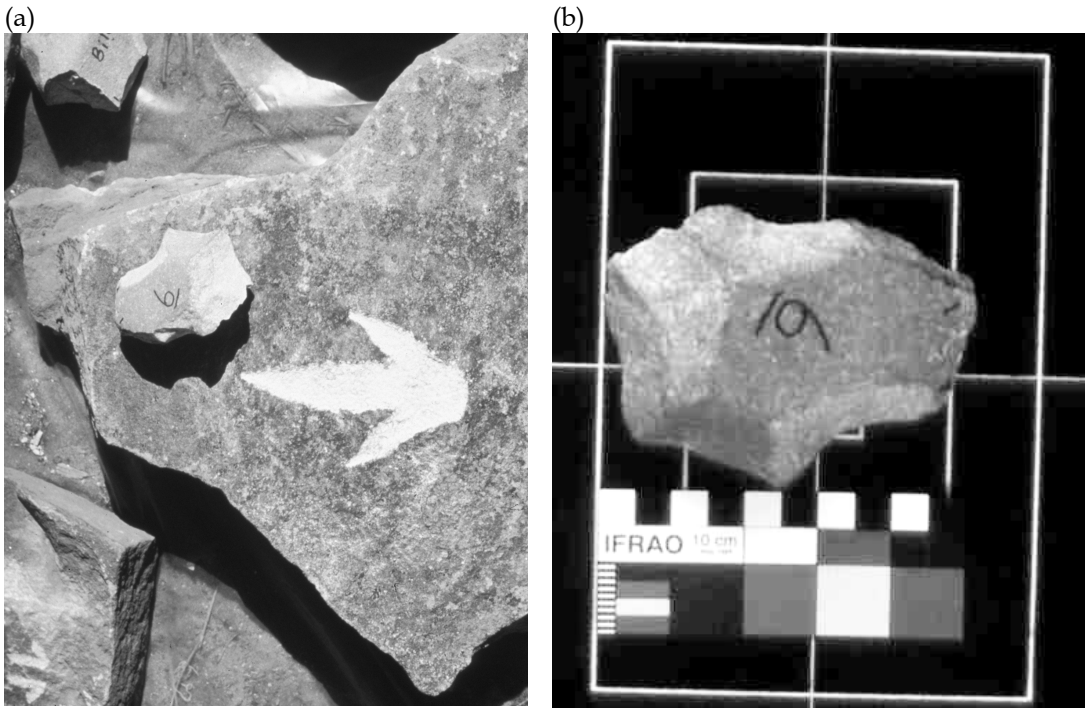


Figure 3.1.1.2. (a.) Experimental sandstone engraving E1 and (b.) quartzite tool T6.

The microdebitage (BH-E1) is derived from the manufacturing of engraving E1 with tool T6 (figure 3.1.12a and b). The E1 sandstone slab is composed of rounded to sub-rounded quartz grains, with a size range between 0.1-1mm, in a clay matrix (Appendix 5 graph A5.1 and figures A5.1 and A5.2).

The sandstone slab for the manufacturing of engraving E2 has an average composition of sub-rounded to sub-angular quartz grains in a clay matrix (Appendix 5, graph A5.2, figures A5.3 and A5.4). The microdebitage (BH-E2) is derived from the manufacturing of engraving E2 with quartzite tool T7 (figure 3.1.1.3a and b). The microdebitage was sieved in four size ranges and labelled as in table 3.1.1.4.

Table 3.1.1.4. Size range of the sieved microdebitage from engraving E2.

Microdebitage from experimental engraving E2	
Sample Label	Sample Size range
BH-E2	Entire sample (1000-63µm)
BH-E2A	1000-500µm
BH-E2B	500-250µm
BH-E2C	250-125µm
BH-E2D	125-63µm

(a) (b)

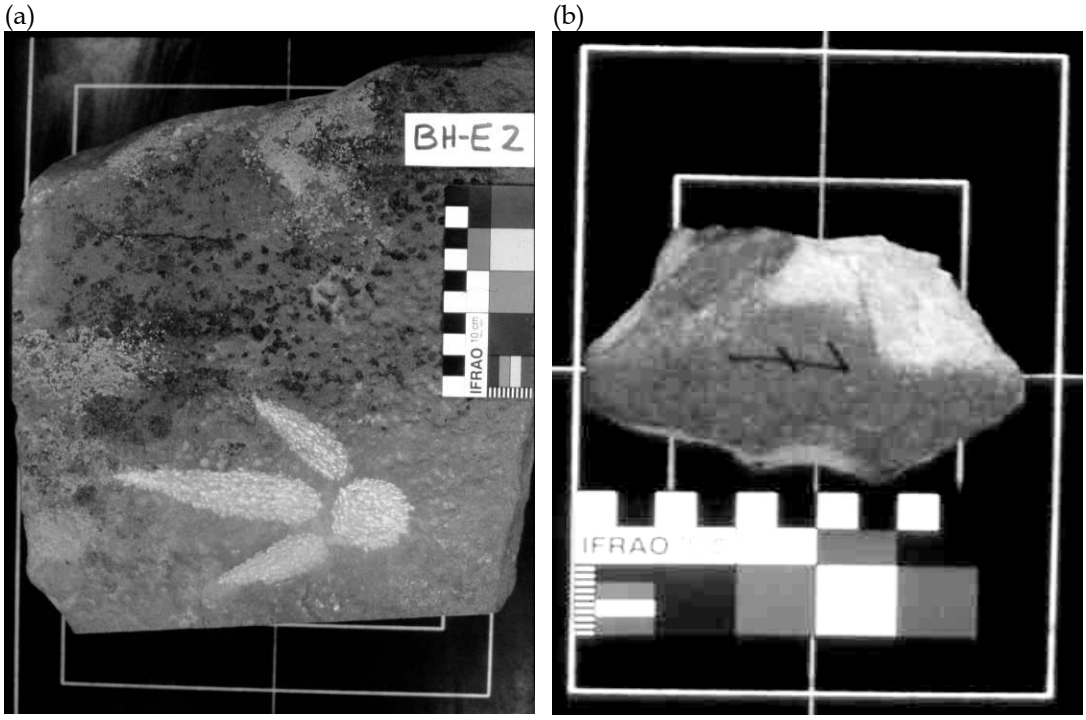


Figure 3.1.1.4. (a) Experimental sandstone engraving E2 and (b) quartzite tool T7.

The sandstone slab for the manufacturing of engraving E3 is composed of sub-rounded to sub-angular quartz grains in a clay matrix (Appendix 5, graph A5.3, figures A5.5 and A5.6). The microdebitage (BH-E3) is derived from the manufacturing of engraving E3 with quartz tool T9 (figure 3.1.1.4a and b). The microdebitage was sieved in four size ranges and labelled as in table 3.1.1.5.

Table 3.1.1.5. Size range of the sieved microdebitage from engraving E3

Microdebitage from experimental engraving E3	
Sample Label	Sample Size range
BH-E3	Entire sample (1000-63µm)
BH-E3A	1000-500µm
BH-E3B	500-250µm
BH-E3C	250-125µm
BH-E3D	125-63µm

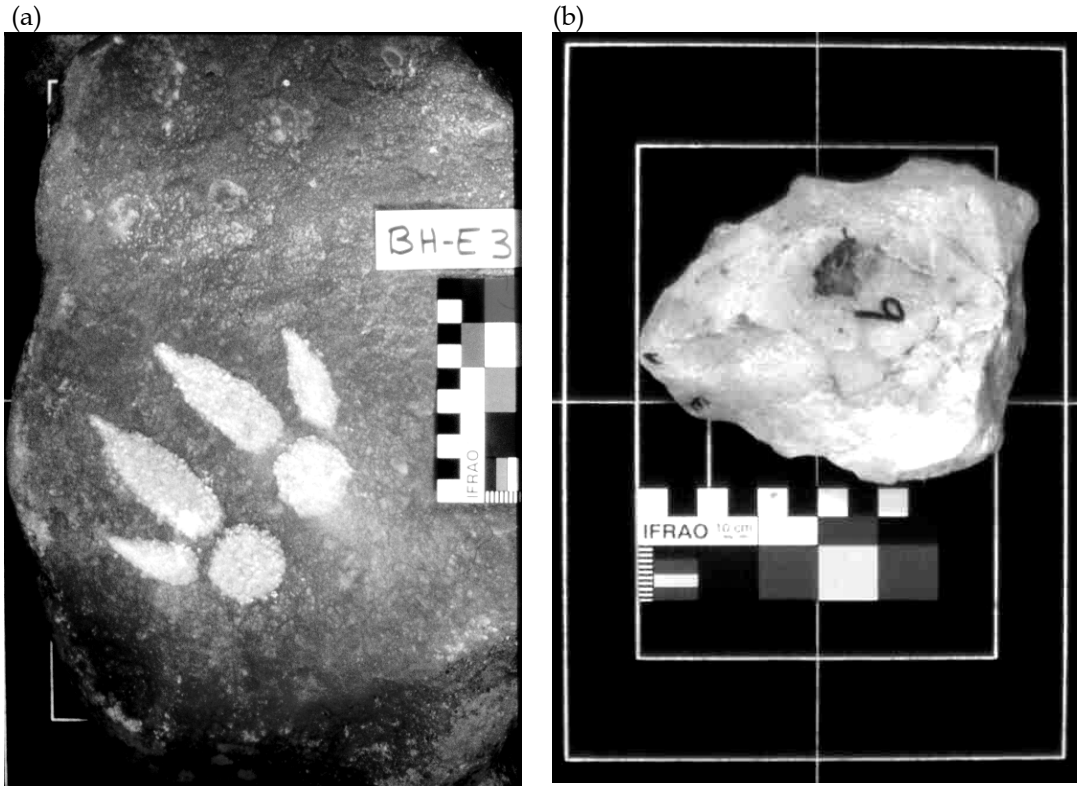


Figure 3.1.1.4. (a) Experimental sandstone engraving E3 and (b) quartz tool T9.

All the sandstone slabs reflect similarities that are consistent with them being from the same environment and geological area. The differences between slabs are minimal and generally reflect minor differences in grain size.

3.1.2 Sediment samples from Mutawintji

Dr Witter collected sedimentary material from the same environment where the sandstone slabs originated for experimental engraving. Samples were collected from an unnamed ridge at the southern extension of what is known as *Western Ridge,* about 1 to 2 km south of *Two Mile Tank* (Two Mile Creek, Mutawintji National Park, Broken Hill, NSW, Fig 3.1.2.1).

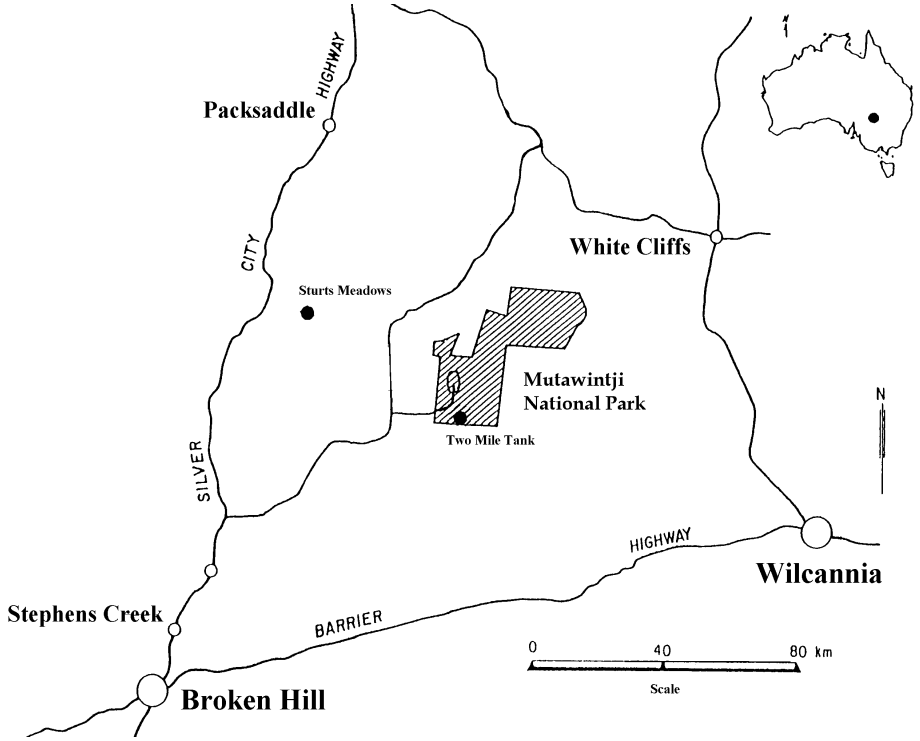


Figure 3.1.1.2. Location of Two Mile Tank, Mutawintji National Park (Broken Hill, NSW).

Dr Witter collected a sediment sample (as requested for this research) from the mid-slope position. Since the ridge is stripped of soil, consisting mostly of sandstone bedrock (Mootwingee series) and weathered sandstone rubble, it was difficult to find any sediment accumulations. However, he found a place where a dead mulga tree trunk had trapped slope wash at one point, probably stabilising the underlying sediment. Dr Witter dug a pit about 20 cm by 10 cm to a depth of 8 cm, with a sequence as follows:

> *Surface to 2 cm in depth.* Top part of the trapped deposit is probably mostly slope wash, with possibly some aeolian sediment blown up from the dunes at the base of the ridge.

Thus, it is likely to be a mixture of sand grains that have weathered out from the sandstone and been transported down slope, and sand grains from the plains further to the west (the winds are predominantly from the west). The origin of the dune sand is not known (sample BH-C1, table 3.1.2.1).

Table 3.1.2.1. Sample labelling of the sieved sediment from Mutawintji.

Mutawintji soil (0-2 cm depth) Sample BH-C1	
Sample Label	Sample Size range
BH-C1	Entire sample (1000-63µm)
BH-C1A	1000-500µm
BH-C1B	500-250µm
BH-C1C	250-125µm
BH-C1D	125-63µm

From 2 to 4 cm in depth. This may be similar in origin to the surface layer. It overlies the sandstone outcrop. Thus, the complete depth of sediment overlying the outcrop was only 4 cm (sample BH-C2, table 3.1.2.2).

Table 3.1.2.2. Sample labelling of the sieved sediment from Mutawintji.

Mutawintji soil (2-4 cm depth). Sample BH-C2	
Sample Label	Sample Size range
BH-C2	Entire sample (1000-63µm)
BH-C2A	1000-500µm
BH-C2B	500-250µm
BH-C2C	250-125µm
BH-C2D	125-63µm

From 4 to 8 cm in depth. Sediment was dug out from between the cracks in the sandstone outcrop, some of which go down to 8 cm. This sediment is most likely to have been derived from the sandstone itself, and contain very little transported material. It would therefore be the best representative of sand grains weathered directly out of the outcrop (sample BH-C3, table 3.1.2.3).

Table 3.1.2.3. Sample labelling of the sieved sediment from Mutawintji

Mutawintji soil (4-8 cm depth). Sample BH-C3	
Sample Label	Sample Size range
BH-C3	Entire sample (1000-63µm)
BH-C3A	1000-500µm
BH-C3B	500-250µm
BH-C3C	250-125µm
BH-C3D	125-63µm

3.1.3 Beach sand sample from Maroubra

The Division of Geography (University of Sydney) provided this sample for the purpose of comparison with microdebitage and sediment from Mutawintji. Dr Dragovich collected the sample. The Maroubra sample was used as an example of a modern beach environment.

Table 3.1.3.1. Sample labelling of the sieved sediment from Maroubra beach.

Maroubra beach sands (Sydney). Sample SY-C2	
Sample Label	Sample Size range
SY-C2	Entire sample (1000-63µm)
SY-C2A	1000-500µm
SY-C2B	500-250µm
SY-C1C	250-125µm
SY-C2D	125-63µm

Table 3.1.3.1 shows the labelling and the sub-sample fractions used for this research.

3.1.4 Dune sand sample from Pagewood

Dr Dragovich provided samples of material from a Pleistocene sand dune at Pagewood (NSW), as an example of ancient beach environment. This and the Maroubra sample are the ancient and modern environmental equivalent. These two samples were analysed to highlight differences and similarities between ancient and modern littoral environments in relation to microdebitage, disaggregating sandstone and aeolian environments. Although labelled for convenience and continuity, the sample did not contain material in the 125-63µm range (fraction SY-C1D).

Table 3.1.4.1. Sample labelling of the sieved sediment from Pagewood sand dune.

Pagewood sand dune (Sydney). Sample SY-C1	
Sample Label	Sample Size range
SY-C1	Entire sample (1000-63µm)
SY-C1A	1000-500µm
SY-C1B	500-250µm
SY-C1C	250-125µm
SY-C1D	*125-63µm (no material in this size range)*

Table 3.1.4.1 shows the size fractions and the labelling of the sample.

3.1.5 Sample of decaying Hawkesbury sandstone from Sydney

This sample differs from the others as it was scraped from a Hawkesbury sandstone building block at the northern end of the Main Quadrangle at the University of Sydney. The sample was collected by rubbing fingers against a weathered section of the sandstone block and the material collected on a paper sheet at the bottom of the wall. The material collected resembled microdebitage at low magnification, still containing matrix and quartz grains.

Representing heavily weathered and decaying sandstone, this sample is of value for its diagenetic variation. The Hawkesbury sandstone has sub-angular to sub-rounded quartz grains (Standard, 1969). The sample may show changes in quartz grain shape in response to exposure in an urban environment.

Table 3.1.5.1. Sample labelling of the sieved sandstone material from Sydney University.

University of Sydney sandstone. Sample SY-C3 (Hawkesbury sandstone building block)	
Sample Label	Sample Size range
SY-C3	Entire sample (1000-63µm)
SY-C3A	*1000-500µm (no material in this size range)*
SY-C3B	500-250µm
SY-C3C	250-125µm
SY-C3D	125-63µm

Table 3.1.5.1 shows the size fractions and labelling used for this research. The material in this sample was strongly weathered. The sample did not contain particles in the 1000-500µm size range (SY-C3A).

3.1.6 Sample of broken glass

Fladmark (1982) wrote about the observation of features on obsidian microdebitage. The sample of broken glass was chosen to represent material with a high silica content, in order to record differences in fracturing patterns when compared with quartz microdebitage from the manufacturing of rock engravings. The sample was sieved in the same size ranges as all the other samples (table 3.1.6.1).

Table 3.1.6.1. Sample labelling of the sieved broken glass from Sydney.

Broken Glass (Sydney). Sample SY-G1	
Sample Label	Sample Size range
SY-G1	Entire sample (1000-63µm)
SY-G1A	1000-500µm
SY-G1B	500-250µm
SY-G1C	250-125µm
SY-G1D	125-63µm

This sample was used only for a quick visual reference regarding similarities and differences between rock engraving microdebitage and material with high silica content (obsidian or glass). The comparison of these materials is discussed further with the use of scanning electron microscopy.

3.2 Quartz grains—preparation of samples

The method followed by Fladmark (1982) was modified in order to reflect the material at hand. All the samples were unconsolidated and resembled loose sand. Samples were cleaned primarily for the purpose of SEM analysis (see Appendix 3 and Appendix 4). In addition, all the samples were prepared in the same manner.

1. Each sample was gently crushed in order to break up the lumps, and air-dried for 24 hours.
2. The sample was placed in a beaker with dispersing solution [tetra potassium pyrophosphate ($K_4P_20_7$) at 1.65g per 1000ml of distilled water] for 12 hours.

3. The sample was wet sieved with dispersant in a 63 microns sieve until the dispersant passed clear. The sieve contents were gently flushed into a beaker. The sieving was done to remove the clay content from the sample.
4. The sample was then placed in a beaker with hydrogen peroxide (H_20_2) for 2 hours. Organic material persisted in the sample, so the sample was boiled gently in 30% hydrogen peroxide (H_20_2) at 90^0C for 20 minutes. This was to digest the organic material remaining in the sample.
5. The sample was then gently rinsed with distilled water seven times, and flushed into a beaker.
6. The sample was then mixed with a 30% hydrochloric acid (HCl) solution for removal of carbonates.
7. The HCl was decanted and the sample retained in a beaker.
8. The sample was washed with distilled water seven times.
9. The sample was dried overnight in an oven at 60^0C.

The samples were sieved separately and dry screened through 1000µm, 500µm, 250µm, 125µm, and 63µm sieves. Following the procedure set out by Fladmark (1982), the microdebitage remaining in the 1000µm sieve, and the material remaining under 63µm, was not used for analysis, All the samples from the screening process were weighed and bagged separately according to size fraction and source. Each fraction was further divided and randomised with a riffle box. These were then mounted on slides for light microscopy, and on aluminium stubs for scanning electron microscopy.

Initially, glass slides were produced by placing a small amount of the material on the slide with a small drop of *DePeX Gurr* mounting medium and covered with a No. 1 cover slip. This method was proved to be unsuitable due to the large air bubbles produced. As an alternative, the material was placed in a petri dish and examined with a dissecting stereo microscope (30-100x) with incident light.

Stubs for the SEM were prepared by placing a double-sided carbon tape on an aluminium stub, and dipping the stub in the sample.

This resulted in the particles adhering to the tape. Two stubs were made for each sample. One sample was coated with carbon and one with gold. The two types of coating were used to produce the best possible results. The gold coating was used for micrography while the carbon coating was used for an energy dispersive x-ray analyser (EDX), to identify the chemical composition of the minerals in the sample.

3.2.1 Preparation of samples—other methods

Other methods were evaluated in an effort to speed up the cleaning process, without interfering with the quartz grain features and retaining a clean sample. Hashimoto (1993) has provided cleaning methods from laboratory standards in Geosciences. These methods used for the analysis of quartz grains followed closely the methods of Krinsley and Doornkamp (1973), in which:

> "A sub-sample of approximately 20 g was washed in distilled water to remove mud and salt, then oven dried at 60°C. The sample was placed in an oxidising solution of 1.5 g each of potassium dichromate and potassium permanganate dissolved in 15 ml of concentrated sulfuric acid to remove organic particles and grain coating, after which it was rinsed 7 times in distilled water and oven-dried at 60°C. Carbonate fragments and oxides were removed by boiling the sample in concentrated hydrochloric acid for 10 minutes, then the sample was rinsed 7 times in distilled water and oven-dried at 60°C. 15-20 grains were selected at random from the cleaned sample, mounted on a 7 mm specimen stub with double-sided adhesive tape, then coated with 200Å thickness of platinum in a vacuum evaporator, after which it was viewed and the type and occurrence of surface features noted." (Hashimoto, 1993: 22).

The method proposed by Hashimoto (1993; after Krinsley and Doornkamp, 1973) was not used in this research due to the possibility of surface etching caused by the hydrochloric acid. Instead a variation of Fladmark's (1982; Shackley, 1975) methodologies were used.

Lentfer and Boyd (1999: 31-44) devised a systematic way for the removal of clays. Their method involved a treatment to disaggregate the sediment, and two treatments for the removal of clays:

1. Disaggregate the sediment by shaking it in 5% Calgon solution for 12 hours.
2. After the removal of organics and carbonates [and iron oxides], sieve through 5µm mesh, wash through with 5% Calgon solution, or
3. Deflocculate in 5% Calgon solution, centrifuge at 2000 rpm for 2 min, decant and repeat until the supernatant clears.

The Lentfer and Boyd (1999) method is innovative and has proven to be reliable for the disaggregation of sediments. This research used a more conventional and simplified method.

Procedures for the removal of iron oxides (Fladmark, 1982 oxalic acid method, after Shackley, 1975) were based on Leith (1950). Other methods were available for the removal of free iron oxides by a dithionite-citrate solution (Jackson, 1958: 168; Mehra and Jackson, 1960: 317-327), and by ammonium oxalate under ultraviolet irradiation (Le Riche and Weir, 1963). Oxalic acid was selected for its low impact on the surface features of the grains. However, studies on lichens (Jones *et al.*, 1981; Wilson *et al.,* 1981) have revealed that the oxalic acid by-product produces etching on grain surfaces:

> "Although quartz is traditionally regarded as extremely resistant to weathering, distinctively corroded grain surfaces can be observed beneath growing lichen [under SEM]. The etching of quartz is of interest because it is most likely to be due to the acidic properties of the attacking acid, rather than to its complexing characteristics." (Jones *et al.*, 1981: 100).

The experiments conducted by Jones *et al.* (1981) and Wilson *et al.* (1981) have replicated the etching action of oxalic acid on quartz grains, simulating the concentrations of acid secreted by lichen. The studies did not discuss what percentage of concentration of oxalic acid was used, or for how long the quartz was subjected to the acid attack.

Tests were carried out to identify the best procedure for removing iron oxides from the samples without altering the features on the surface (see Appendix 2, Sample 3). The best method was using oxalic acid (Leith, 1950).

It was decided that for the cleaning purposes, quartz grains were added to a 15% solution of oxalic acid and boiled gently with a strip of aluminium for 20 minutes. The oxalic acid concentration was sufficiently low so the surface of the grain was not etched (Fladmark, 1982).

3.3 Quartz microdebitage—shape and roundness

Fladmark (1982) has studied the recognition of microdebitage under light microscopy. However, it was necessary for this research to determine under SEM the differences were between microdebitage and naturally occurring particles from differing environments. To apply these ideas to the material, the first procedure was to employ a roundness index to microdebitage and quartz grains from other environments.

3.3.1 Roundness index and its application to quartz grains

The analysis undertaken was a shape analysis on all size components of the BH-E (Mutawintji sediment) SY-C (Pagewood, Maroubra, Sydney sandstone block) and BH-C samples (Broken Hill microdebitage). The particle shape analysis was based on *Powers' Scale of Roundness* (Briggs, 1977; Powers, 1953) and the *visual comparison chart* for the assessment of Powers' roundness index has been used for this research:

> "Procedure: Compare particles with images on Power's chart [table 3.3.2.1]. Assign each particle to appropriate sphericity and roundness class. Calculate percentage of total sample in each roundness class, multiply this percentage by the class midpoint and sum values obtained. From this summed value, obtain mean roundness value. Evaluation of form, sphericity or roundness by measurement of axes or angles of individual particles is a painstaking and difficult task, especially with small particles. Many attempts have therefore been made to design swift, accurate visual methods of assessing these parameters. These visual comparison charts consist of reference shapes of known sphericity or roundness, with which sedimentary particles can be compared. Many of them are based upon a measure of roundness, which relates the outline of the particle to that of a circle in which ρ (rho) is the index of roundness, r is the radius of

curvature of the largest circle just inscribed by the particle, and ***R*** is the mean radius of curvature of the particle.

$$\rho = \frac{r}{R}$$

The index ranges from **0** to **1**, a perfect circle having a value of **1**. Although measurement of these parameters is obviously difficult in practice, estimation by reference to visual comparison charts is easy and, with care, produces consistent results. Of the visual comparison charts available, one of the most useful is that designed by Powers (1953). This consists of six roundness classes, the limits of which are defined using an index of roundness, and arranged on a logarithmic scale [table 3.8.3]. The classes range from roundness values of 0.12 to 1.00; the range from 0.00 to 0.12 is excluded because natural particles never seem to attain such low degrees of roundness. A logarithmic scale is used because distinction of differences at the rounder end of the range is more difficult than at the angular end; consequently, less resolution can be achieved with very rounded particles." (Briggs, 1977: 118-119).

Fladmark (1982) recommended a 10,000-particle analysis for each size fraction of his samples, which were of unknown origin. This project deals with microdebitage that has a known provenance, and has not been deposited in sediment. The sample used for analysis was therefore smaller than Fladmark (1982) suggested, ranging between ~300 to ~500 particles per sample. The samples used for this research were divided into the same size fractions as the microdebitage investigated by Fladmark (1982), allowing ~100 particles per sub-sample.

Fladmark (1982) did not apply a roundness index to the soil control samples or to the soil samples containing microdebitage described in his research.

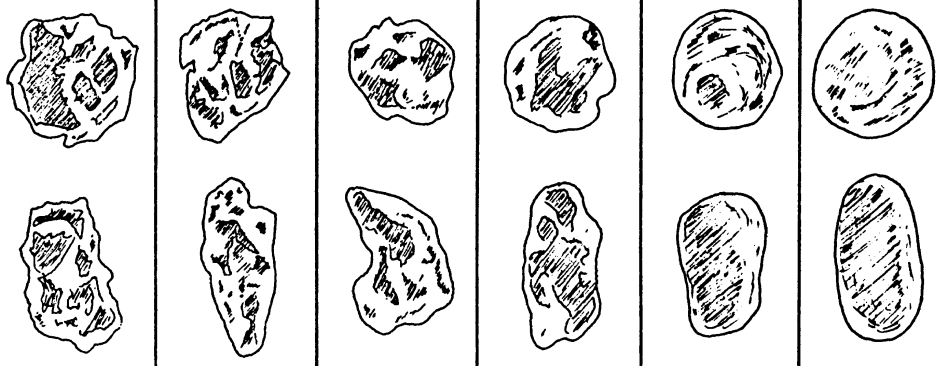
The methodology used for this analysis diverges somewhat from Briggs' (1977) roundness index, and Fladmark's (1982) methodology. For consistency, a wide area of the samples were photographed under a Philips 505 SEM, with the micrographs enlarged to A4 size. A grid composed of 1-cm squares was applied to the photograph. The grains were then counted using a magnifying lens, and

allotted according to the comparison chart (Powers, 1953). This method was used as opposed to Fladmark's (1982) light microscopy. The method has proven reliable with quartz grains, and the higher magnification of the SEM, allowed greater accuracy in tallying of quartz grains. This method also proved to be less time consuming than using a light microscope.

3.3.2 Roundness index value

The analysis of the three samples of microdebitage against the beach, sand dune, decaying sandstone grains, and sedimentary material from an aeolian environment, was designed to compare the roundness index value of each individual environment with the microdebitage.

Table 3.3.2.1. Visual comparison chart for roundness index (Briggs, 1977: 120).

Very Angular	Angular	Sub-angular	Sub-rounded	Rounded	Well rounded
					
0.12 - 0.17	0.17 - 0.25	0.25 - 0.35	0.35 - 0.49	0.49 - 0.70	0.70 - 1.00

The assessment of Power's roundness index followed the procedure outlined by Briggs (1977). Based on the mean value of the range used by Briggs in each class (table 3.3.2.2), a mean value was assigned to each class.

Table 3.3.2.2. Roundness index range and mean, as indicated by Briggs' (1977: 119, 120) procedure.

Shape	Roundness index range per category	Mean roundness index range per category
Very angular	0.12-0.17	0.14
Angular	0.17-0.25	0.21
Sub-angular	0.25-0.35	0.30
Sub-rounded	0.35-0.49	0.42
Rounded	0.49-0.70	0.59
Well rounded	0.70-1.00	0.85

To simplify the calculations of the roundness index, each grain counted was assigned to one category with a mean value (table 3.3.2.2) rather than being assigned to sub-categories within the value range. The mean index value used for this test was the mean of the values for each category of the Powers' roundness index (Powers 1953) (Appendix 6, Tables A6.3 and A6.4). The calculations of the mean roundness index for each sample and sub-sample were performed according to the procedure set by Briggs (1977: 118).

3.4 Quartz microdebitage—shape and roundness comparison

The Sydney samples (SY-C series) and the Mutawintji samples (BH-C series) were subjected to comparison with the experimental microdebitage (BH-E series) material. Sample SY-C1 is comprises sand from a dune at Pagewood (Sydney NSW). Sample SY-C2 is sand from Maroubra beach (Sydney NSW), and sample SY-C3 is derived from scraping a block of Hawkesbury sandstone (University of Sydney Main Quadrangle). Samples BH-C are taken from the soil at the top of a hill at Mutawintji National Park (Broken Hill). The three samples are in stratigraphic sequence.

For comparing shape and roundness of microdebitage and quartz from different environments, each sample of experimental microdebitage was compared with all other samples. The main focus of this test was to compare the microdebitage from the manufacturing of rock engravings (BH-E samples) to the sediment grains from Mutawintji (BH-C samples). These samples are from the same geographical area, and should illustrate roundness differences.

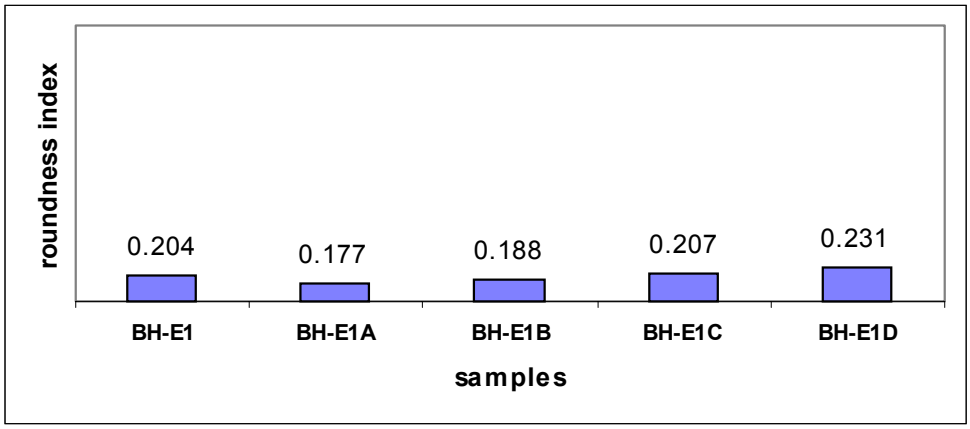
The roundness comparison will show that each sample has an index of roundness different from the microdebitage samples, denoting the different environment of origin.

The samples of microdebitage from the manufacturing of rock engravings were originally part of sandstone slabs removed from a Mutawintji sandstone outcrops. Those grains originated from an ancient ocean floor deposit, in which the grains were sub-rounded to sub-angular (Packham, 1969a; Packham, 1969b).

The mean roundness value based on Powers' visual comparison chart on sample BH-E1, derived from the manufacturing of engraving E1 (Clegg, 1997a), shows that the total sample is angular (Table 3.4.1).

Table 3.4.1. Number of grains counted and mean roundness index: Samples BH-E1. (Broken Hill engraving E1 microdebitage).

	BH-E1A	**BH-E1B**	**BH-E1C**	**BH-E1D**	**BH-E1**
Very Angular	59	41	54	72	226
Angular	14	29	45	19	107
Sub-angular	8	6	13	7	34
Sub-rounded	0	2	3	6	11
Rounded	1	0	2	7	10
Well rounded	0	0	1	4	5
Total grains counted	82	78	118	115	393
Roundness index	**0.177**	**0.188**	**0.207**	**0.231**	**0.204**

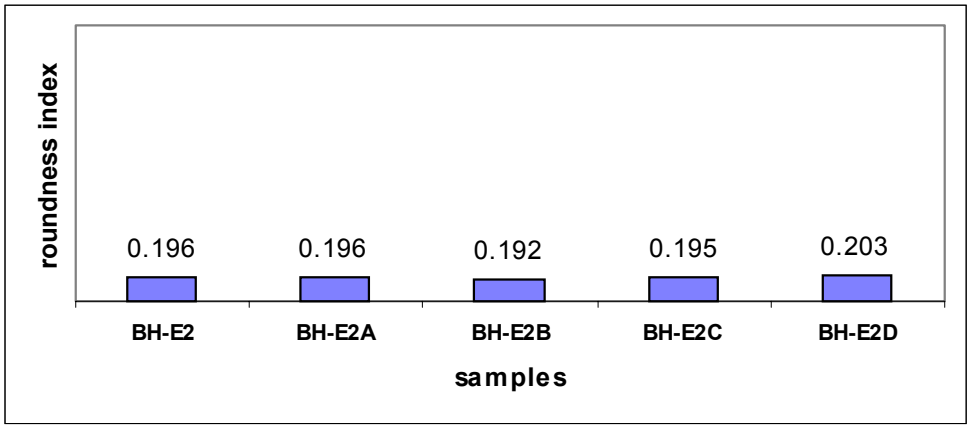


Angularity, together with irregular shape, is one of the main features in the identification of microdebitage. The sample has a roundness index of 0.204, which is, according to the Powers' roundness chart, within the *angular* range (table 3.4.1).

Sample BH-E2, derived from the manufacturing of engraving E2 (Clegg, 1997a), has a mean value of 0.196, which is within the *angular* range. The angularity is consistent throughout the sample (Table 3.4.2).

Table 3.4.2. Number of grains counted and mean roundness index: Samples BH-E2 (Broken Hill engraving E2 microdebitage).

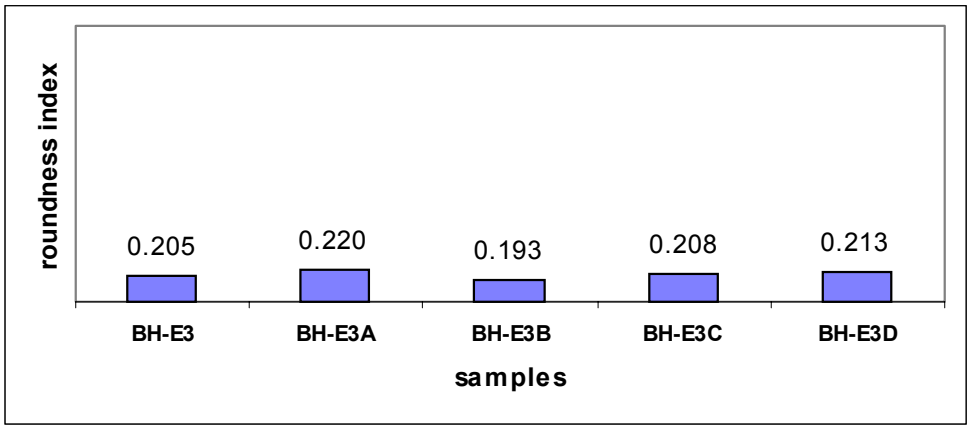
	BH-E2A	**BH-E2B**	**BH-E2C**	**BH-E2D**	**BH-E2**
Very angular	50	92	57	85	284
Angular	17	33	36	23	109
Sub-angular	10	12	9	8	39
Sub-rounded	4	9	6	8	27
Rounded	1	1	0	4	6
Well rounded	0	0	0	1	1
Total grains counted	82	147	108	129	466
Roundness index	**0.196**	**0.192**	**0.195**	**0.203**	**0.196**



Sample BH-E3, derived from the manufacturing of engraving E3 (Clegg, 1997a), has similar results in angularity with samples BH-E1 and BH-E2. Table 3.4.3 shows the angularity of this sample is to the microdebitage from the other engravings. The differences in sandstone and tool use during production of the engravings are minimal, and have been highlighted by the roundness index.

Table 3.4.3. Number of grains counted and mean roundness index: Samples BH-E3. (Broken Hill engraving E3 microdebitage).

	BH-E3A	BH-E3B	BH-E3C	BH-E3D	BH-E3
Very angular	41	106	61	60	268
Angular	21	54	41	32	148
Sub-angular	12	19	14	11	56
Sub-rounded	4	9	8	9	30
Rounded	4	0	2	2	8
Well rounded	0	0	0	1	1
Total grains counted	82	188	126	115	511
Roundness index	**0.220**	**0.193**	**0.208**	**0.213**	**0.205**



The similarity between these samples refers to the similarity in the sandstone slabs and origin of the raw material. The fracturing method used for the manufacturing of the engravings was the same in all experiments. Further, the tools used were about the same size and weight and were used by the same person. This discussion leads to the understanding that similar statistical patterns would appear in samples that are of similar origin (figure 3.4.1).

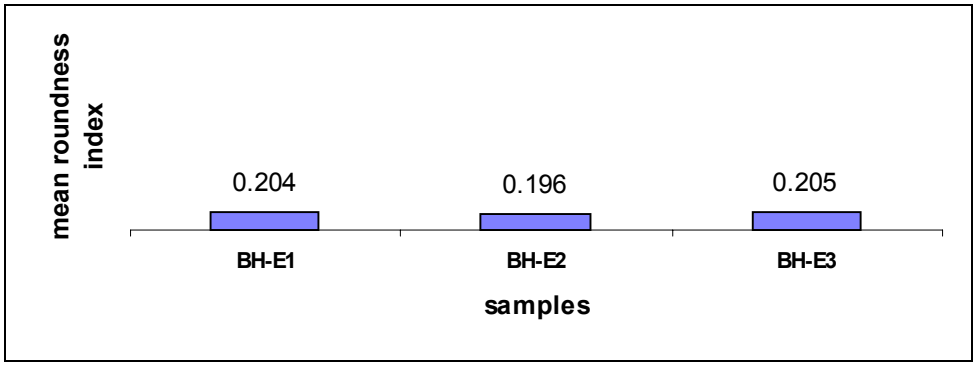
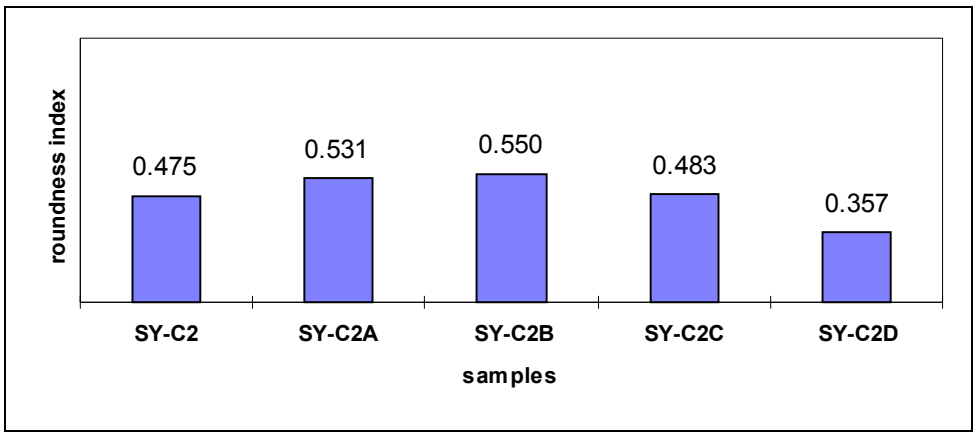


Figure 3.4.1. Total mean roundness index of the Broken Hill microdebitage samples (BH-E).

The sample from Maroubra Beach (SY-C2) has a mean value of 0.475 (table 3.4.4). The roundness index of this sample is about double that of the microdebitage samples from the rock engravings (BH-E samples). The sample denotes an index of *sub-rounded* to *rounded* grains, with features typical of a beach environment.

Table 3.4.4. Number of grains counted and mean roundness index: Samples SY-C2 (Maroubra beach sand).

	SY-C2A	**SY-C2B**	**SY-C2C**	**SY-C2D**	**SY-C2**
Very angular	0	0	0	5	5
Angular	1	2	3	15	21
Sub-angular	12	10	15	39	76
Sub-rounded	20	34	28	30	112
Rounded	33	28	31	9	101
Well rounded	10	21	5	3	39
Total grains counted	76	95	82	101	354
Roundness index	**0.531**	**0.550**	**0.483**	**0.357**	**0.475**

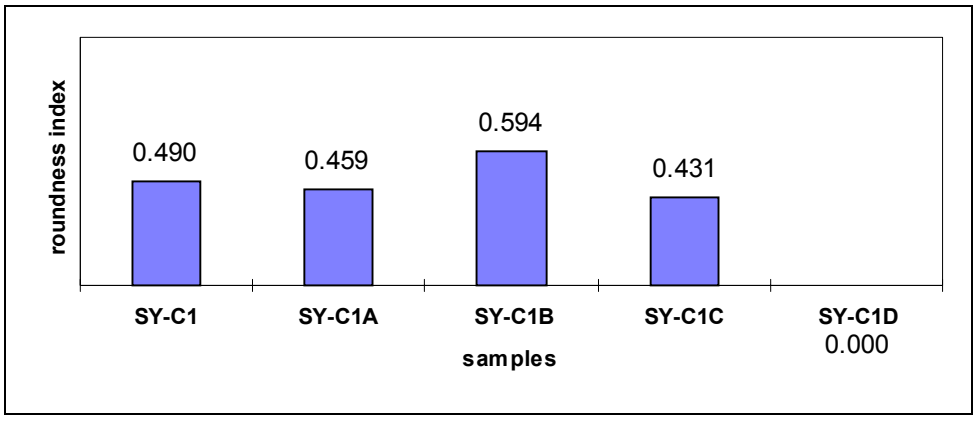


Sample SY-C1 has a mean value of 0.49 (table 3.4.5). The roundness of this sand dune environment is marginally higher than the beach sample. The higher roundness may be the result of littoral and aeolian features combined. This may be due to reworking of the sediments before dune stabilisation. The material from the sand dune, originally from beach sediment, has been in a stable environment since the Pleistocene.

This sample (table 3.4.5) lacked material in the 125-63µm range. This is probably due to the natural sorting of the material within the dune sediment.

Table 3.4.5. Number of grains counted and mean roundness index: Samples SY-C1. (Pagewood sand dune).

	SY-C1A	**SY-C1B**	**SY-C1C**	***SY-C1D***	**SY-C1**
Very angular	1	0	0	*0*	1
Angular	5	0	9	*0*	14
Sub-angular	27	10	25	*0*	62
Sub-rounded	60	20	38	*0*	118
Rounded	23	36	17	*0*	76
Well rounded	13	25	7	*0*	45
Total grains counted	129	91	96	*0*	316
Roundness index	**0.459**	**0.594**	**0.431**	***0.000***	**0.490**

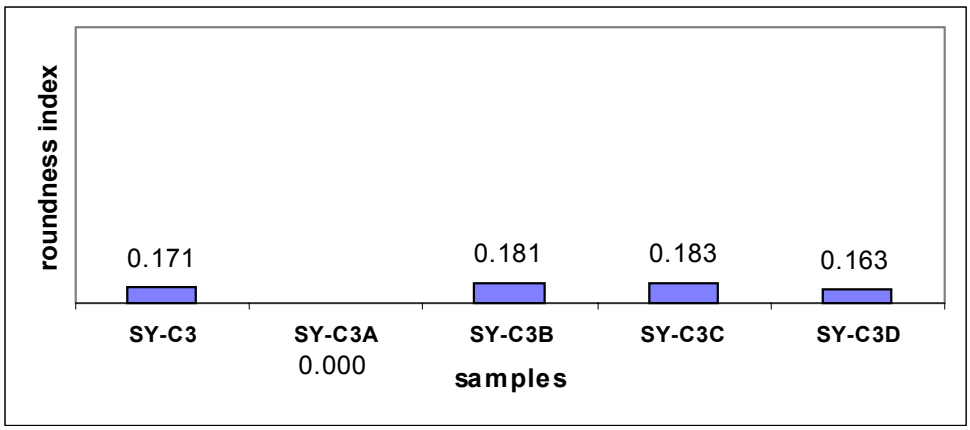


Sample SY-C3 is typical of high-energy chemical environments it originates from a weathered building stone, and has an angularity higher than the BH-E microdebitage samples, with a mean value of 0.171 (table 3.4.6). The high angularity is probably caused by considerable solution weathering of the quartz crystals, which is often the result of an urban environment. The sample has been rubbed off a sandstone block. The method used to retrieve material from the building block of sandstone is different from the manufacturing of microdebitage from rock engravings. The material from the sandstone block was gently rubbed off with the fingers, while the material from the manufacturing of rock engravings was made from pounding the sandstone with a tool and greater force.

There is no material in the 1000-500µm range from this sample (table 3.4.6). This is probably due to the maximum size of the particles in the sandstone being smaller.

Table 3.4.6. Number of grains counted and mean roundness index: Samples SY-C3. (Sydney University sandstone block).

	SY-C3A	**SY-C3B**	**SY-C3C**	**SY-C3D**	**SY-C3**
Very angular	*0*	92	102	69	363
Angular	*0*	62	27	21	110
Sub-angular	*0*	13	11	2	26
Sub-rounded	*0*	0	6	0	6
Rounded	*0*	0	1	0	1
Well rounded	*0*	0	0	0	0
Total grains counted	*0*	167	147	92	506
Roundness index	***0.000***	**0.181**	**0.183**	**0.163**	**0.171**

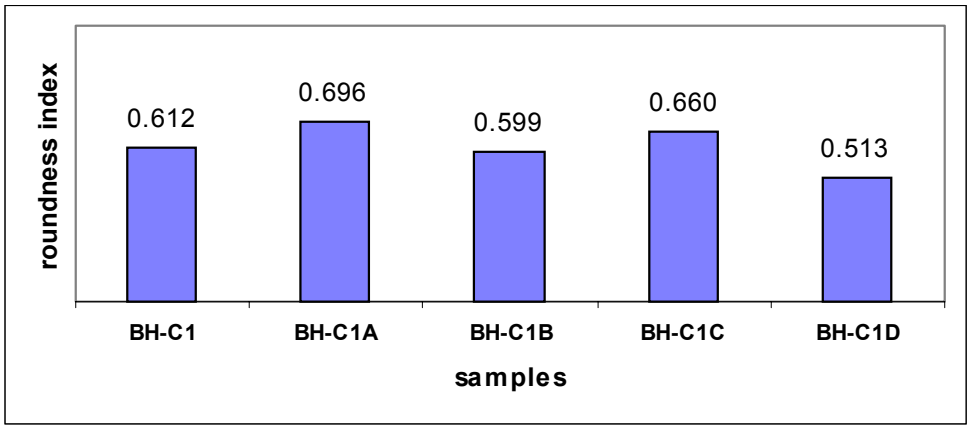


Sample SY-C3 has highly angular grains that at high magnification under SEM exhibit changes in shape due to chemical solution and weathering action upon the quartz crystals.

The surface sample of sediment from Mutawintji (BH-C1) has a mean roundness index of 0.612, which is in the rounded category (table 3.4.7). The differences in roundness between the littoral environment samples and the aeolian environment samples are discernible by the greater roundness of the aeolian sand. The origin of the sands is not known. Semi-arid climatic conditions have reworked the quartz grains before sedimentary incorporation. This sample has a greater roundness than the other Mutawintji sediment samples.

Table 3.4.7. Number of grains counted and mean roundness index: Samples BH-C1. (Mutawintji sediment, 0-2cm depth).

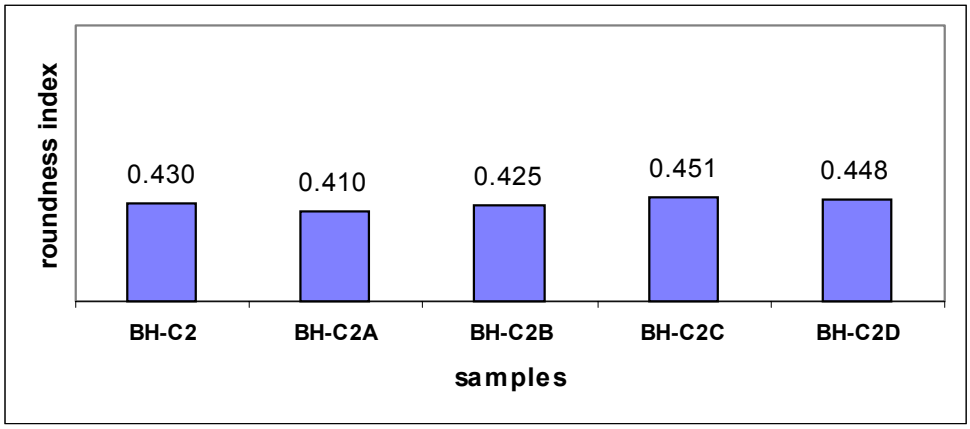
	BH-C1A	**BH-C1B**	**BH-C1C**	**BH-C1D**	**BH-C1**
Very angular	0	0	0	0	0
Angular	3	3	1	6	13
Sub-angular	31	15	10	4	60
Sub-rounded	72	75	126	94	367
Rounded	27	17	28	20	92
Well rounded	1	0	6	6	13
Total grains counted	134	110	171	130	545
Roundness index	**0.696**	**0.599**	**0.660**	**0.513**	**0.612**



The mean roundness index of the Mutawintji sediments at 2-4 cm (table 3.4.8) is similar to that of the lower sample, and greater than that of the surface sample.

Table 3.4.8. Number of grains counted and mean roundness index: Samples BH-C2. (Mutawintji sediment, 2-4cm depth).

	BH-C2A	BH-C2B	BH-C2C	BH-C2D	BH-C2
Very angular	1	0	1	2	4
Angular	6	7	4	4	21
Sub-angular	13	13	6	10	42
Sub-rounded	102	100	100	96	398
Rounded	8	19	17	20	64
Well rounded	1	1	7	7	16
Total grains counted	131	140	135	139	545
Roundness index	**0.410**	**0.425**	**0.451**	**0.448**	**0.430**



The sample from the bottom of the deposit is similar in roundness to the middle samples (figure 3.4.2). This sample may reflect the roundness of the quartz grains in the sandstone slabs on the surface of the *Western Ridge* (Mutawintji National Park). However, if quartz grains are already rounded and were derived from a parent rock with rounded grains, it is not possible to determine whether inheritance of aeolian environment is responsible for the outcome.

Table 3.4.9. Number of grains counted and mean roundness index: Samples BH-C3. (Mutawintji sediment, 4-8cm depth).

	BH-C3A	BH-C3B	BH-C3C	BH-C3D	BH-C3
Very angular	1	0	0	0	1
Angular	16	6	8	30	60
Sub-angular	12	11	21	20	64
Sub-rounded	94	117	131	84	426
Rounded	4	11	14	16	45
Well rounded	0	3	1	4	8
Total grains counted	127	148	175	154	604
Roundness index	**0.386**	**0.424**	**0.412**	**0.393**	**0.405**

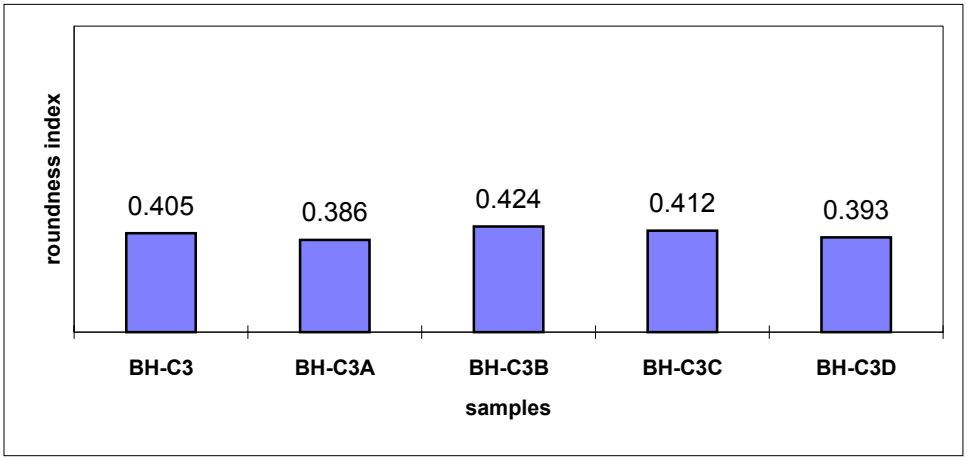


Table 3.4.7 shows that sample BH-C1, from the surface, has a roundness index higher than the other samples. The material may have remained within the aeolian environment for a longer period of time.

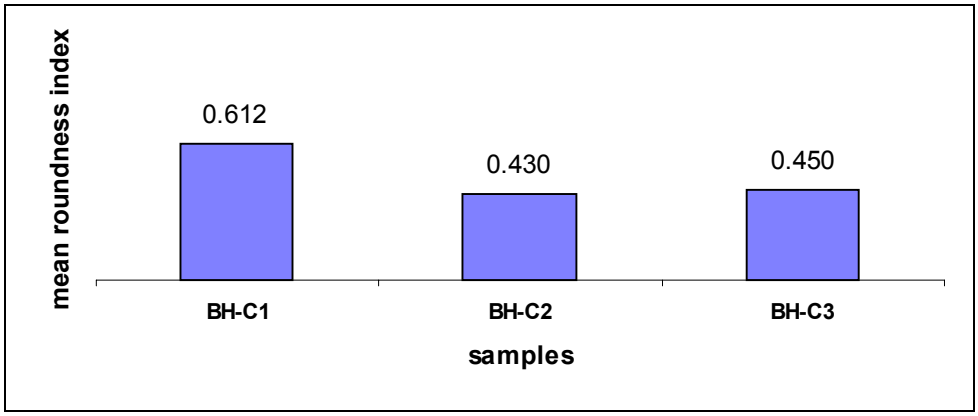


Figure 3.4.2. Mean roundness index of the Mutawintji sediment samples (BH-C).

3.5 Shape and roundness comparison—results and discussion

Results of comparison between the experimental microdebitage (BH-E samples) and the sediment samples from Mutawintji National Park (BH-C) have shown that the angularity of microdebitage in comparison to the roundness of the sediment may permit microdebitage to be easily distinguished in the soil (figure 3.4.2).

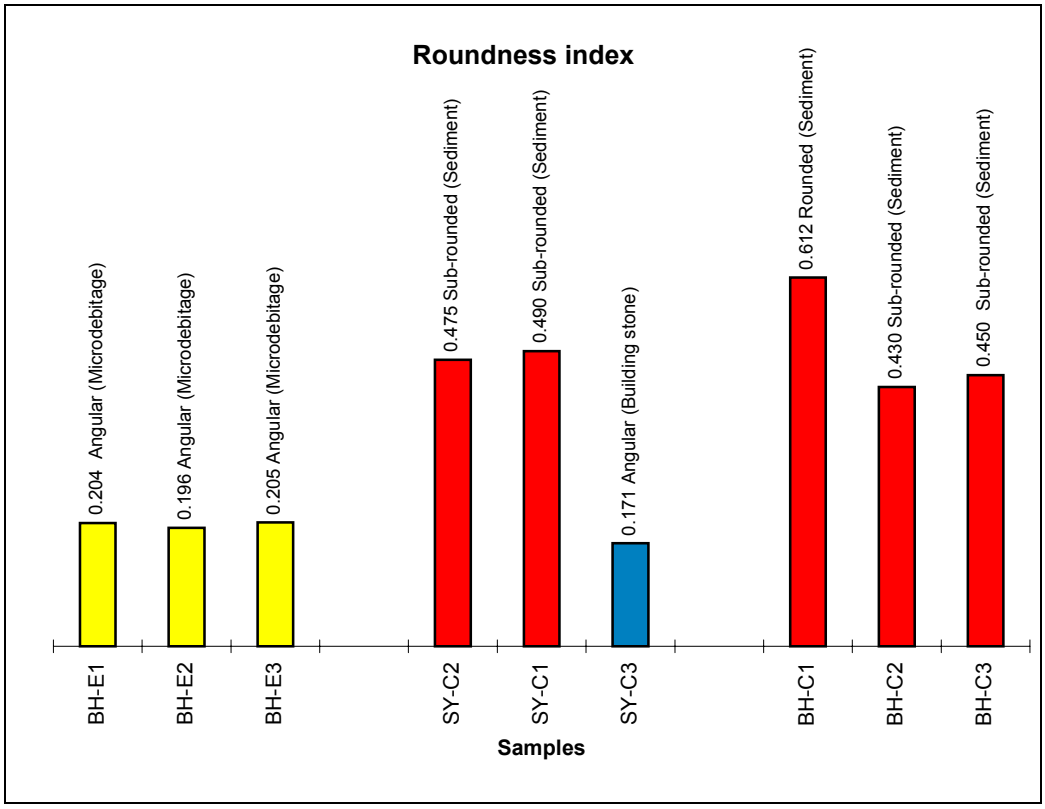


Figure 3.5.1. Mean roundness index by total samples.

The result of this comparison illustrates a discernible difference between microdebitage from experimental rock engravings and other sediment samples (figure 3.5.1). The particle roundness index shows that each of the samples has a different dominant shape. The percentage of very angular particles in the microdebitage from experimental rock engravings (BH-E samples) contrasts with the beach and sand dune samples (SY-C2 and SY-C1) which show greater rounding. The sandstone building block subjected to weathering in an urban environment (sample SY-C3) presented a higher ratio of very angular particles (Appendix 6, graph A6.1).

Results indicate differences can be discerned in grain shape between microdebitage (BH-E) and the natural soil background (BH-C).

The sand dune sample (SY-C1), the beach sand samples (SY-C2) and Mutawintji sediment samples (BH-C) are classified as well-rounded to sub-angular. According to Krinsley and Doornkamp (1973: 28-29) and Briggs (1977: 120), features exhibited in these samples are consistent with their environmental origin. The sample from the weathered sandstone building block (SY-C3) exhibits very angular particles at low magnification (Briggs 1977: 120). At high magnification, the sample shows disintegration of the matrix by chemical solution or salt crystal growth (Krinsley and Doornkamp, 1973: 29).

The combined use of 'Powers' roundness index' and the 'Visual comparison chart' have been valuable for identifying easily recognisable differences in grain shape. Microdebitage from the engravings is readily distinguishable from other samples of sedimentary material derived from the same geographical area as the sandstone slabs used for manufacturing the experimental engravings (BH-C) (Appendix 6, tables A6.3 and A6.4).

The roundness index has been adopted here for the understanding of differences in roundness produced on grains from different environments, and for assisting in the identification of microdebitage from naturally occurring quartz grains. The identification of grains as rounded or angular is relevant to the recognition of environmental features. Roundness and angularity of grains are characteristics observed by Krinsley and Doornkamp (1973) and by Fladmark (1982). Table 3.5.1 illustrates the similarity of samples based on a χ^2 test regarding the number of grains in each roundness category.

The χ^2 tests whether independent samples are likely to have been drawn from the same population. All the data relate to the degree of roundness as represented by categories. The results of the chi-squared test highlighted some similarities not evident in the roundness index test. Shown in figure 3.5.1, the samples are colour coded according to source or environmental origin. The χ^2 test applied to the

microdebitage samples BH-E1, BH-E2 and BH-E3 concluded that there is a 95% probability that the samples are from the same population.

Table 3.5.1 Chi-squared test values: similarities between samples.

Paired samples	*df*	χ^2 Value	95% Probability
BHE1 and BH E2	4	0.3623	similar
BHE1 and BH E3	4	0.3230	similar
BHE2 and BHE3	4	0.6421	similar
SYC1 and SYC2	4	0.5401	similar
SYC1 and SYC3		*	
SYC2 and SYC3		*	
BHC1 and BHC2	4	0.3683	similar
BHC1 and BHC3	4	0.0022	different
BHC2 and BHC3	4	0.0517	different
BHE1 and SYC3	4	0.0641	similar
BHE2 and SYC3	4	0.1519	similar
BHE3 and SYC3	4	0.0042	different

* The chi-squared test was not applied as some cells had zero counts.

The tests also revealed that samples BH-E1 and SY-C3, and samples BH-E2 and SY-C3, have a 95% probability of being from the same population. These samples are similar only in relation to roundness; at high magnification (SEM) the samples exhibit unmistakable differences in surface features.

The χ^2 test allows the determination of the similarities among samples based on the number of grains counted within each roundness category. This test helps in identifying any differences or similarities in roundness among different samples, which are not apparent when applying a mean value for the roundness index.

3.6 Quartz microdebitage—surface features

Quartz is a monocrystalline mineral composed of silicon dioxide (SiO_2); the crystal structure is mainly hexagonal prisms terminating in rhombohedra (Griffen, 1992; Reed, 1962). Quartz microdebitage can be defined as grains that have been deliberately shattered or released from their matrix by human action. This can occur in the process of manufacturing stone tools or in the manufacturing of rock engravings.

Quartz may be the only monocrystalline mineral to have been frequently employed in antiquity by Aboriginal people in Australia as lithic raw material. It is also one of the most common minerals available in outcrops and natural sediments.

Stemming from the literature on sedimentary analysis outlined in Chapter 2, it must be understood that sediments are part of a wider geological and geographical context. Sedimentary rocks (Reed and Watson, 1977) play a large role in the environment of an archaeological site and in the detail of rock engraving sites, as rock engravings are often made by carving sedimentary rock faces. The remnant debitage material will eventually be incorporated into the nearby sedimentary deposits, if it is not blown or washed away first.

The objective to identify differences between natural and human-modified quartz grains is central to this thesis. Quartz weathering patterns as recorded by Krinsley and Doornkamp (1973) show the difference between glacial and experimental quartz grains (table 3.6.1). The experimentally crushed grains do not exhibit irregular solution-precipitation surfaces, nor do they exhibit flat cleavage faces, both of which appear on the features of grains from glacial environments.

Table 3.6.1. Quartz grain features: Glacial/Experimental (Krinsley and Doornkamp, 1973:26-27).

Glacial environment features	**Experimentally crushed features**
1. Irregular solution-precipitation surface.	1. *(Feature not duplicated by experiments).*
2. Conchoidal fracture.	2. Conchoidal fracture.
3. Mechanically formed upturned plates.	3. Mechanically formed upturned plates.
4. Flat cleavage face.	4. *(Feature not duplicated by experiments).*
5. Cleavage planes (semi-parallel lines).	5. Cleavage planes (semi-parallel lines).
6. Adhering particles.	6. Adhering particles.

Based on Krinsley's and Doornkamp's observations (1973), it is more likely that quartz microdebitage from sediments, rather than the experimental material, will have features on the surface consistent with irregular solution-precipitation. Any microdebitage available may have been incorporated into a sedimentary deposit

for a considerable time, and thus be subjected to diagenesis. Prior to becoming microdebitage, quartz grains were part of a rock. The shattering action against the rock during the manufacture of the engravings releases microdebitage into the surrounding environment, creating the broken grains subject to the environmental specific weathering. The recognition of quartz grain features on microdebitage may be rendered difficult if the grains are subjected to some degree of aeolian weathering, prior to incorporation in sediment.

Following from the observations of Krinsley and Doornkamp (1973), it has been observed there is a possibility that microdebitage found in archaeological or rock engraving deposits of great antiquity may have a combination of features which reflect similarities to the 'experimental' broken grains and the environment of deposition.

At Mutawintji, microdebitage from the rock engravings may reflect broken grains and aeolian features combined. The microdebitage may have been transported within the aeolian environment for some time before incorporation into the sediment. Further, sediments change over time and solution or other diagenetic actions may partly obscure the 'glacial' or 'mechanical' features, however, the grain would retain different features from those of the *background* soil grains (figure 3.6.1).

(a) (b)

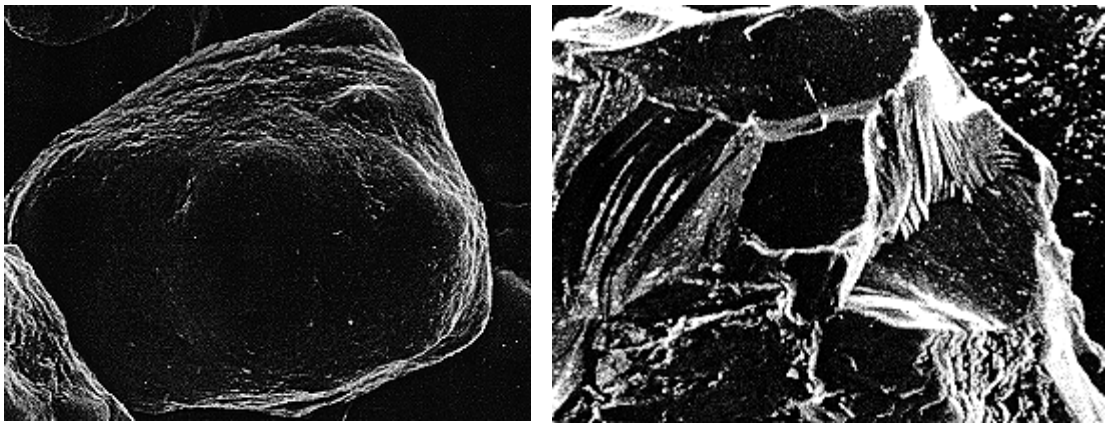


Figure 3.6.1. Micrograph of (a) aeolian quartz grain, and (b) glacial quartz grain (micrographs from Krinsley and Doornkamp, 1973: 63, 46).

3.7 Quartz microdebitage—environmental features

Initially this research envisaged the use of light microscopy for the recognition of microdebitage features, as used by Fladmark (1982), but the usefulness of light microscopy is limited when dealing with quartz grains in sandy deposits. Light microscopy to a magnification of about 100x is not sufficient to separate quartz grains from quartz microdebitage when sandy soil may have similar shapes to the microdebitage (Nicholson, 1983). Light microscopy can be used for preliminary work for the general description of detrital material (Pryor, 1971; Reed and Watson, 1977). However, it was decided to use scanning electron microscopy for the description of general features of quartz grains. The electron microscope was used for its higher magnification and better resolution when more than just shape had to be observed to separate microdebitage from soil. At the lower magnification of a light microscope, features on quartz grains are difficult to observe, even under polarisation.

A visual comparison between randomly chosen grains was undertaken to understand and assess surface features of microdebitage and quartz grains from different environments.

These comparisons were designed to understand quartz microdebitage in relation to environmental surface features described by Krinsley and Doornkamp (1973) in conjunction with observations made by Fladmark (1982) on microdebitage from stone tools. In addition, the comparisons were designed to understand the differences between sedimentary material and microdebitage.

3.7.1 Comparison of features—microdebitage and broken glass

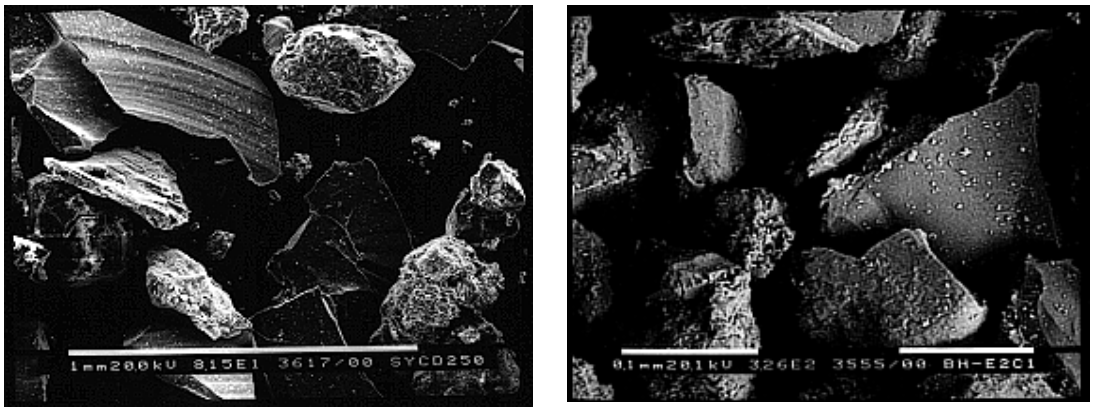
A preliminary experiment was undertaken on quartz grains and microdebitage to understand the visual difference between features observed on microdebitage by Fladmark (1982) with a light microscope, and the same material viewed under SEM. A sample of broken glass was used to simulate features appearing on material with high silica content (similar to obsidian microdebitage investigated

by Fladmark, 1982). The broken glass (SY-G1) was compared with microdebitage from the experimental rock engravings (sample BH-E1).

The features on the broken glass and the microdebitage particles are similar to the features observed by Krinsley and Doornkamp (1973) on mechanically broken quartz grains. These features are also similar to those observed by Fladmark (1982) on obsidian microdebitage.

This confirms that material with a high silica content has a tendency to break in the same manner as microdebitage resulting from knapping stone tools. Fladmark (1982) reports his successful search for obsidian microdebitage in a sandy soil matrix. Some material differences may be expressed as differences in colour, which can easily be seen under an optical microscope. The present research aims at the most difficult scenario, where there are no colour differences between microdebitage and sedimentary quartz grains, which only exhibit differences in shape and surface textures.

The sample of broken glass, compared to microdebitage, is more angular. However, similar features are discernible in both samples under SEM high magnification, as shown in Figure 3.7.1.1 (a) and (b).



(a) (b)

Figure 3.7.1.1. (a) Broken glass particles (SY-G1), (b) Rock engraving microdebitage (BH-E2).

Figure 3.7.1.1 (a) shows that features on particles of broken glass have similarities with the microdebitage particles in (b). The broken glass is composed of amorphous silica and shows the extreme features of highly siliceous material.

It is suggested that broken glass has surface features similar to microdebitage in an exaggerated form (note top left corner of figure 3.7.1.1 a, conchoidal fracture).

The system used by Krinsley and Doornkamp (1973) in listing features from different environments was, in many instances, much more detailed than Fladmark's (1982). The major difference between these researchers was Krinsley and Doornkamp's use of SEM rather than light microscopy.

3.8 Comparison of features—microdebitage and sediment

The roundness index only considered the shape of the quartz grains. This comparison will take in consideration a series of features, of which shape is only one. Krinsley and Doornkamp (1973) have categorised glacial and experimental quartz grains as highly angular and aeolian grains as rounded. Fladmark (1982) has observed that microdebitage is highly angular and has unusual shapes.

The features used in a visual comparison between the samples are based upon the observations of Krinsley and Doornkamp (1973). In conjunction with the description of quartz grains observed by Krinsley and Doornkamp (1973), the microdebitage and other material was also compared using the shape identification used by Fladmark (1982).

The Pagewood (SY-C1) and Maroubra (SY-C2) samples in the SEM appear well rounded to sub-angular. Features exhibited in both samples are consistent with their environmental origin, according to Krinsley and Doornkamp (1973) and Briggs (1977). Sample SY-C3 (Building stone) exhibits very angular particles at low magnification (Briggs 1977: 120). At high magnification, the sample showed disintegration of the matrix by chemical solution or salt crystal growth (Krinsley and Doornkamp, 1973). The building stone sample (SY-C3) differed considerably from the high angularity and surface features of the BH-E series material (microdebitage) (figure 3.7.1.2. a,). Further, it is noticeably different from the rounded particles in samples SY-C1 (Pagewood) and SY-C2 (Maroubra) (figure 3.7.1.2. b; see also plate I, and plate IV).

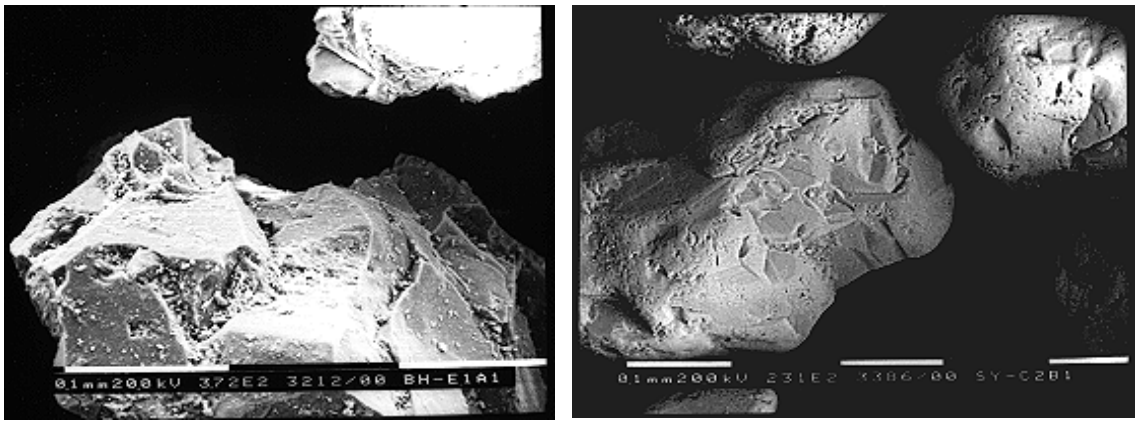


Figure 3.7.1.2. (a) Angular microdebitage (BH-E1), (b) Rounded beach quartz grains (SY-C2).

This comparison of features on the grains was conducted since the experimental microdebitage from Broken Hill was composed of material broken from the parent rock with very little environmental modification.

The hypothesis that microdebitage from rock engravings has similar features to quartz grains of glacial origin and those of grains mechanically crushed has been tested against quartz grains from different environments. Table 3.8.1 lists the features or textures on quartz grains catalogued by Krinsley and Doornkamp (1973) and Fladmark (1982) as belonging to experimentally broken quartz and microdebitage. All these features were noted on microdebitage from experimental rock engravings.

The comparison of features uses the descriptive terminology employed by Krinsley and Doornkamp (1973). It is also possible that grains subjected to different environments will retain features from earlier environments.

The features listed in table 3.8.1 are the same as those described by Krinsley and Doornkamp (1973) for mechanically crushed quartz grains, adding that Fladmark (1982) listed high angularity as a feature. High angularity and unusual shapes were observed in the microdebitage samples.

Table 3.8.1. Features recognised on microdebitage from Broken Hill (experimental).

A.	High angularity (FL)
B.	Conchoidal fracture (K&D)
C.	Mechanically formed upturned plates (K&D)
D.	Unusual shape (FL)
E.	Cleavage planes (semi-parallel lines) (K&D)
F.	Adhering particles (K&D)

(FL) Feature listed by Fladmark, 1982.
(K&D) Feature listed by Krinsley and Doornkamp, 1973.

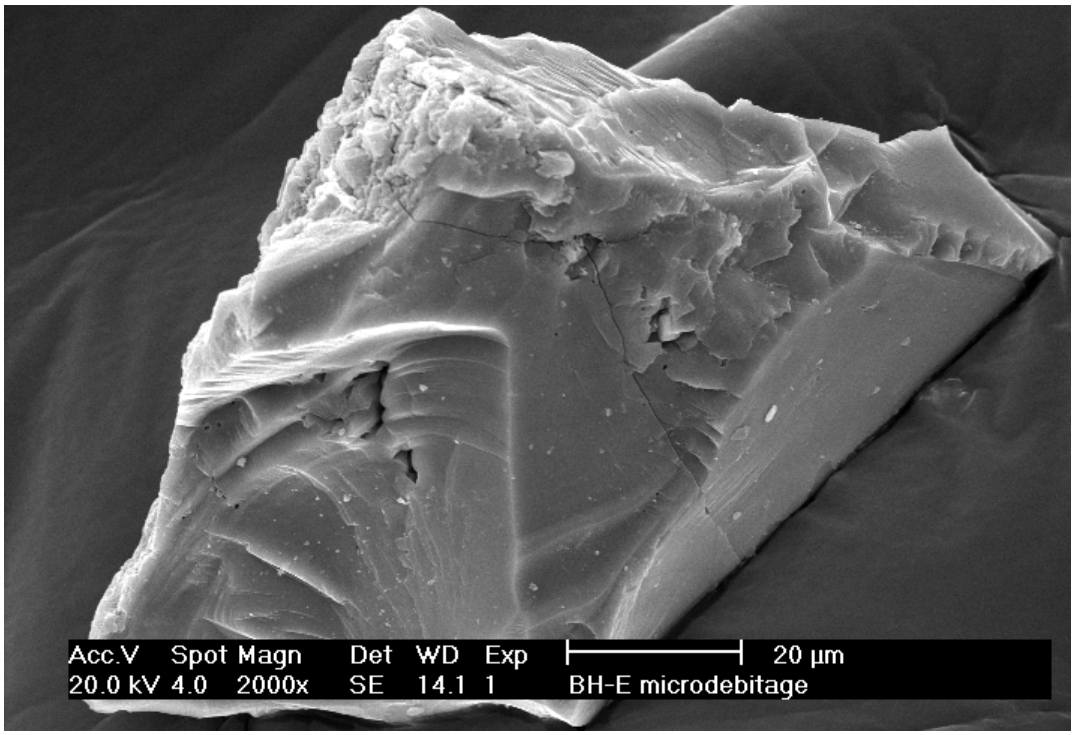


Figure 3.8.1. Features recognised on microdebitage from Broken Hill (experimental).
(Enlargement with features reference, plate XI).

Features listed in table 3.8.1, and on plate XI, are the select features for quartz microdebitage. In the comparison under SEM, high angularity and conchoidal fractures (Plate XI) are the main indicators differentiating microdebitage and grains from other environments. The minor component features are used for further accuracy in distinguishing between marginally similar environments.

Grains from Pagewood (SY-C1) have been retrieved from a Pleistocene sand dune, and the features are similar to those for subaqueous and aeolian environments combined (table 3.8.2 and figure 3.8.2). It is possible for quartz

grains to exhibit features from earlier environments. This depends on how long the grains remain in a given environment, and how quickly they are buried within a sedimentary deposit.

Table 3.8.2. Features recognised on quartz grains from Pagewood.

A.	Rounded grains (K&D)
B.	Smooth precipitation surface (K&D)
C.	Chemically etched V-forms (K&D)
D.	Mechanically formed upturned plates (K&D)
E.	Flat cleavage face (K&D)
F.	Some dish-shaped concavities (K&D)

(K&D) feature listed by Krinsley and Doornkamp, 1973.

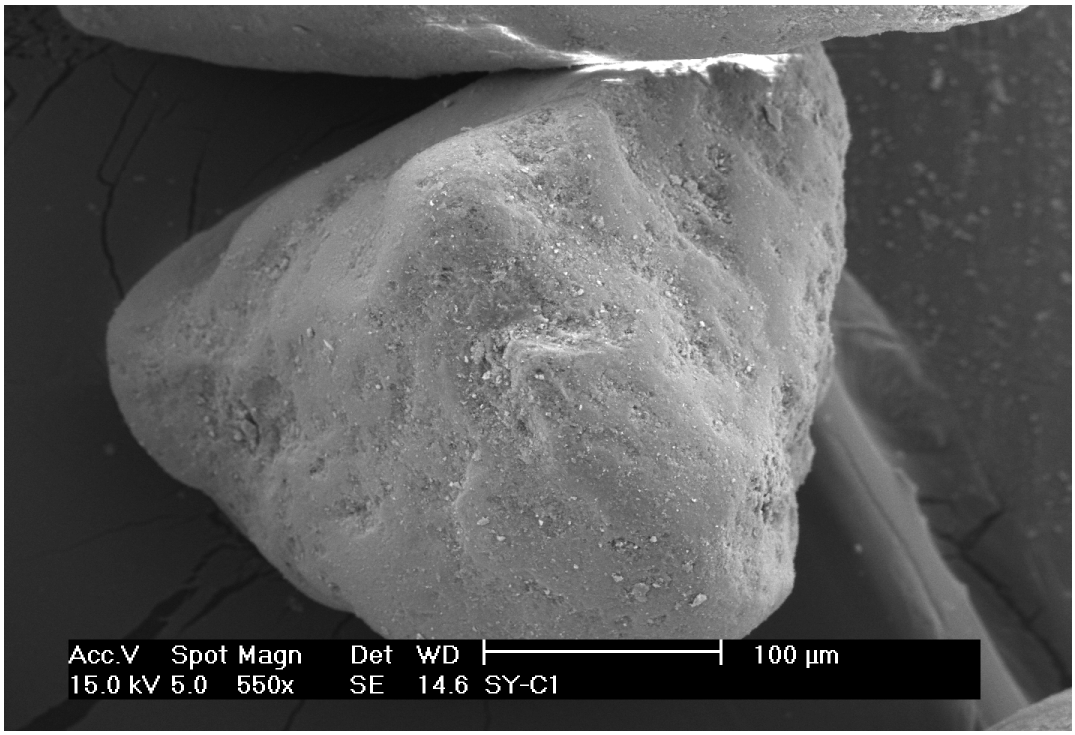


Figure 3.8.2. Features recognised on quartz grains from Pagewood.
(Enlargement with features reference, plate VII).

The features listed in Table 3.8.2 and Plate VII are comparable to the features observed by Krinsley and Doornkamp (1973) for features on quartz grains in subaqueous and aeolian environments (figure 3.8.2).

Figure 3.8.3 illustrates features on quartz grains from a beach environment at Maroubra (SY-C2), which has the same six features observed by Krinsley and Doornkamp (1973) for subaqueous environments (table 3.8.3).

Table 3.8.3. Features recognised on quartz grains from Maroubra samples.

A.	Rounded grains (K&D)
B.	Mechanically formed upturned plates (K&D)
C.	Mechanical V-forms (K&D)
D.	Smooth precipitation surface (K&D)
E.	Conchoidal fractures (K&D)
F.	Straight or slightly curved grooves (K&D)

(K&D) features listed by Krinsley and Doornkamp, 1973.

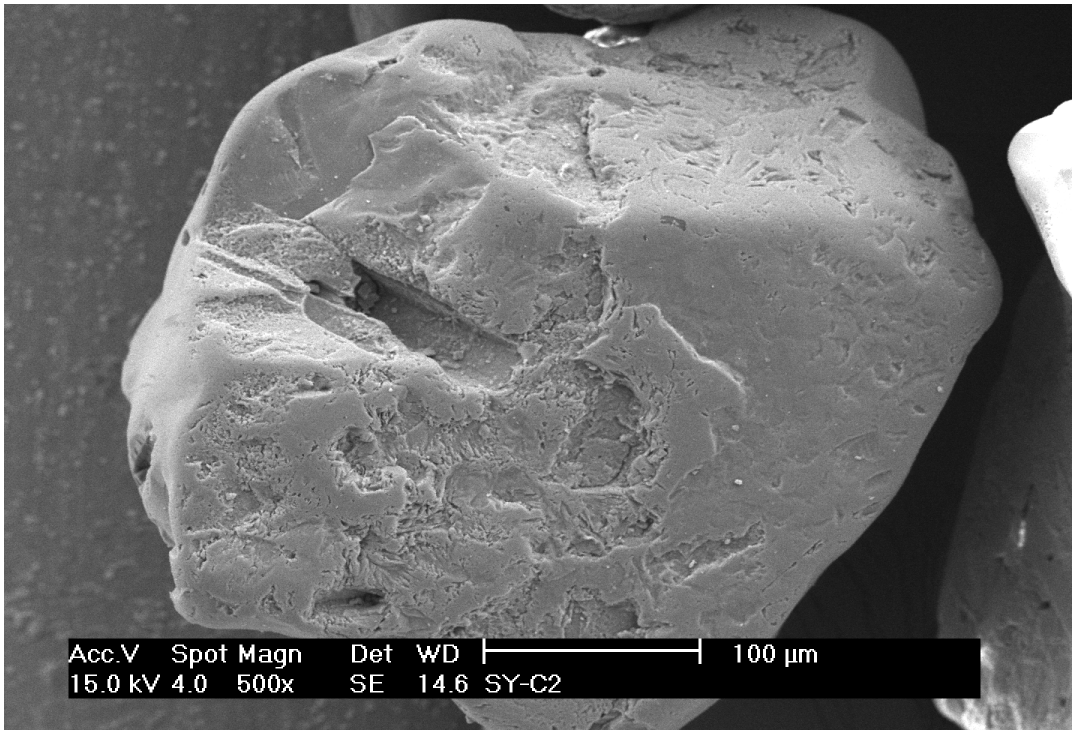


Figure 3.8.3. Features recognised on quartz grains from Maroubra.
(Enlargement with features reference, plate V).

The weathering building block sample (SY-C3) exhibits features consistent with quartz grains exposed to a chemically corrosive urban environment (figure 3.8.4). This environment produces distinct quartz solution features by the action of salt weathering. The Hawkesbury sandstone block from the University of Sydney (Main Quadrangle) has five features complying with Krinsley's and Doornkamp's (1973) observations for a high-energy chemical environment, and one complying with Fladmark (1982) (table 3.8.4).

Table 3.8.4. Features on quartz grains from weathered sandstone block.

A.	High angularity (FL)
B.	Mechanically formed upturned plates (K&D)
C.	Quartz crystal growth (K&D)
D.	Deep surface solution (K&D)
E.	Disintegration by solution or by salt crystal growth (K&D)
F.	Large-scale chemical decomposition (K&D)

(FL) feature listed by Fladmark, 1982, (K&D) feature listed by Krinsley and Doornkamp, 1973.

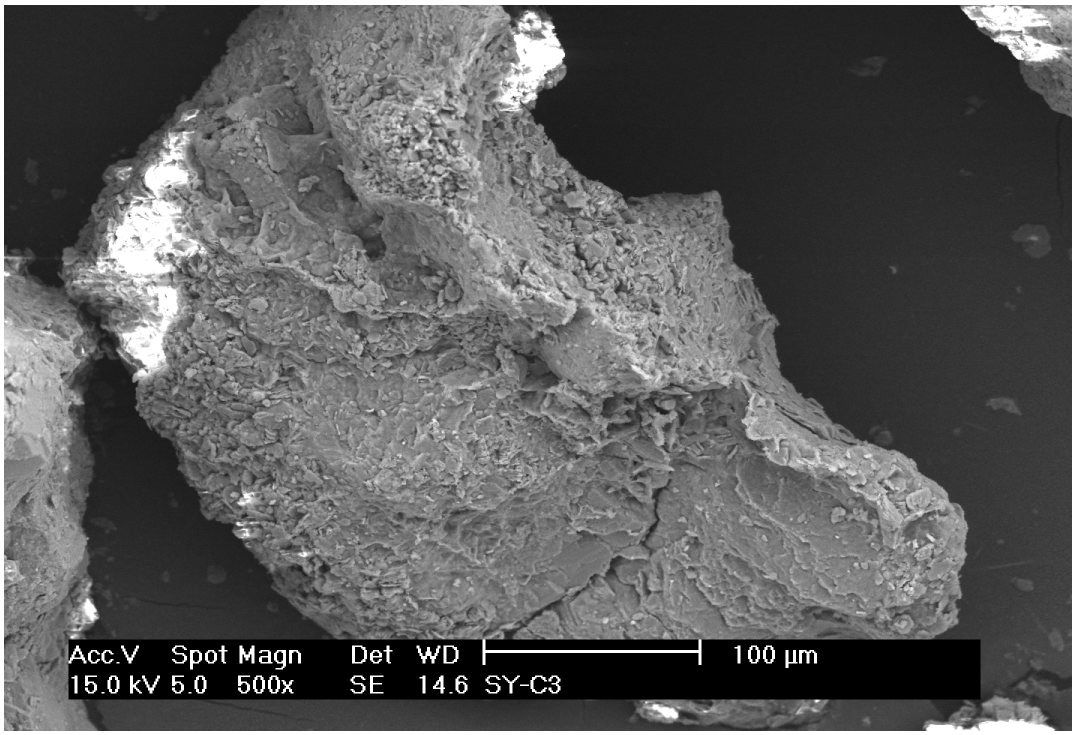


Figure 3.8.4. Features recognised on quartz grains from weathered sandstone block.
(Enlargement with features reference, plate XIV).

Typical of aeolian environments, the features on the quartz grains from the Mutawintji sediment samples are the same as those observed by Krinsley and Doornkamp (1973) (table 3.8.5; figure 3.8.5).

Table 3.8.5. Features recognised on quartz grains from Mutawintji sediment samples.

A. Rounded grains (K&D)
B. Disintegration by solution or by salt crystal growth (K&D)
C. Dish- shaped concavities (K&D)
D. Mechanically formed upturned plates (K&D)
E. Smooth or irregular precipitation surface (K&D)
F. Precipitated upturned silica plates (K&D)

(K&D) feature listed by Krinsley and Doornkamp, 1973.

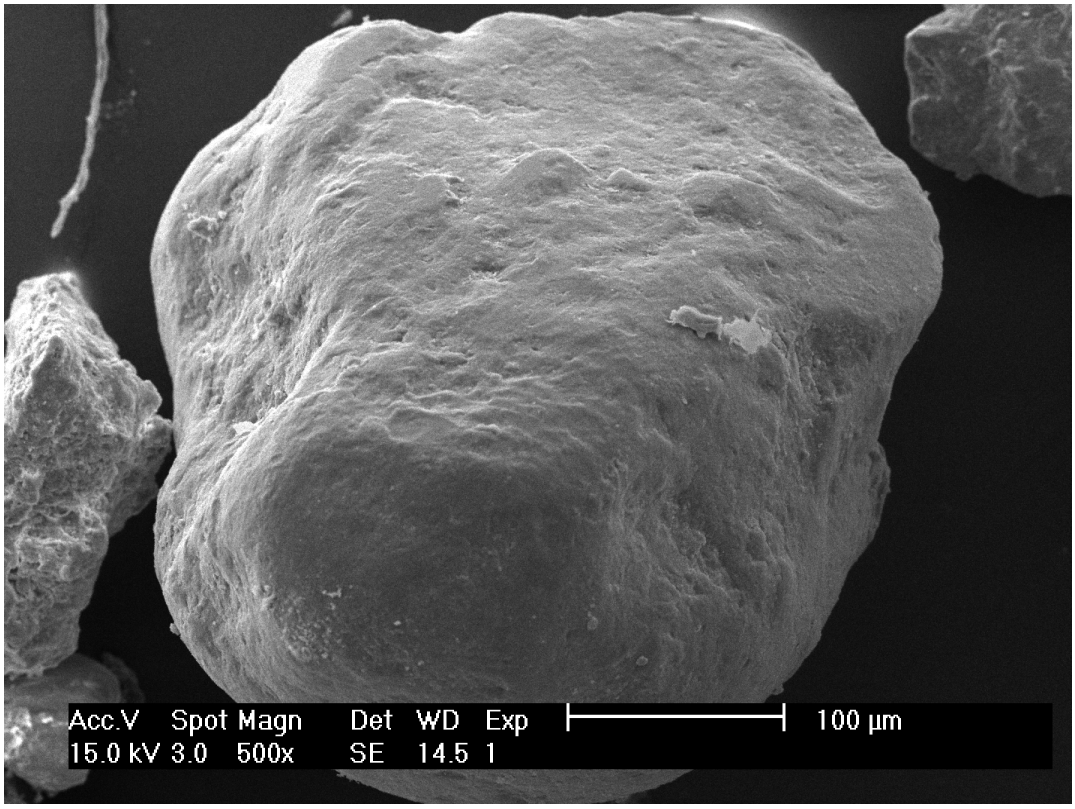


Figure 3.8.5. Features recognised on quartz grains from Mutawintji sediment.
(Enlargement with features reference, plate VI).

3.9 Quartz microdebitage—discussion of surface features

The experimental microdebitage produced by Clegg (1997a; 1997b) for this research project is similar to quartz grains from glacial environments, and those experimentally crushed, and resembles unweathered grains recently broken off source material (Krinsley and Doornkamp, 1973). The features catalogued by Krinsley and Doornkamp (1973), Krinsley and Margolis (1971), and Krinsley and Donahue (1968) for mechanically crushed grains and glacial environment grains all conform to descriptions given by Fladmark (1982) for quartz microdebitage.

The microdebitage samples from the manufacturing of rock engravings (BH-E), the samples from Sydney (SY-C) and the samples from Mutawintji (BH-C), are all different based upon the features on the quartz grains surface. Features at high magnification show that the microdebitage samples (BH-E) resemble mechanically broken grains, while the samples from Maroubra (SY-C1) and Pagewood (SY-C2) look like samples from littoral, subaqueous and aeolian environments combined. The sample of decaying Hawkesbury sandstone (SY-C3) has features on the quartz grains consistent with weathering from a polluted urban environment, while the sedimentary material from Mutawintji (BH-C samples) has features consistent with aeolian, arid and semi-arid environments.

All these features have been identified with the use of the electron microscope, which has highlighted the limited capacity of light microscopy to analyse such detailed features on quartz grains. According to Krinsley and Doornkamp (1973):

> "The light microscope with its maximum resolution of about 2000 Å is not sufficient to resolve fine surface detail on quartz grain particles which are less than about 1 mm in diameter. Geologists realised a number of years ago that the use of the electron microscope with its greater resolving potential (presently about 1.5 Å for the transmission and 100 Å for the scanning electron microscopes) would revolutionise the study of surface texture on fine particles." (Krinsley and Doornkamp, 1973:3).

The use of SEM and EDX combined has been useful not only in the recognition of quartz grain features but also in identifying the material type of the particles.

Some particles in the samples may not be quartz, hence the need to identify material chemical composition by x-ray spectrometry.

In this chapter, two major comparative analyses were undertaken. The first dealt with assigning a roundness index to each of the quartz samples; and the second dealt with the visual recognition and comparison of different environmental features on quartz grains. Both these analyses involved visual comparisons with reference charts and figures. The results of the shape analysis identified the angularity of microdebitage against different environments. In terms of this research, the microdebitage from the manufacturing of rock engravings is consistently more angular than the sedimentary material. It may be argued that the microdebitage would be immediately recognisable in the deposit in an aeolian environment situation.

The second comparative analysis dealt with the visual recognition of environment-specific features on quartz grains. This analysis concluded that the experimental microdebitage had features consistent with quartz grains which were freshly crushed (similar to those observed in the experimental crushed grains by Krinsley and Doornkamp, 1973), and closely resembles grains broken during release in glacial environments. The crushed grains have different features from those of an aeolian environment. These features on the quartz grains may also offer easily recognised differences between microdebitage and aeolian sediment. The visual comparisons in this chapter have revealed the differences exhibited by microdebitage if compared with sedimentary material from the same environment (samples BH-E and BH-C).

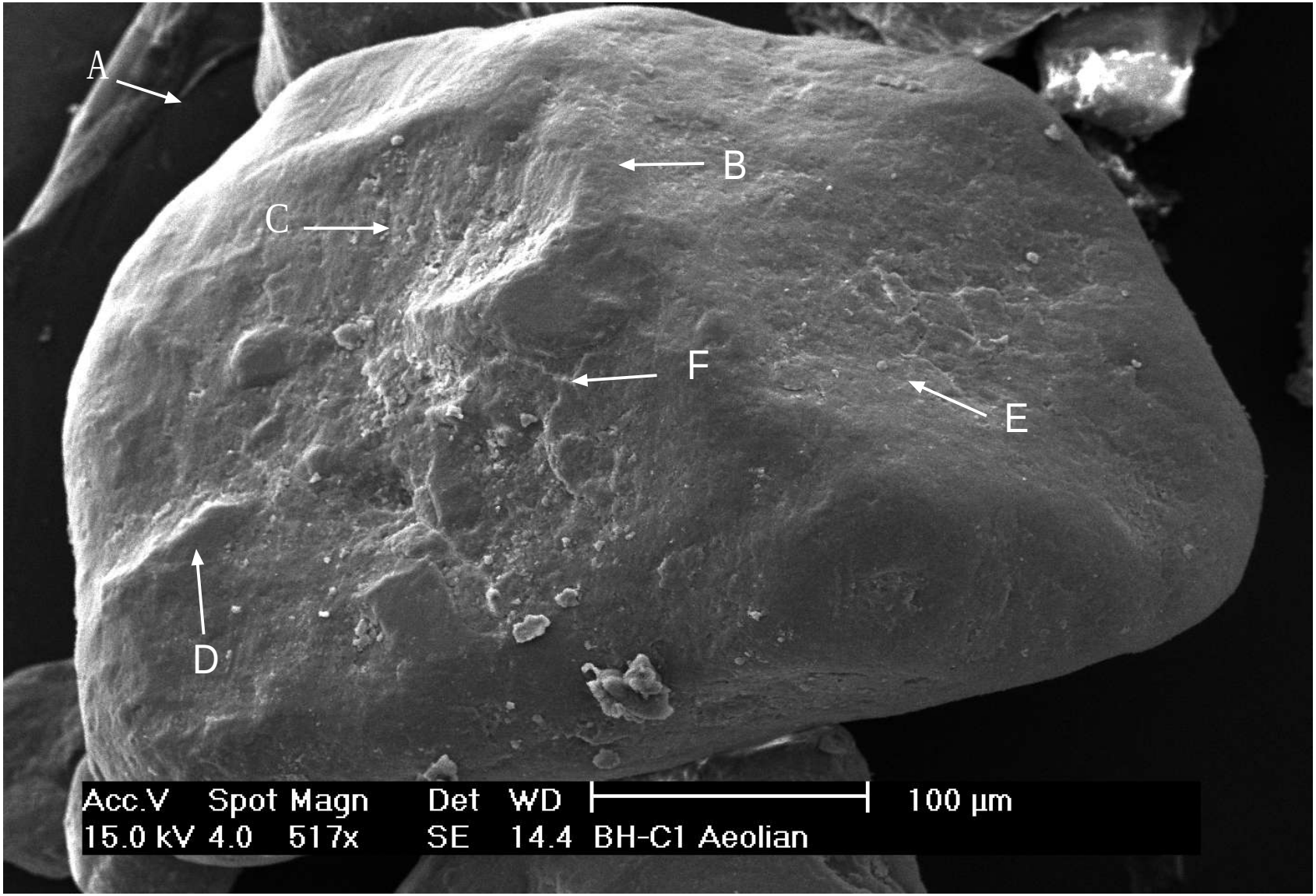


Plate I. Aeolian Sediment Features (Mutawintji topsoil, sample BH-C1).

A. Rounded grain. B. Disintegration by solution or by salt crystal growth. C. Smooth or irregular precipitation surface. D. Mechanically formed upturned plates. E. Dish- shaped concavities. F. Upturned silica plate.

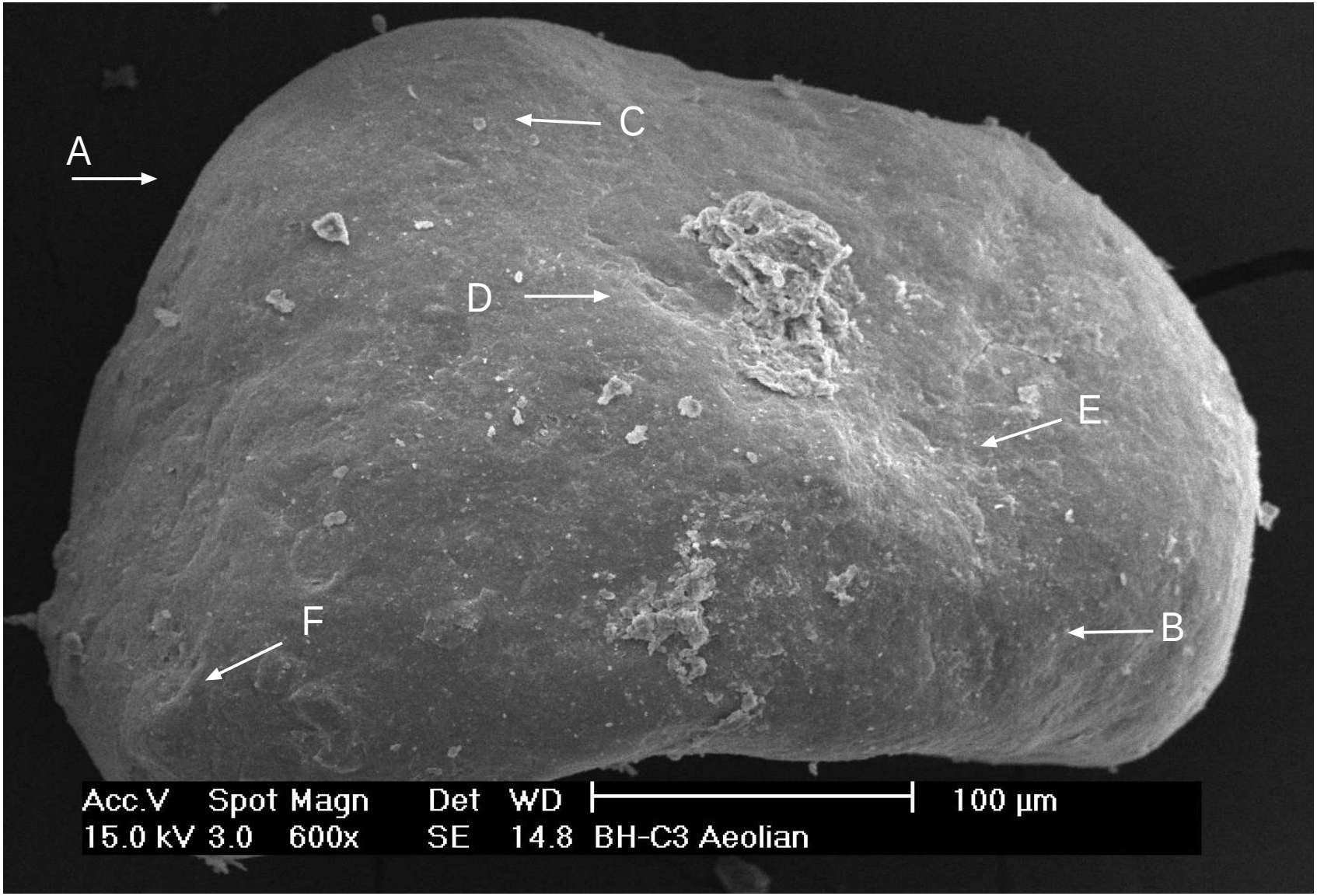


Plate II. Aeolian Sediment Features (Mutawintji sedinent, sample BH-C3).

A. Rounded grain. B. Disintegration by solution or by salt crystal growth. C. Irregular precipitation surface. D. Mechanically formed upturned plates. E. Dish- shaped concavities. F. Upturned silica plate.

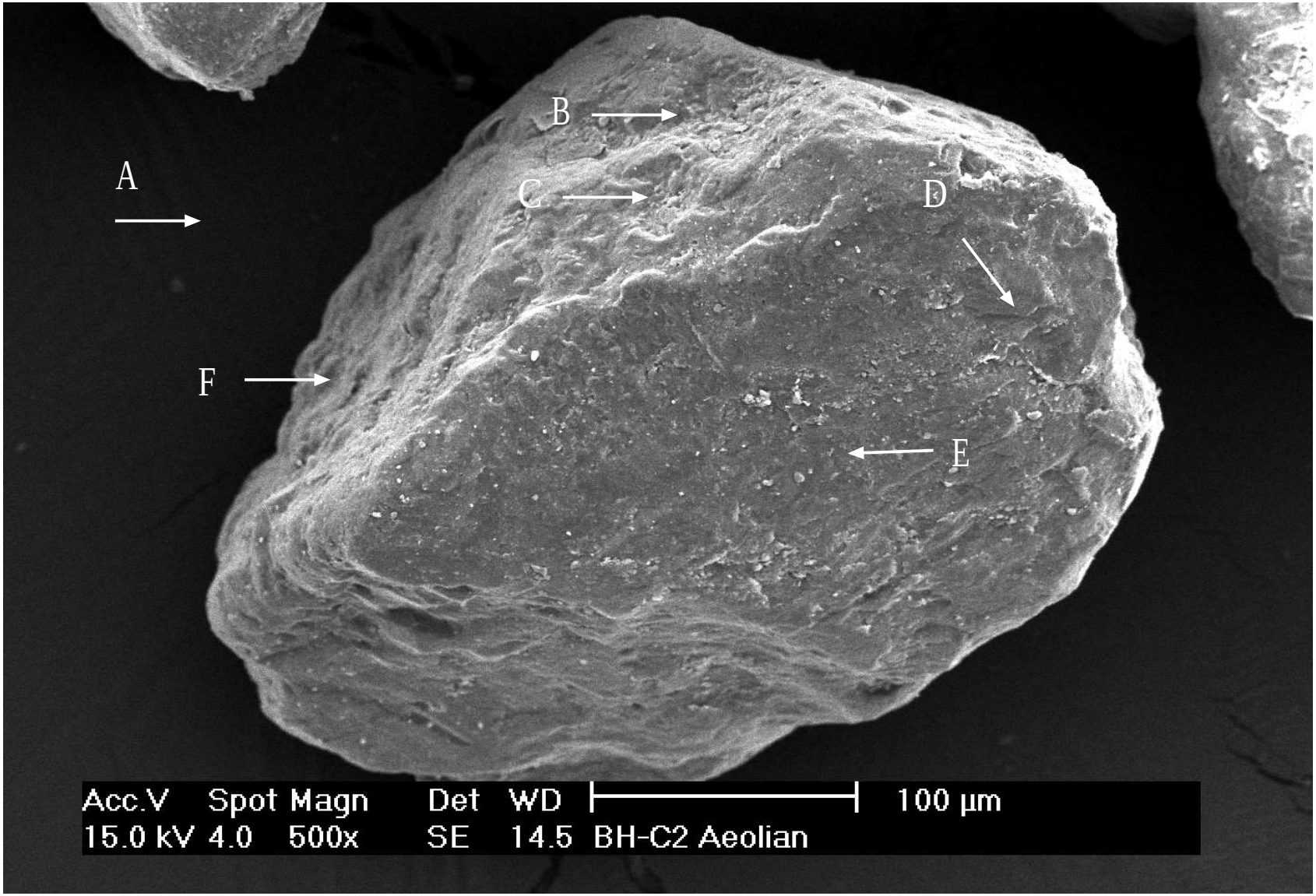


Plate III. Aeolian Sediment Features (Mutawintji sediment, sample BH-C2).

A. Sub-rounded grain. B. Disintegration by solution or by salt crystal growth. C. Dish- shaped concavities.
D. Mechanically formed upturned plates. E. Smooth or irregular precipitation surface. F. Precipitated upturned silica plate.

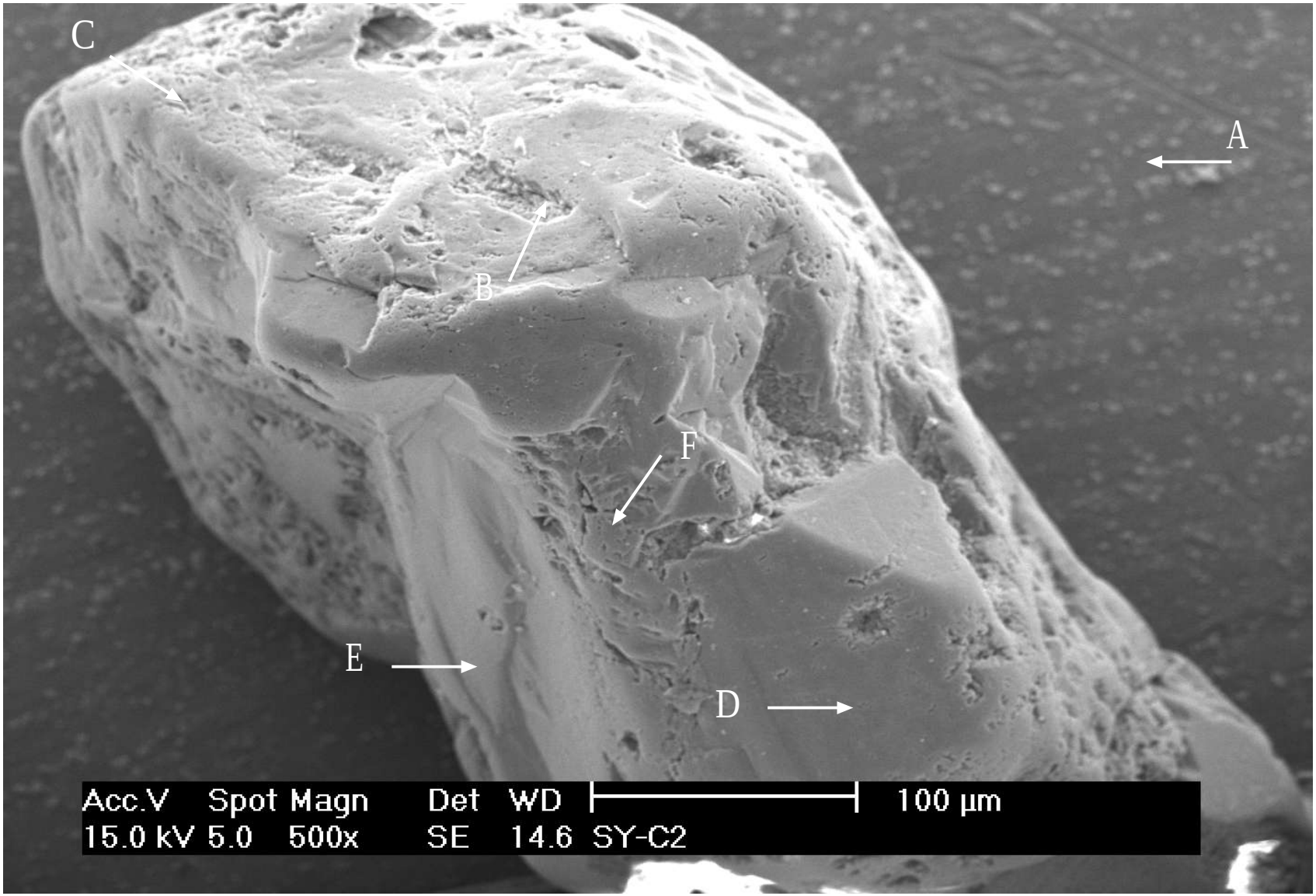


Plate IV. High Energy Subaqueous Features (Maroubra Beach, sample SY-C2).

A. Rounded grain. B. Mechanically formed upturned plates. C. Mechanical V-forms. D. Smooth precipitation surface. E. Conchoidal fractures. F. Straight or slightly curved grooves. G. Flat cleavage face.

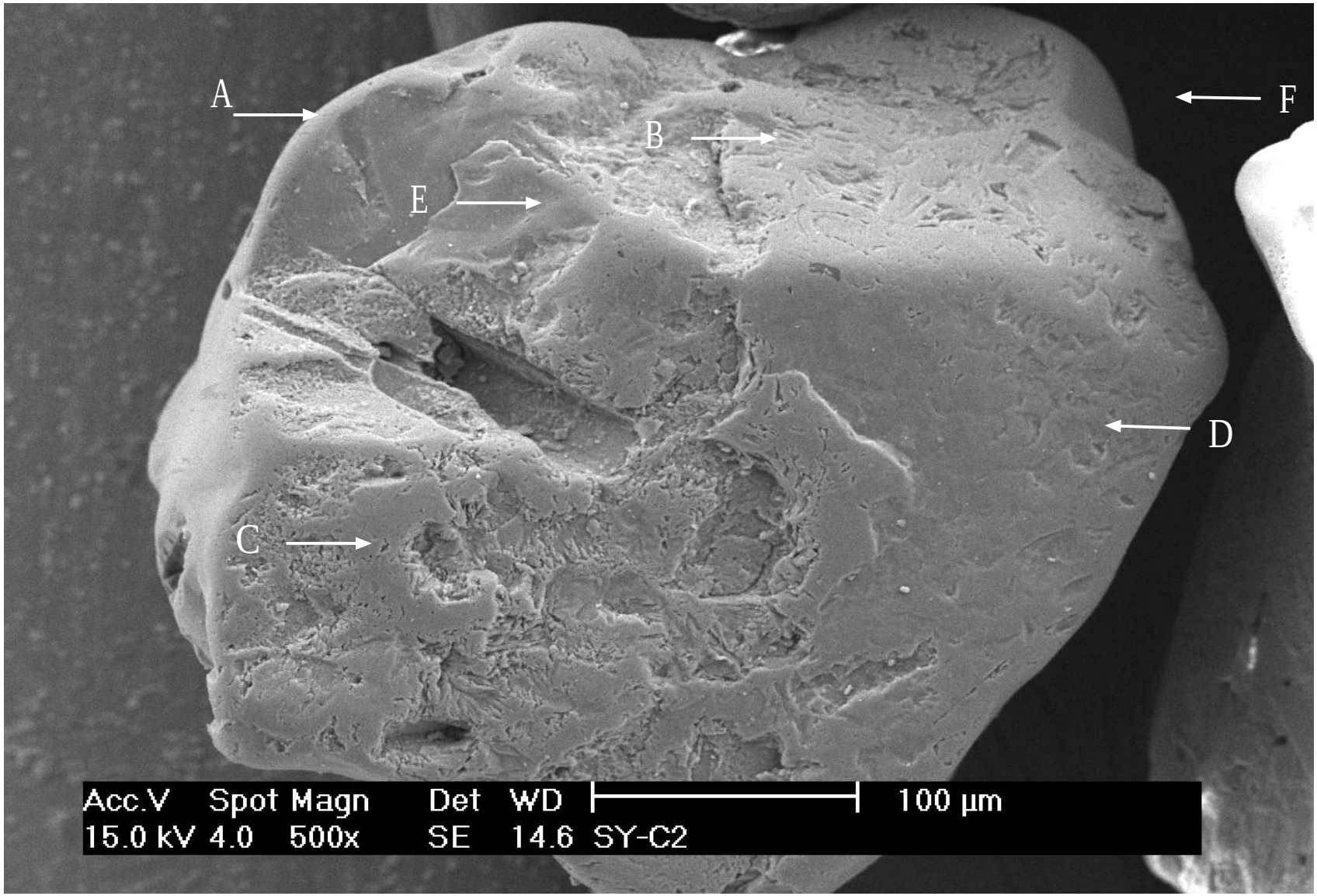


Plate V. High Energy Subaqueous Features (Maroubra Beach, sample SY-C2).

A. Rounded grain. B.Mechanically formed upturned plates. C. Mechanical V-forms. D. Smooth precipitation surface.
E. Conchoidal fractures. F.Straight or slightly curved grooves.

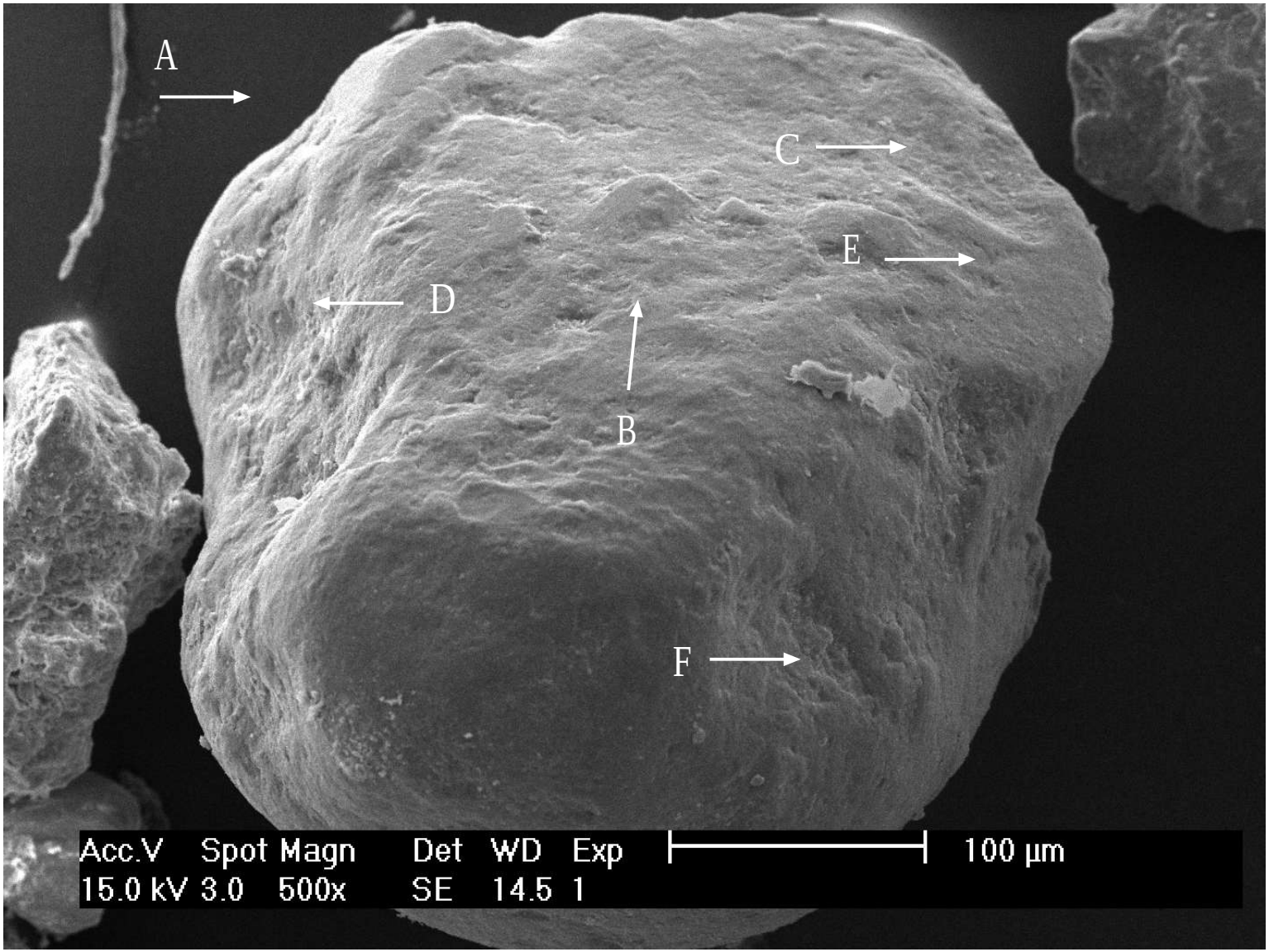


Plate VI. Aeolian and Subaqueous Features Combined (Pagewood sand dune, sample SY-C1).

A. Rounded grain. B. Smoothed precipitation surface. C. Etched V-forms. D. Mechanically formed upturned plates. E. Flat cleavage face. F. Some dish-shaped concavities.

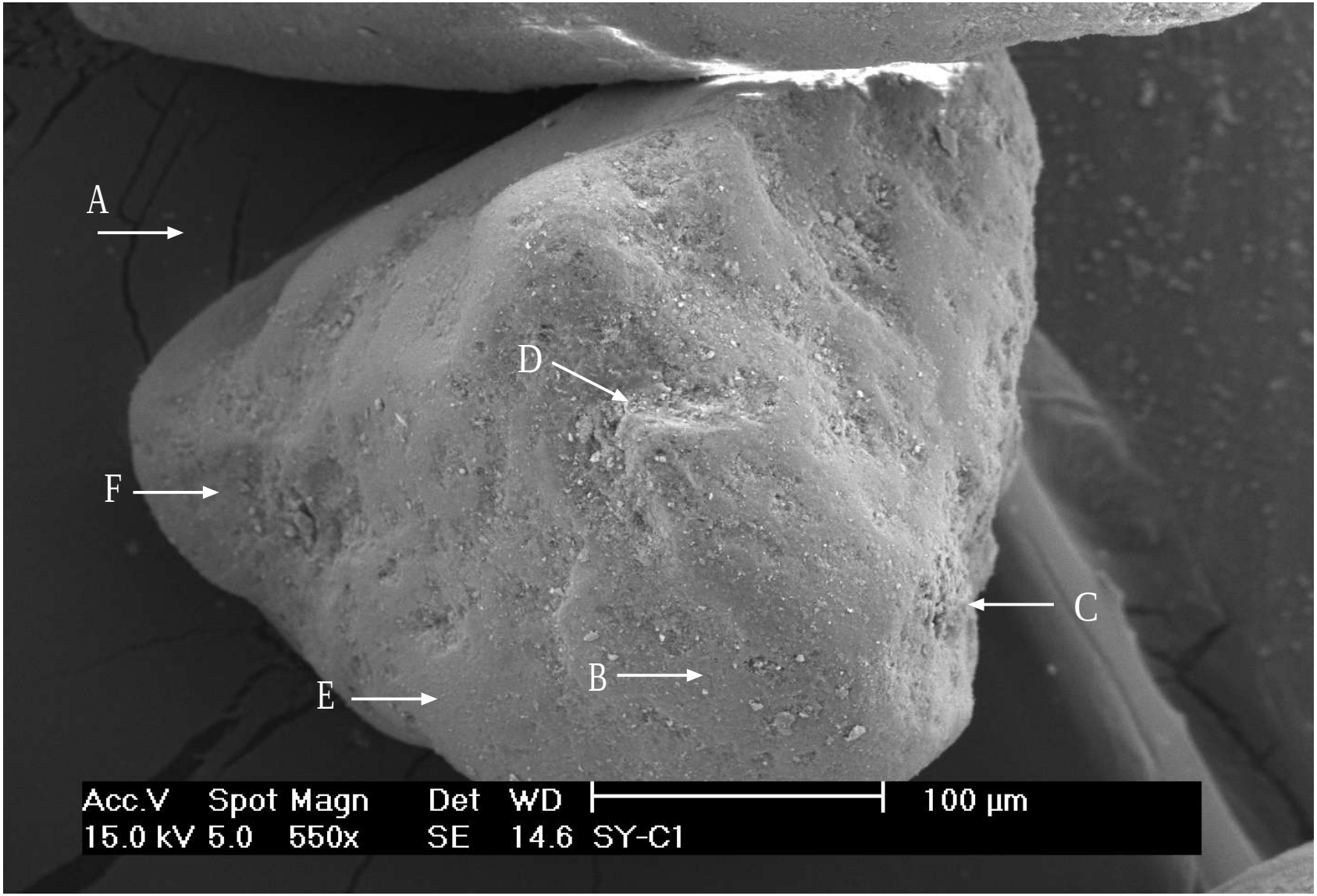


Plate VII. Aeolian and Subaqueous Features Combined (Pagewood sand dune, sample SY-C1).

A. Rounded grain. B. Smooth precipitation surface. C. Etched V-forms.
D. Mechanically formed upturned plates. E. Flat cleavage face. F. Some dish-shaped concavities.

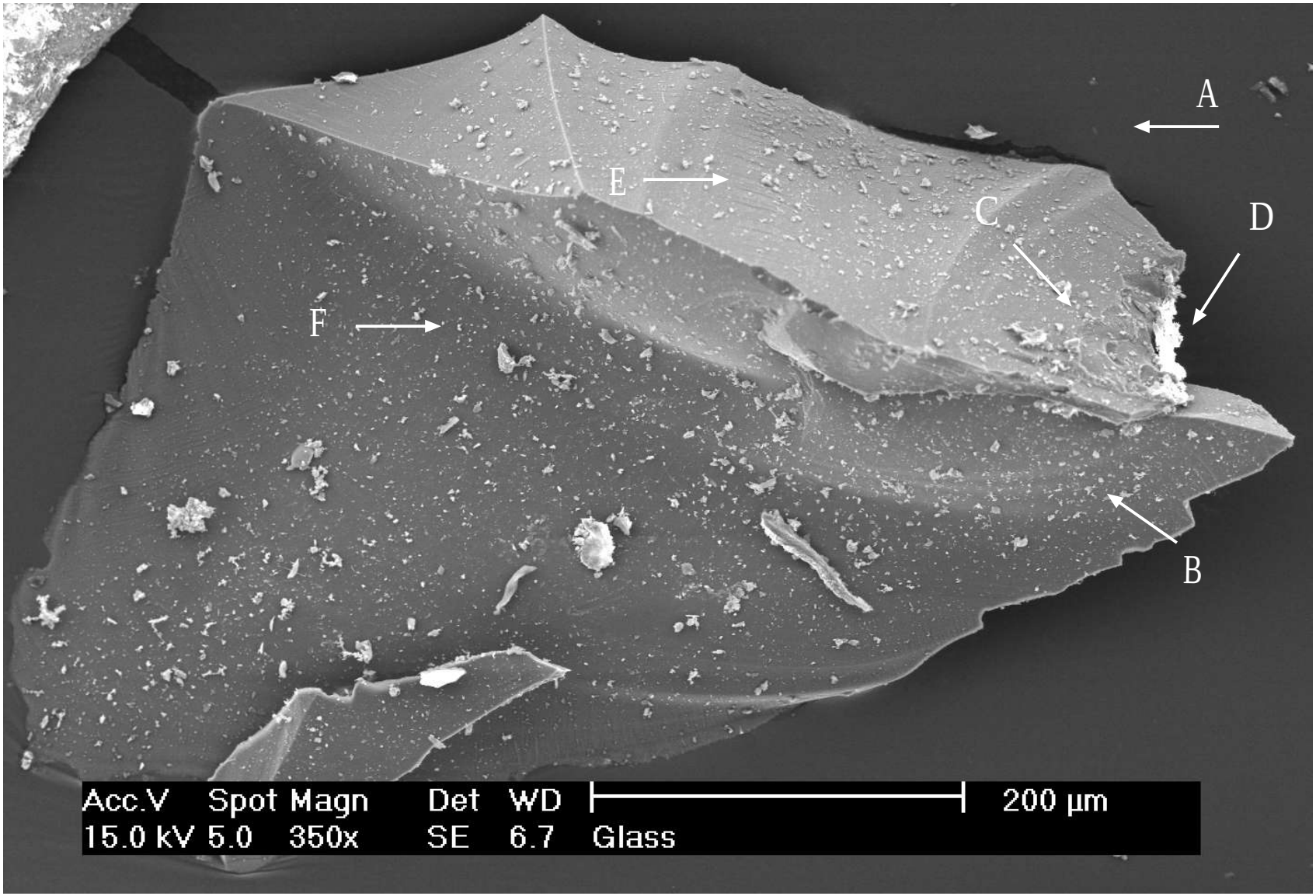


Plate VIII. Glass Microdebitage (Broken ashtray, sample SY-G1).

A. High angularity. B. Conchoidal fracture. C. Mechanically formed upturned plates. D.Unusual shape.
E. Cleavage planes (semi-parallel lines). F. Adhering particles.

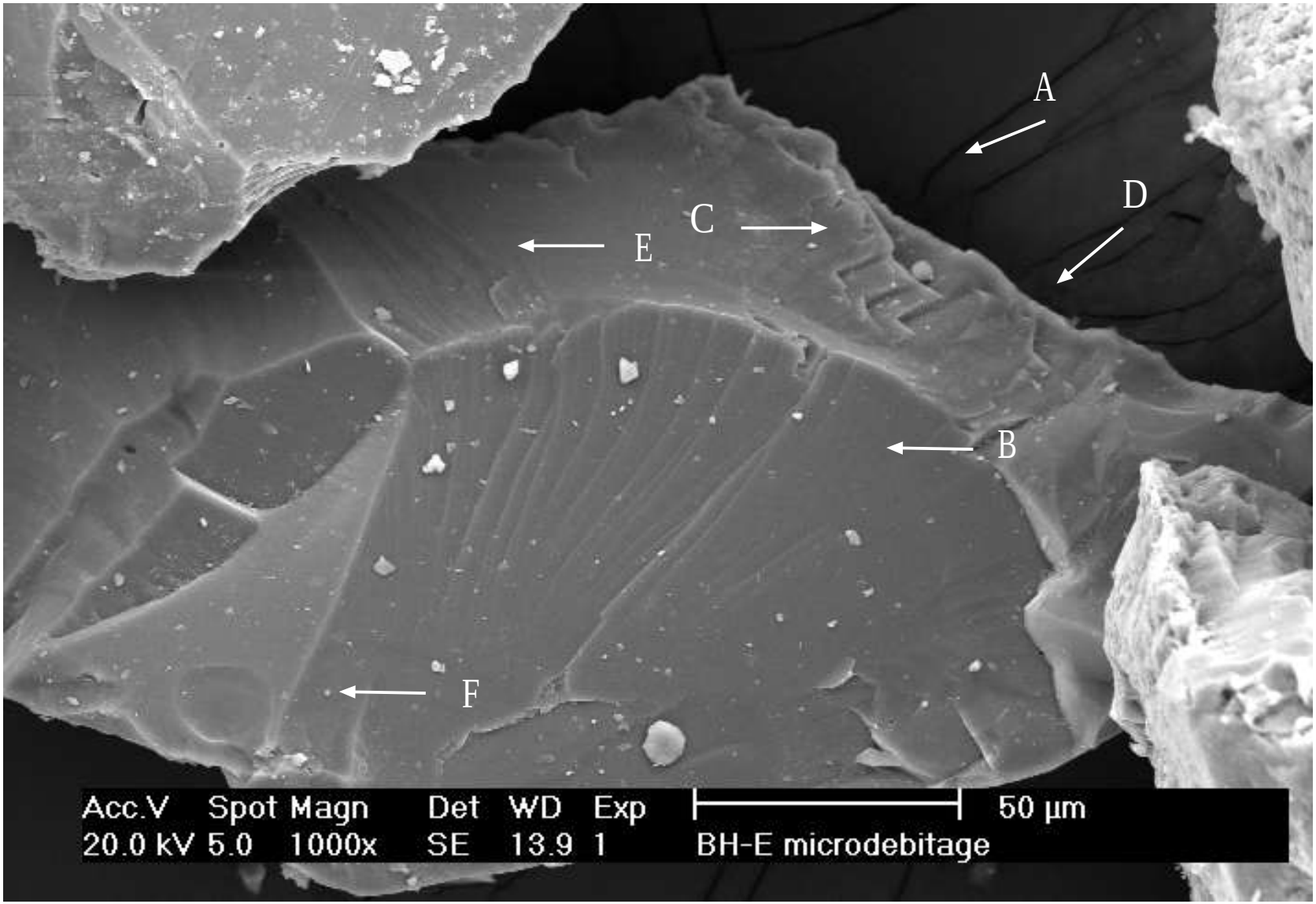


Plate IX. Microdebitage Features (experimental engraving, sample BH-E1).

A. High angularity. B. Conchoidal fractures. C. Mechanically formed upturned plates. D. Unusual shape.
E. Cleavage planes (semi-parallel lines). F. Adhering particles.

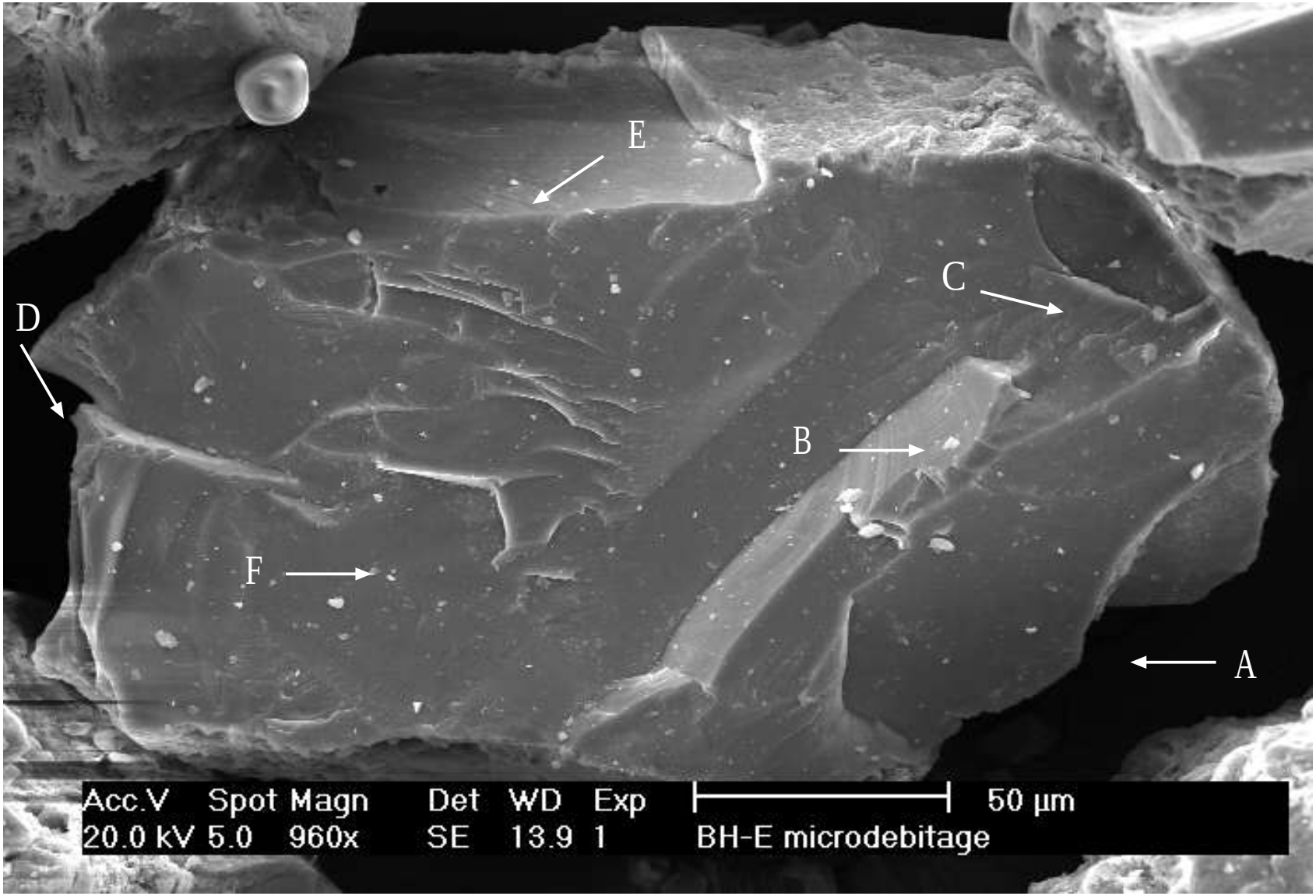


Plate X. Microdebitage Features (experimental engraving, sample BH-E3).

A. High angularity. B. Conchoidal fractures. C. Mechanically formed upturned plates. D. Unusual shape.
E. Cleavage planes (semi-parallel lines). F. Adhering particles.

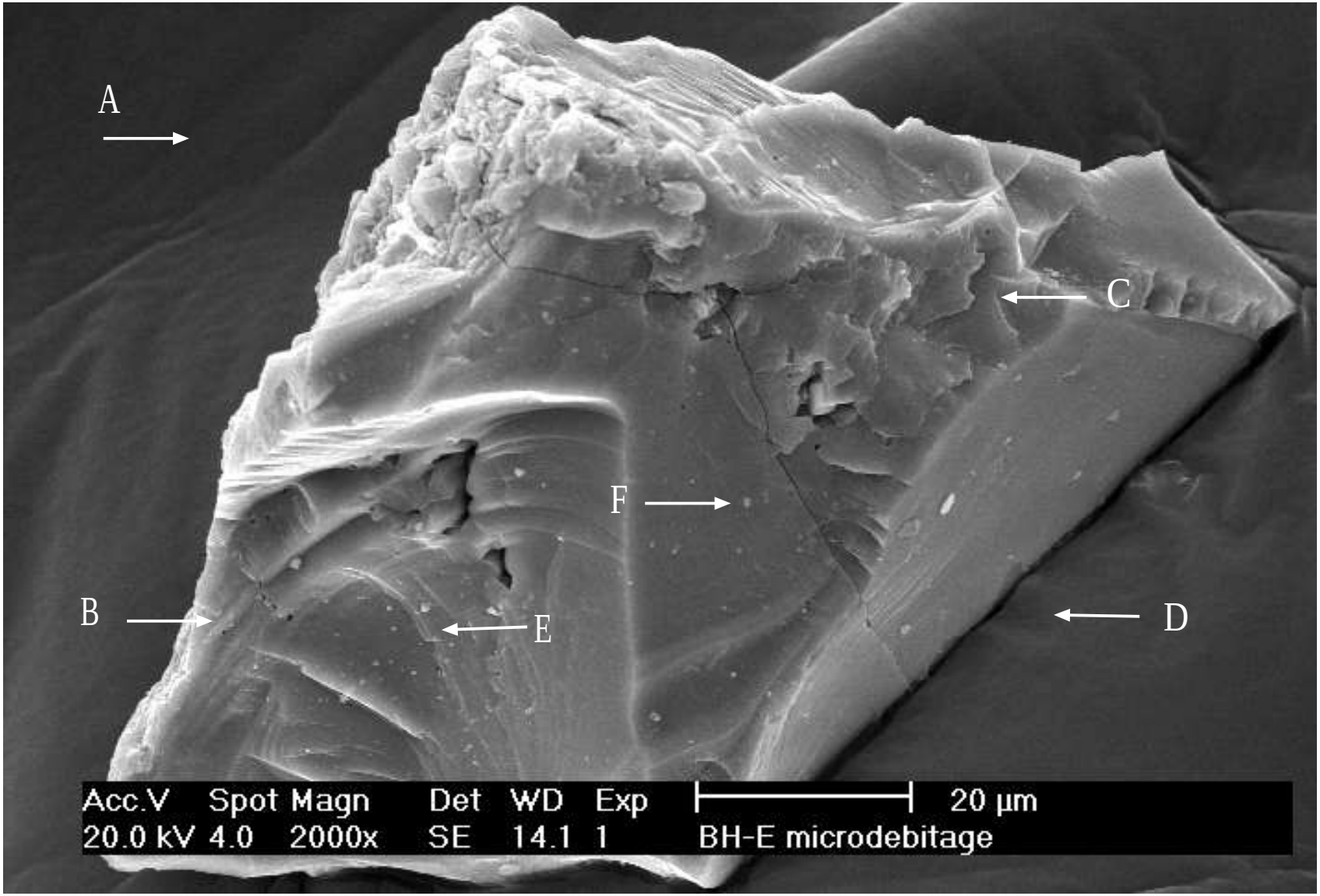


Plate XI. Microdebitage Features (experimental engraving, sample BH-E2).

A. High angularity. B. Conchoidal fractures. C. Mechanically formed upturned plates. D. Unusual shape.
E. Cleavage planes (semi-parallel lines). F. Adhering particles.

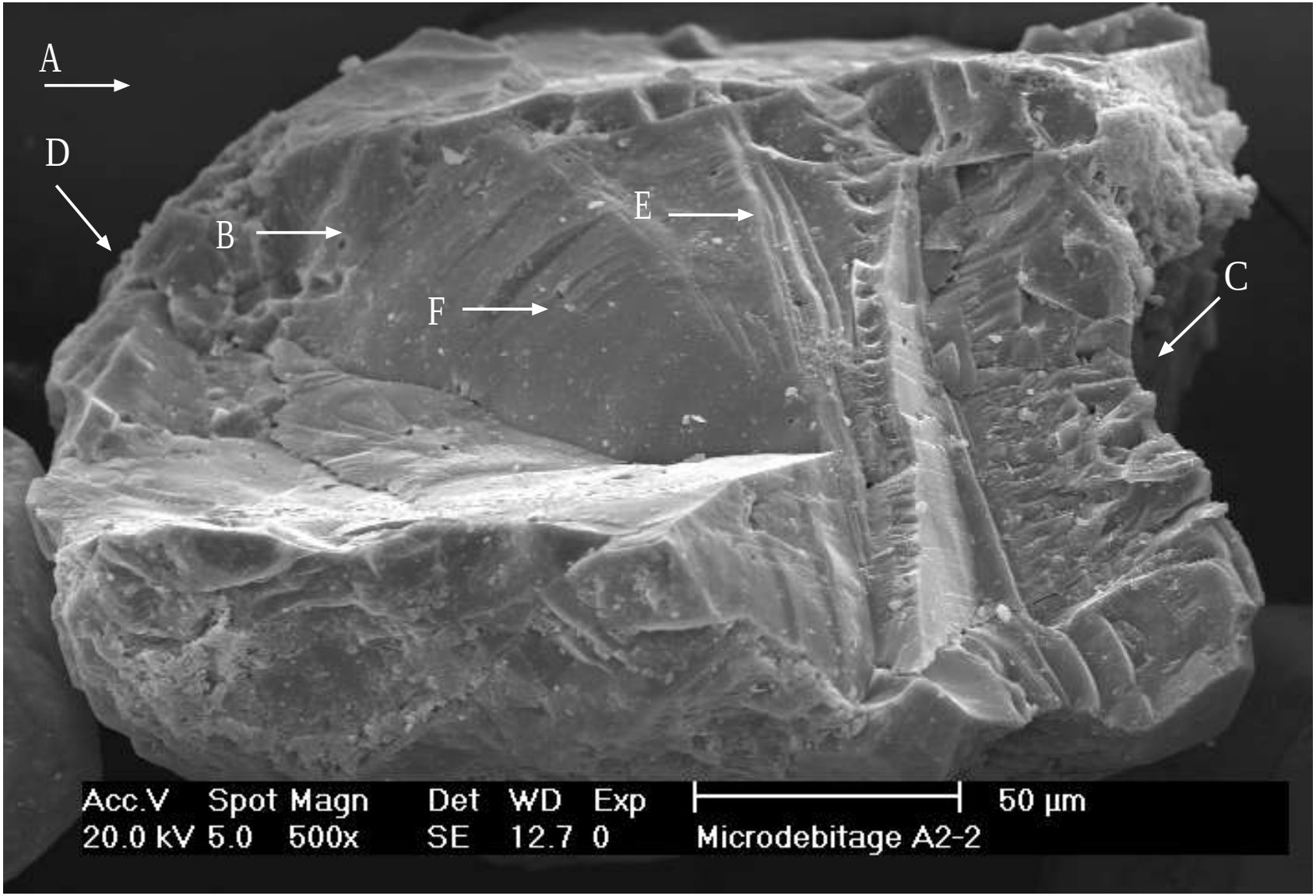


Plate XII. Microdebitage Features (experimental engraving, sample BT-A2/2).

A. High angularity. B. Conchoidal fractures. C. Mechanically formed upturned plates. D. Unusual shape.
E. Cleavage planes (semi-parallel lines). F. Adhering particles.

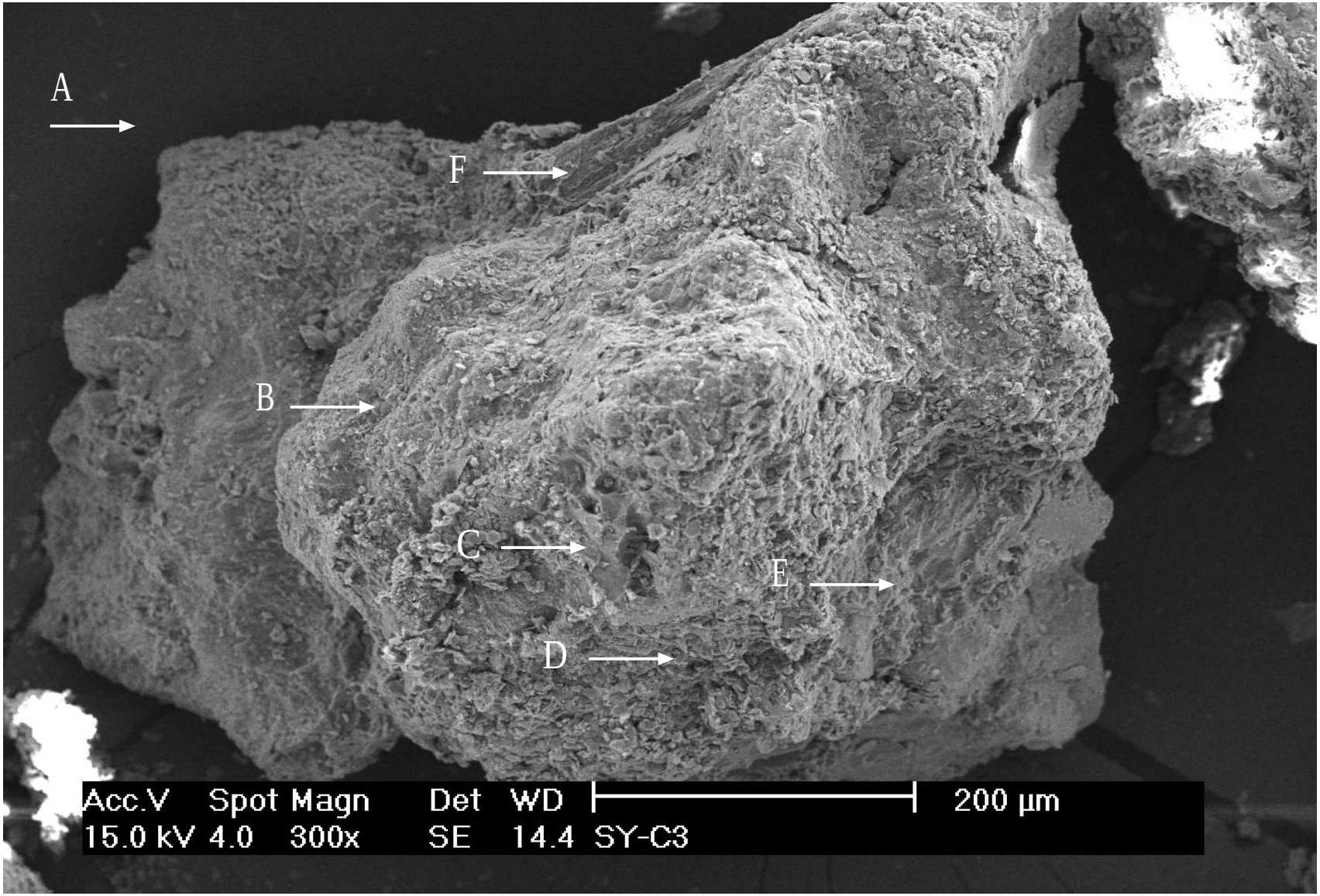


Plate XIII. High Energy Chemical Environment Features (Sandstone block, sample SY-C3).

A. High angularity. B. Upturned plates. C. Quartz crystal solution. D. Deep surface solution.
E. Disintegration by solution or by salt crystal growth. F. Large-scale chemical decomposition

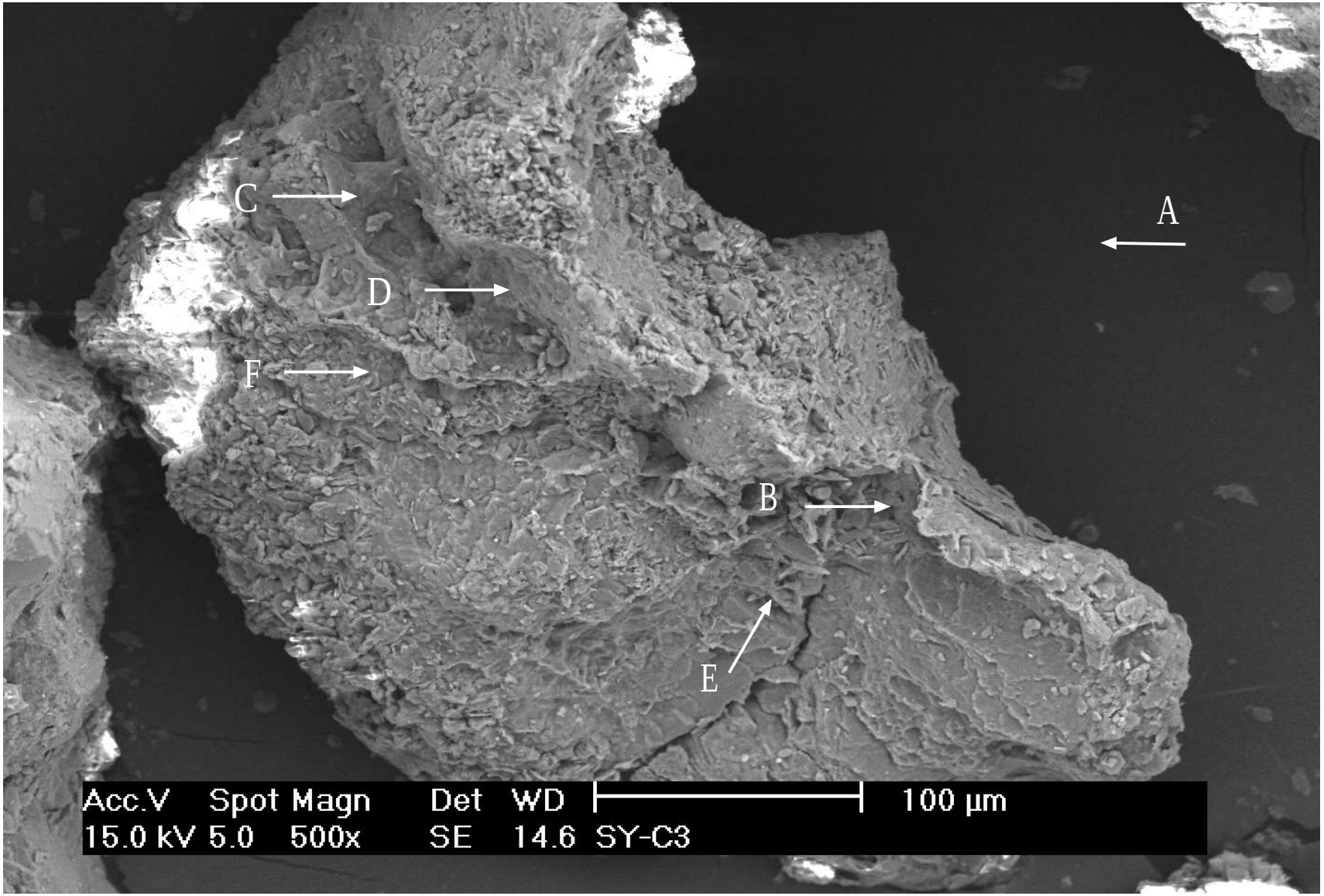


Plate XIV. High Energy Chemical Environment Features (Sandstone block, sample SY-C3).

A. High angularity. B. Upturned plates. C. Quartz crystal solution. D. Deep surface solution.
E. Disintegration by solution or by salt crystal growth. F. Large-scale chemical decomposition.

Chapter four

> *"The vast majority of the weathered, patinated, older-looking engravings have been chipped or pecked out of the rock. Small pits, nicks or indentations are produced on a rock by percussion with a hard pointed stone implement, either by a hand-held stone hammer (direct percussion) or use of a stone hammer and chisel (indirect percussion)... Contrary to the conventional view, they* [John Clegg and Dan Witter] *found direct percussion with a fist-sized quartz hammerstone far more effective than the indirect method."*
>
> *Josephine Flood (1997:103).*

Quartz sediments and microdebitage surface features

In Chapter 3 the comparison of samples revealed that microdebitage from experimental rock engravings is different from the sedimentary material from Mutawintji. This has prompted a further visual comparison, which would incorporate microdebitage and sedimentary material in the same sample. The sample to be analysed should emulate the number of microdebitage particles available in an archaeological deposit. The work of Fladmark (1982) and Hull (1983) assisted in determining the number of microdebitage particles found in archaeological deposits.

In this chapter, this research attempts to test new procedures for distinguishing naturally occurring quartz grains and microdebitage produced during the manufacture of rock engravings. As the material used, for practical purposes, was experimental, it was not feasible to provide detailed procedures and methods for use in the field. The recognition of experimental rock engraving microdebitage in sediments has not been attempted previously. It would be appropriate in the future to apply some of the outcomes of this thesis to material of archaeological provenance.

It is envisaged that with further work, it may be possible to apply the recognition of rock engraving microdebitage to archaeological investigations. At present, the recognition of microdebitage is extremely time-consuming, and it would be a matter for the individual archaeologist to decide if this type of investigation should be pursued in the field.

This chapter outlines the relationship between environments, sediments, and the recognition of microdebitage through environmental features on quartz grains. An examination was made of possible differences between microdebitage and soil *background*. For this purpose, part of the Mutawintji sediment sample (BH-C1) was mixed with the experimental microdebitage sample (BH-E1).

Mutawintji sedimentary material was used in order to emulate possible conditions found at archaeological sites containing rock engravings pounded or abraded on sandstone outcrops. The tests undertaken are not designed specifically for field application, but to investigate the possibility that quartz microdebitage from the manufacturing of rock engravings can be distinguished from other sedimentary material.

Fladmark (1982) has successfully investigated and field tested microdebitage analysis. Fladmark (1982) used light microscopy to determine the surface features of microdebitage with success on material other than quartz. This chapter investigates the use of scanning electron microscopy, as applied by Krinsley and Doornkamp (1973) to quartz grains of different provenance, to identify features that would allow quartz microdebitage to be distinguished sedimentary quartz.

For the purpose of recognising microdebitage against sediment, the sediment was used as *'background'* to the particles of quartz microdebitage. This will allow the SEM observer to count the incidences of microdebitage in the sample, according to a table of features.

The visual recognition test described in this chapter is based upon the features on quartz grains, as observed by Krinsley and Doornkamp (1973), and the shape recognition observed by Fladmark (1982). Prior to the application of these observations, some explanation is required of the issues concerning quartz grains, sandstone, sediments, deposits, and their relation to rock engravings.

4.1 Quartz grains and archaeological deposits

The assessment of surface environmental features on quartz grains is based upon:

1. The presence or absence of conchoidal fractures.
2. The presence or absence of flat cleavage planes and their expression on the margins of the quartz grains in an unaltered form.
3. The presence of upturned plates on cleavage or crystal faces.
4. The degree and nature of the alterations of these features.
   (Krinsley and Doornkamp, 1973: 8).

The environment does not only determine these features, but also the pre-existing nature of the quartz grains. Sandstone is composed mainly of quartz grains and clay matrix, bound together by a siliceous, ferruginous or carbonate cement. The grains may have been previously part of oceanic or fluvial sediments; hence, the grains within the cement bond will reflect those environments. In time, the grains released from the matrix will slowly acquire the features of the environment into which they are released. In the case of Mutawintji and Sturts Meadows, the grains in the sandstone were originally ocean floor sediments. The grains may reflect roundness from the subaqueous environment. When released into an aeolian environment, the grains become ever more rounded, and the surface will become worn in a manner consistent with a semi-arid environment. Both subaqueous and aeolian environments produce rounded grains, so grain shape provides only a partial discrimination between previous environments.

Research on environmental determination of deposits has been largely based on the work of Krinsley and Doornkamp. In Australia, Ly (1978a; 1978b) used scanning electron microscopy as an effective tool for the study of quartz grain features. Other overseas studies on different environments (Margolis and Krinsley, 1971, 1974; Manker and Ponder, 1978; Smith *et al.*, 1991) also reflect the widespread use of the methods developed by Krinsley and Doornkamp.

To analyse and incorporate the propositions put forward by Krinsley and Doornkamp (1973) a further comparison test was devised for this research.

This test was designed to examine the hypothesis that quartz microdebitage is recognisably different from the grains naturally occurring in sediments. The results of the comparisons among samples in Chapter 3 showed that there are differences in shape and features between the microdebitage and the Mutawintji samples. Mixing sedimentary material with microdebitage at a known rate may test this proposition further.

4.2 Preparation of samples

The preparation of samples to be tested has followed a similar pattern from the first comparison test (chapter 3). Fladmark's method (1982) (see appendix 1) closely followed methods set forth by Shackley (1975). The methods used in this research reflect closely, with some exception, the sample preparation set out as standard laboratory procedures followed by Fladmark (1982). Other methods and variations on the techniques were tested. The results added little or no difference to the methods used by Fladmark (1982) (Appendix 2).

Iron oxides were not removed from the microdebitage (BH-E) samples and the sedimentary material (BH-C) for SEM analysis. There is no need for iron oxide removal if the SEM is in secondary scanning electron mode, as the electrons penetrate the surface of the grain. If the SEM is used in the backscatter electron mode, which does not penetrate the grain, showing only the surface, the sample should have the iron oxides removed. Both types of scanning can give good results.

For this research the secondary electron mode was used because of its clarity in showing the surface features. For this comparison, the *natural* sedimentary material used is the sample BH-C1, derived from the top two centimetres of sediment at Two Mile Tank, Mutawintji National Park (Broken Hill, NSW).

4.2.1 Preparation of samples for SEM/EDX analysis

In the absence of any reference to sampling sizes and proportions, it was decided to use the sampling technique used by Fladmark (1982) in which a sample of 10,000 particles per size fraction was used. This sampling size suited this research since it was close enough to the field conditions encountered by Fladmark (1982). Fladmark (1982) identified a maximum of 200 particles of microdebitage per 10,000 of sediment. The preparation of the samples for SEM followed standard procedures for this type of material. The procedure followed for all the contents of the mixed sediment (BT) vials is:

1. A 25mm diameter SEM aluminium stub with a 25mm diameter carbon-impregnated adhesive tape (ProSciTech, cat. No. IA024) was used to fix the particles for SEM analysis.
2. A 1.25mm platinum rod (diameter of 100µm) was placed and fixed in the radius of the stub for orienting the sample in the SEM.
3. The particles were applied evenly, after randomising the sub-sample, on the stub (s), and the stub shaken to eliminate the excess and loose particles (loose particles were returned to the vial for the next stub).
4. The completed stubs were inserted into an Edwards sputter coater. Coated with 300Å of gold (rate of coating: 5Å/sec. @ 5.5cm from the magnet to the stub, with argon admittance pressure at $1x10^{2}$ mbar in a vacuum of 10^{-4} mbar).
5. The stubs were then kept in a drying cabinet ready for use. All stubs were labelled (eg. BT-A1/1) (table 4.2.1.1).

Table 4.2.1.1. Labelling and number of stubs per size range.

Sample vial	Number of stubs	Size range	Sample vial	Number of stubs	Size range
			BT-C2	8 (BT-C2/1-8)	500-250µm
BT-A1	33 (BT-A1/1-33)	1000-500µm	**BT-D2**	8 (BT-D2/1-8)	500-250µm
BT-B1	34 (BT-B1/1-34)	1000-500µm	**BT-E2**	7 (BT-E2/1-8)	500-250µm
BT-C1	32 (BT-C1/1-32)	1000-500µm	**BT-A3**	1 (BT-A3/1)	250-125µm
BT-D1	33 (BT-D1/1-34)	1000-500µm	**BT-B3**	1 (BT-B3/1)	250-125µm
BT-E1	34 (BT-E1/1-34)	1000-500µm	**BT-C3**	1 (BT-C3/1)	250-125µm
BT-A2	8 (BT-A2/1-8)	500-250µm	**BT-D3**	1 (BT-D3/1)	250-125µm
BT-B2	8 (BT-B2/1-8)	500-250µm	**BT-E3**	1 (BT-E3/1)	250-125µm

The prepared samples (table 4.4.2.1) were placed into the vacuum chamber of a Philips XL30 SEM for scanning. The samples were visually analysed with a secondary electron scanner (SE) at 20KeV of current. Scanning at 480 lines per frame and 0.42 milliseconds per line was used for scanning across the sample.

The basic magnification for the blind test was kept constant for each size fraction. The <500µm fraction used a magnification of 150x for general scanning, and a maximum of 1500x for features recognition. The <250µm fraction used a magnification of 200x, and a maximum of 2000x. The <125µm fraction used a magnification of 250x with a maximum of 2500x for the finer detail of the features.

The samples were scanned using the platinum bar in the radius of the stub as an indicator of the circumference of the sample, and moving up one screen each revolution until the centre of the stub was reached (figure 4.2.1.1).

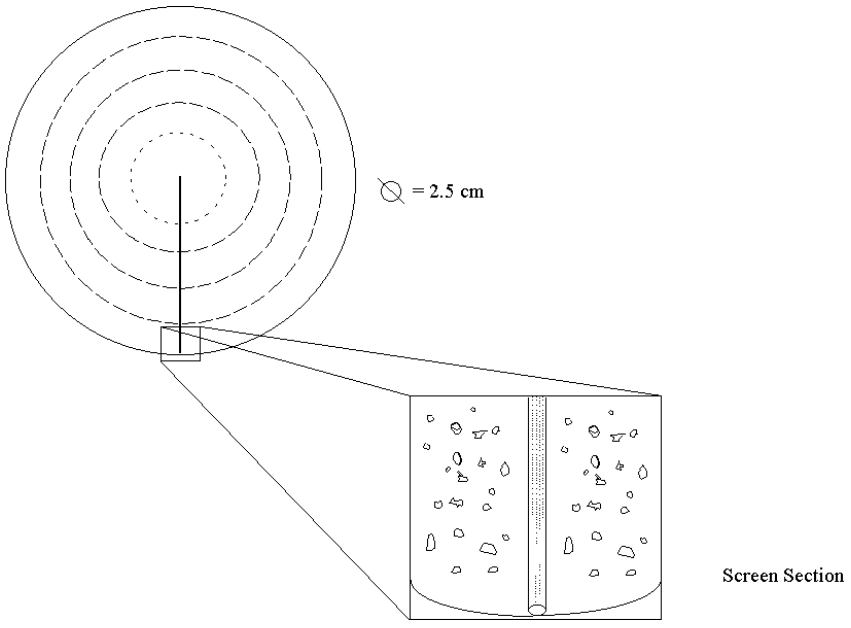


Figure 4.2.1.1. Method for scanning through a 2.5mm stub under SEM.

The following table of features, coupled with EDX analysis, was used to determine quartz microdebitage from a *background* of aeolian sediment grains.

4.3 Blind testing a mixed sample—visual comparison

The blind test, using microdebitage and sediment as *background,* was devised to apply the understanding of environmental features to samples which contain microdebitage and soil at a known rate. This was done in reply to the question related to the application of environmental features to microdebitage and naturally occurring quartz grains:

1. *Can quartz microdebitage be distinguished from other material in the samples by using surface features and roundness?*

This question was posed to test the possibility that microdebitage can be seen as separate material in an aeolian sediment. To do so the material chosen as *background* for the microdebitage was the aeolian topsoil from Mutawintji.

The terms of this test were to determine, under SEM and EDX, which particles of quartz are from aeolian sediment, and which are microdebitage. This was done by identifying and counting the number of quartz microdebitage grains within a sample containing 10,000 particles of aeolian quartz grains. The samples reflect as closely as possible 10,000 particles for each size sub-samples. Fladmark's weights for sub-sampling were used, for the following size fractions: 1000-500µm, 5g; 500-250µm, 0.75g; 250-125µm, 0.06g; 125-63µm, 0.02g (table 4.3.1).

Table 4.3.1. Background material (BH-C1) and the microdebitage (BH-E1) placed on stubs.

Sediment	**Size range**	**Sample origin**	**Particles**
BH-C1A	1000-500um	Fraction of the top 2cm of soil from Mutawintji	10,000
BH-C1B	500-250um	Fraction of the top 2cm of soil from Mutawintji	10,000
BH-C1C	250-125um	Fraction of the top 2cm of soil from Mutawintji	10,000
Microdebitage	**Size range**	**Sample origin**	**Particles**
BH-E1A	1000-500um	Fraction of microdebitage from experimental engraving E1	0, 50, 100, 150, 200
BH-E1B	500-250um	Fraction of microdebitage from experimental engraving E1	0, 50, 100, 150, 200
BH-E1C	250-125um	Fraction of microdebitage from experimental engraving E1	0, 50, 100, 150, 200

The test samples are a mixture of approximately 10,000 particles from sub-

samples BH-C1A to BH-C1C (table 4.3.1) (microdebitage from the first experimental rock engraving) with particles ranging from approximately 50 to approximately 200 of sample BH-E1A to BH-E1C (sediment from the top 2cm of Mutawintji soil).

The samples of the first 2-cm of sediment from Mutawintji were used to provide a background in which to add microdebitage. The aim was to determine whether it was possible to identify the relatively low incidences of microdebitage from the large amount of other material. The sample without microdebitage was used as a calibration blank (table 4.3.2).

Table 4.3.2. Sediment particle vial labelling used for aeolian environment *background*.

Vial	Particles (approx.)	Weight	Particle size range	Sub-sample
BT-A1	10,000	5g	1000-500µm	BH-C1A
BT-B1	10,000	5g	1000-500µm	BH-C1A
BT-C1	10,000	5g	1000-500µm	BH-C1A
BT-D1	10,000	5g	1000-500µm	BH-C1A
BT-E1	10,000	5g	1000-500µm	BH-C1A
BT-A2	10,000	0.75g	500-250µm	BH-C1B
BT-B2	10,000	0.75g	500-250µm	BH-C1B
BT-C2	10,000	0.75g	500-250µm	BH-C1B
BT-D2	10,000	0.75g	500-250µm	BH-C1B
BT-E2	10,000	0.75g	500-250µm	BH-C1B
BT-A3	10,000	0.06g	250-125µm	BH-C1C
BT-B3	10,000	0.06g	250-125µm	BH-C1C
BT-C3	10,000	0.06g	250-125µm	BH-C1C
BT-D3	10,000	0.06g	250-125µm	BH-C1C
BT-E3	10,000	0.06g	250-125µm	BH-C1C

Fifteen vials were prepared with *background* sediment at a rate of 10,000 particles from sample BH-C1 (table 4.3.2). The samples were prepared by weighing the material at the rates set by Fladmark (1982: 218).

Twelve vials were prepared with the microdebitage from sample BH-E1. The first four vials called D1-D4, contained particles from sub-sample BH-E1A (<500µm fraction). Vials D5-D8 contained particles from sub-sample BH-E1B (<250µm fraction). Vials D9-D12 contained particles from sub-sample BH-E1C (<125µm fraction). The number of particles in each vial were: D1, D5, and D9

contained approximately 200 particles; vials D2, D6, and D10 contained approximately 50 particles; vials D3, D7, and D11 contained approximately 100 particles; vials D4, D8, and D12 contained approximately 50 particles. All the particles were retained within their particle size range (table 4.3.3).

Table 4.3.3. Microdebitage particles added to the soil particles from Mutawintji.

Vial	Particles (approx.)	Weight (approx.)	Particle size range	sample
D1	200	0.1g	1000-500µm	BH-E1A
D2	150	0.075	1000-500µm	BH-E1A
D3	100	0.05g	1000-500µm	BH-E1A
D4	50	0.025g	1000-500µm	BH-E1A
D5	200	0.015	500-250µm	BH-E1B
D6	150	0.01125g	500-250µm	BH-E1B
D7	100	0.075g	500-250µm	BH-E1B
D8	50	0.00375g	500-250µm	BH-E1B
D9	200	0.0012g	250-125µm	BH-E1C
D10	150	0.0009g	250-125µm	BH-E1C
D11	100	0.0006g	250-125µm	BH-E1C
D12	50	0.0003g	250-125µm	BH-E1C

These vials were only used once to hold the weighed particles to be transferred into the *background* sediment vials. As this test was set as blind, the vial labelling was randomised by Dr Dragovich (Division of Geography, University of Sydney), so that at no time, the amount of microdebitage particles in each of the *background* vials was known by the SEM analyst.

The D1-D4 vials content was transferred to vials BT-A1 to BT-E1; vials D5-D8 were transferred into vials BT-A2 to BT-E2, leaving one sample blank; vials D9-D12 were transferred into vials BT-A3 to BT-E3, leaving one blank for each sub-sample. The content of each size range was transferred to the BT vials containing the 10,000 particles of aeolian sediment, leaving one of the sample vials blank (without microdebitage, to be used as a control sample). The outcome of mixing the materials was recorded, and a copy retained by Dr Dragovich. This was to be returned at the end of the SEM/EDX comparison test on the material in the vials. The samples in the BT vials were transferred to SEM stubs for SEM/EDX analysis.

4.4 Testing the comparison of features

The SEM/EDX comparison test was designed to recognise microdebitage from a background of sedimentary material by using a list of six features (table 4.4.1). The features selected in order to identify microdebitage from the aeolian background particles were derived from Fladmark (1982), and Krinsley and Doornkamp (1973). The test was set as blind, so the number of microdebitage particles set in each sample would not be disclosed to the viewer.

Differences in surface features were used to distinguish microdebitage from the aeolian sediment material. The microdebitage has the same features noted on the experimentally crushed grains made by Krinsley and Doornkamp (1973). These features include: concoidal fractures; mechanically formed upturned plates; cleavage-planes (semi-parallel lines), and adhering particles. The high angularity and irregular and unusual shape definitions are derived from Fladmark's (1982) description of microdebitage (table 4.4.1 and figure 4.4.1 below).

Table 4.4.1. Microdebitage features (experimental engraving E1) used for the test under SEM.

Experimental microdebitage features
A. High angularity
B. Conchoidal fractures
C. Mechanically formed upturned plates
D. Irregular and unusual shape
E. Cleavage-planes (semi-parallel lines)
F. Adhering particles

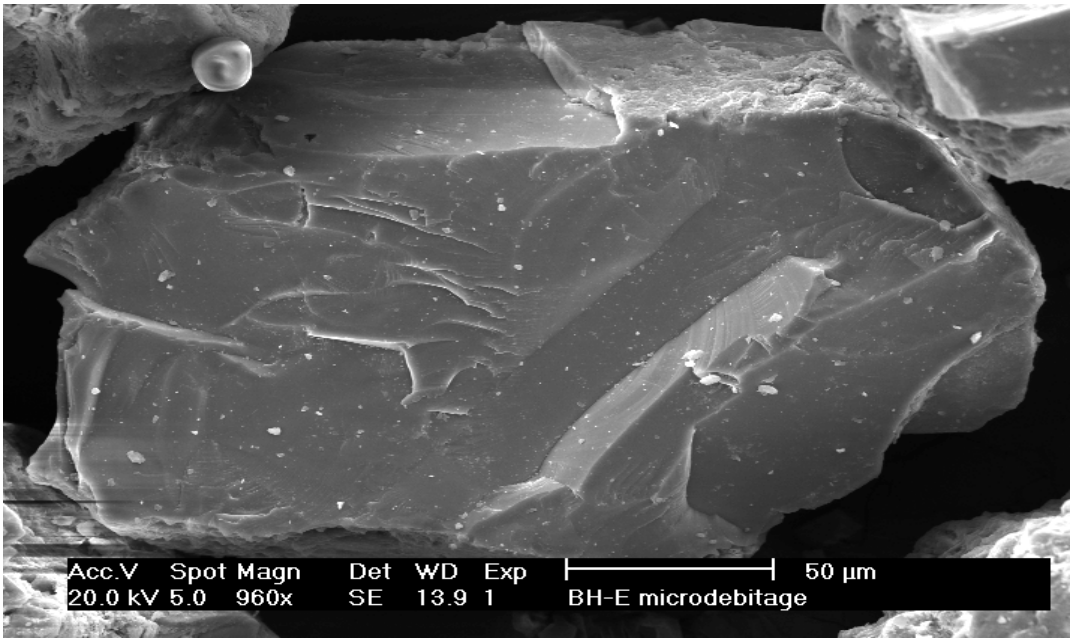


Figure 4.4.1. Microdebitage particle used for the test under SEM
(Enlargement with features reference, plate X).

The aeolian quartz grains used have surface features consistent with the observations of Krinsley and Doornkamp (1973). Six features were selected for the blind tests (table 4.4.2 and figure 4.4.2).

Table 4.4.2. Aeolian grain features used for the test under SEM.

Aeolian environmental features.
A. Rounded grains
B. Disintegration by solution or by salt crystal growth
C. Dish- shaped concavities
D. Mechanically formed upturned plates
E. Smooth or irregular precipitation surface
F. Precipitated upturned silica plates

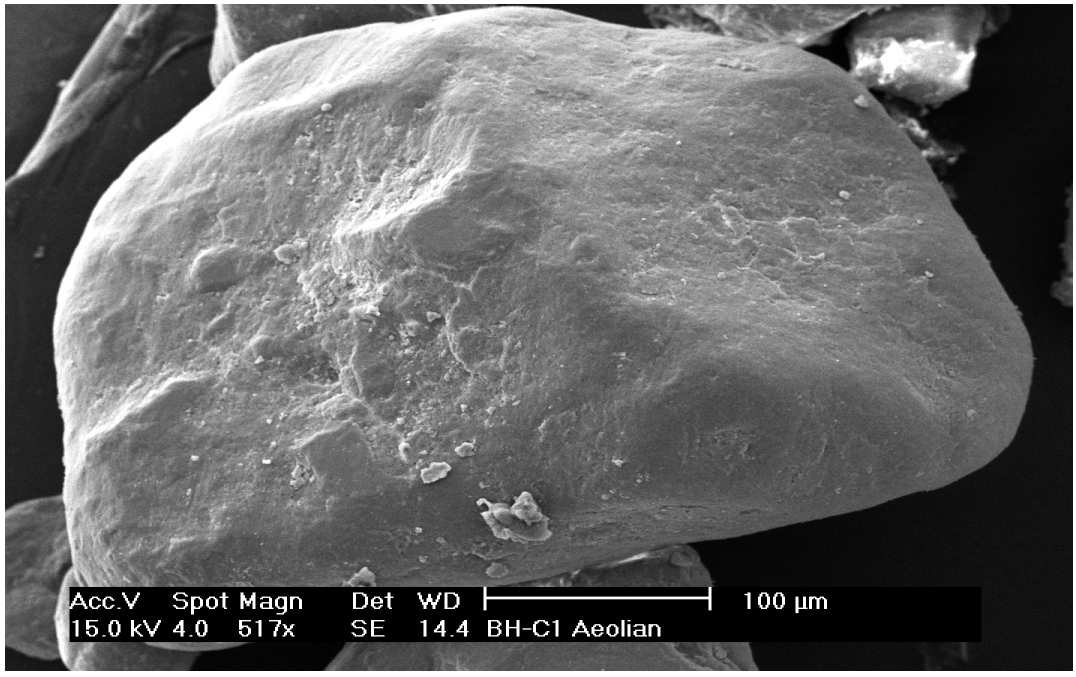


Figure 4.4.2. Aeolian grain used for the test under SEM (Mutawintji sediment *background)* (Enlargement with features reference, plate I).

Differences between quartz and clays needed to be identified. In aeolian environments, clay may present characteristics similar to angular quartz grains. Clay recognition was based on morphology (clay particles look flat and lens-like, and sometimes are angular with well defined sheeting). Quartz grains have greater three-dimensional depth, and can be determined by the lack of aluminium. Chemical composition as determined by EDX can detect minor aluminium oxide in the sample (figures 4.4.3 and 4.4.4).

Quartz can be determined by the oxygen and silica values as shown in figure 4.4.3, in which the aluminium peak is very small, and the same as iron oxide (the Au peaks are the coating on the sample). In Figure 4.4.3 the Al and Fe probably represent dust particles on the surface of the sample. The peaks without a chemical symbol are secondary electrons of the Au coating.

The main visual difference between quartz and clay is that quartz has a blocky rather than a flat and lens-like appearance. Silicate clays may have conchoidal fractures and be angular with features similar to microdebitage. The use of an EDX probe helps to determine if the particle is clay or quartz.

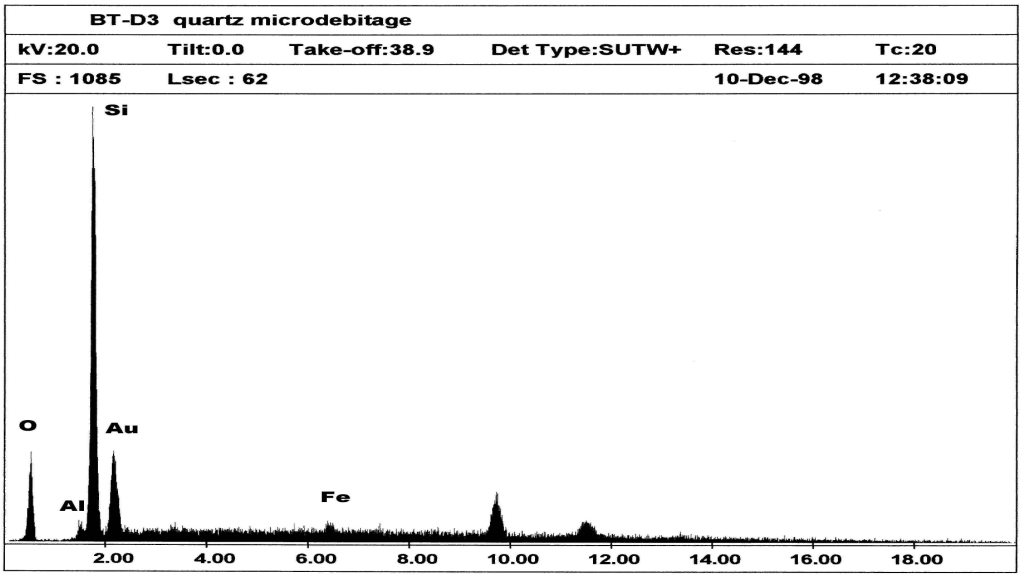


Figure. 4.4.3. Quartz microdebitage, EDX analysis.

The higher aluminium peak in comparison to the silicon distinguishes clays. Mostly composed of oxygen, silica and aluminium, with some adhering iron oxide as in Figure 4.4.4, the clays can be observed as flat and highly angular, with many of the features of broken quartz grains. Silicate clays do not contain Fe. In Figure 4.4.4, the Fe may be colloidal Fe oxide, which are separate from the silicate clays. It is important to note that, because of the large number of grains counted in the test, EDX was used only on morphologically *doubtful* grains.

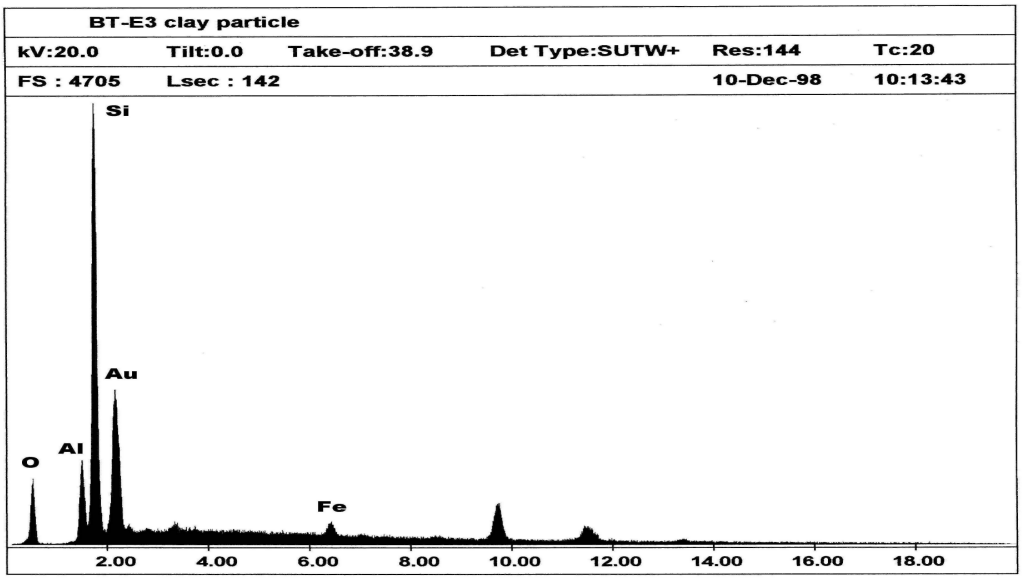


Figure 4.4.4. Clay particle EDX analysis.

Two supplementary observations were noted in conjunction with the microdebitage count for the test. One was described as "possible microdebitage", and the other as "probable microdebitage". Microdebitage was defined as having all the six features described in Table 4.4.1. Probable microdebitage was defined as having at least four of the features including concoidal fractures and high angularity. Possible microdebitage was defined as having at least three features from the list.

The list of the number of microdebitage grains in each sample and the identification of which sample was a control blank were returned at the end of the test by Dr Dragovich.

4.5 Quartz microdebitage recognition—results of the SEM/EDX counts

It took at least 400 hours on the SEM to recognise at a glance microdebitage features from the *background* material. It took about 1000 hours to complete the counting of quartz microdebitage particles in 312 SEM stubs (1.5cm in diameter) (about 200,000 particles observed). This time was justified due to the need to use the SEM with an EDX probe to understand if the particles were quartz or other materials.

The stubs were placed one at a time into the vacuum chamber of the SEM. The stub was placed on the stage at about 12mm from the secondary detector. The stub was oriented by moving the centre of the stub to the middle of the screen by moving the stage along the radius of the stub until the orienting bar was oriented downwards the screen. The stage was then moved along the orienting bar and downwards until the edge of the stub was recognised at the bottom of the screen. The stub was scanned by rotating the stage along the circumference of the stub, moving it up one screen along its radius once the stub was returned to the orienting bar (see figure 4.4.1). The counting of the microdebitage was done with a hand-held tally counter.

Each stub in the 1000-500µm size range took 45-60 minutes to complete; the 500-125µm range took 60-90 minutes for each stub; and for the 250-125µm range, 90-120 minutes for each stub. The recognition of features was difficult at first; however, after 400 hours, only a few seconds were sufficient to distinguish the quartz microdebitage particles from the aeolian *background* grains on the SEM screen.

Upon the return of the list of samples containing microdebitage, it was noted that the amount of counted microdebitage was generally much higher than the amount placed in the samples. At this stage, it was obvious that a revision of at least part of the samples was needed and this was carried out as described below.

The magnification used to identify angularity was that used by Fladmark for light microscopy (40-100x). Once an angular particle was found, a larger magnification was used to assess the features. This magnification was found too low to distinguish angularity in microdebitage from angularity of sandstone aggregates in the 1000-500µm and the 500-250µm samples. It was found that the 1000-500µm and the 500-250µm samples contained a large amount of material derived from broken grains and cemented matrix from sandstone. This material is present in the natural sediment and occurs in the microdebitage samples. The aggregates in the microdebitage samples are derived from the breaking of the grains and the binding. Percussion on the sandstone caused this breakage, while weathering of

the looser cementation of the matrix (figure 4.5.1 and 4.5.2) dislodged the naturally available aggregates.

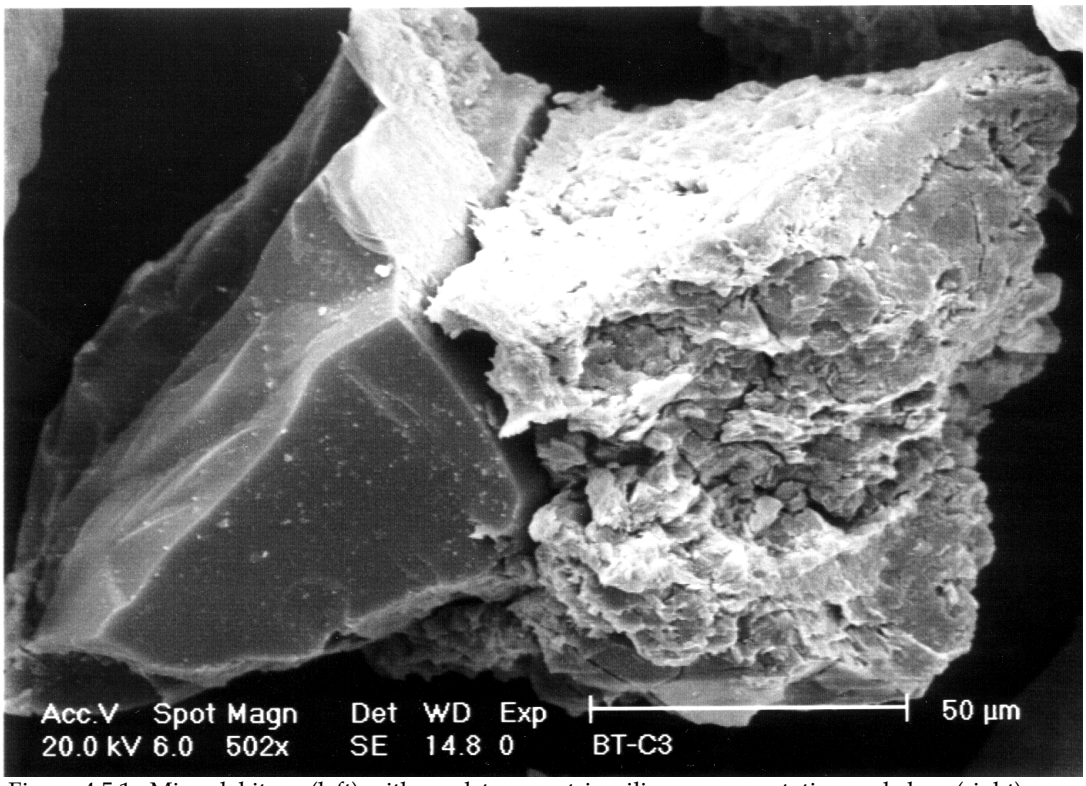


Figure 4.5.1. Microdebitage (left) with sandstone matrix, siliceous cementation and clays (right).

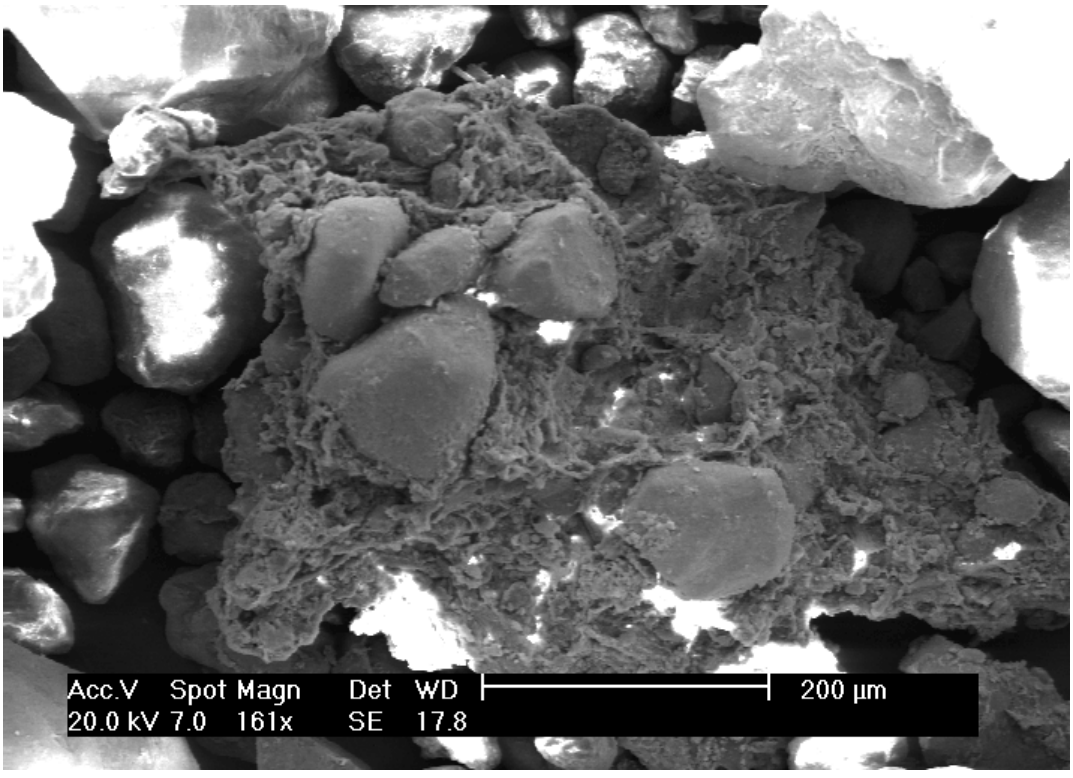


Figure 4.5.2. Quartz grains with sandstone matrix, siliceous cementation and clays.

4.5.1 Results of the SEM/EDX counts on 250-125µm size range

The samples were composed of approximately 10,000 particles of material, derived from the top 2cm of sediment from Mutawintji. Particles from the experimental engraving E1 had been placed at a rate of approximately 50, 100, 150 and 200 particles per sample, plus one sample without microdebitage as a control blank. As this was a blind test, none of the microdebitage amounts in the samples was disclosed except the size fractions of the samples. The blank sample (BTE3) shows 93 quartz particles that have features consistent with microdebitage. It was envisaged that a number of grains would have the same features as microdebitage, which were naturally occurring in the sediment sample (table 4.5.1.1). The 250-125µm sample has almost double the number of quartz grains with microdebitage features in the blank sample (BTE3) than the amount of angular grains available in the sediment sample of the same size fraction (BH-C1C roundness index) (table 4.5.1.1).

In this size range, the amount of grains identified were one angular per 171 grains (Chapter 3 page 72), bringing the amount of angular grains to 58 per 10,000 of sediment (sample BH-C1C). Correcting for the angular grains would give microdebitage counts of BTA3= 38, BTB3= 161, and BTC3= 196. The possible and probable microdebitage particles may well fall within the category of angular naturally-occurring grains, without all the features. The amounts of naturally-occurring grains with features consistent with microdebitage found in the blank sample (BTE3) were larger than the amount of angular grains detected in the roundness index test. However, the real number of angular particles may have been lower than suggested in the roundness test as some clay agglomerates may have been counted as angular grains in error. The error may be partly due to poor recognition skills at the beginning of the test (Appendix 6 table A6.15-A6.19).

Samples BT-A3 to BT-E3 contained the smallest grains, 250-125um in diameter. This size range proved to have the closest association between microdebitage counted and the amount placed (figures 4.5.1.1 and 4.5.1.2).

Table 4.5.1.1. Counts of microdebitage in sample BT-A3 to BT-E3 (250-125µm).

Sample	Microdebitage placed	Possible microdebitage	Probable microdebitage	Microdebitage counted
BTA3	50p	8	10	96
BTB3	200p	19	18	219
BTC3	150p	12	12	254
BTD3	100p	13	13	165
BTE3	Blank sample	12	10	93

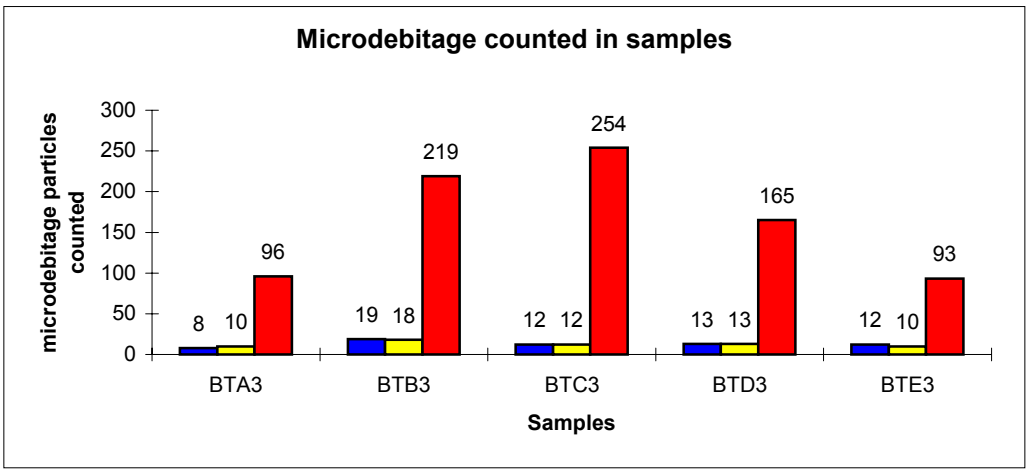


Figure 4.5.1.1. Counts of microdebitage in sample BT-A3 to BT-E3 (250-125µm).

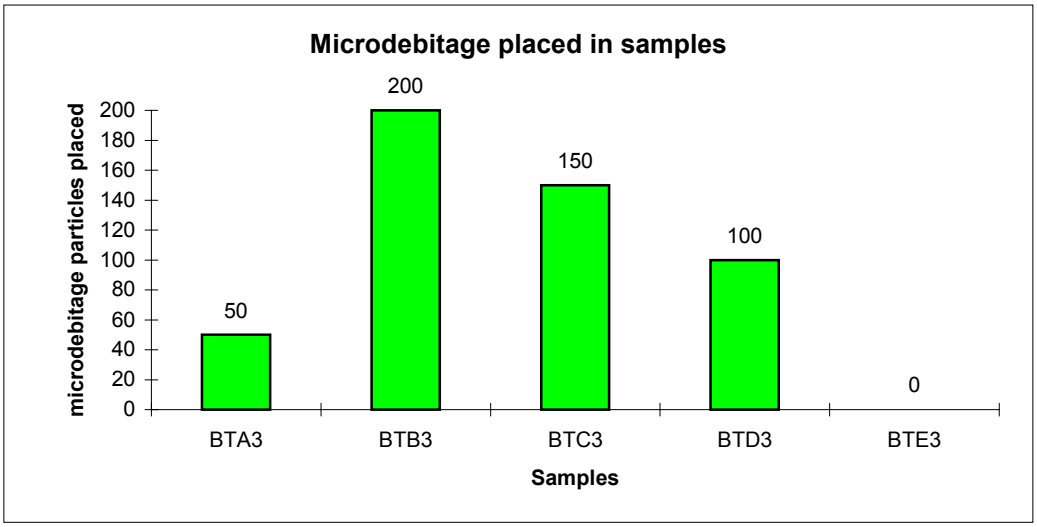


Figure 4.5.1.2. Approximate number of microdebitage grains placed in samples BT-A3 to BT-E3 (250-125µm).

4.5.2 Results of the SEM/EDX counts on 500-250µm size range

The 500-250µm size range samples were found to have 274 grains in the blank sample (BTD2) with features consistent with microdebitage. The naturally-occurring sediment sample from Mutawintji (table 4.5.2.1) contains an unreasonably high count of angular grains. The viewing magnification of 60x has proven to be too low for an effective visual analysis of quartz grain features. These samples were composed of approximately 10,000 particles of sediment from Mutawintji topsoil, with particles of microdebitage of the same size placed in samples at known rates. The proportion of non-quartz particles in the samples used for this test may have been different from those used by Fladmark (1982). The counts of microdebitage particles in each sample may have been much higher than the original estimation of particles according to weight (table 4.5.2.1).

There is a similarity between the number of quartz grains with microdebitage features in the blank sample (BTD2) and the amount of angular grains available in the natural sediment of the same size fraction (BH-C1B). The number of naturally occurring angular grains in sample BH-C1B was 273 per 10,000 particles (Roundness index, Chapter 3 page 72). In the roundness index test where grains were viewed at low magnification, agglomerates and broken sandstone matrix may have been mistaken for angular quartz grains, thereby producing an unreasonably high count for angular grains (see figure 4.5.2).

At higher magnification this sample illustrates a large amount of sandstone aggregated material (quartz grains and siliceous bonding with a clay matrix), which may have been mistaken as microdebitage. However, some quartz microdebitage particles retain part of the clay matrix attached to them as in Figure 4.5.1. The errors between the amount of particles of microdebitage placed into the samples, and the amount counted in this sample, is large. This may be accounted for by the low magnification used; the inexperience in recognising the features in the early stages of the blind test; and the difference in the proportion of non-quartz particles in the samples for the sediment and microdebitage (table 4.5.2.1, figure 4.5.2.1 and figure 4.5.2.2).

Table 4.5.2.1. Counts of microdebitage in sample BT-A2 to BT-E2 (500-250µm).

Sample	Microdebitage placed	Possible microdebitage	Probable microdebitage	Microdebitage counted
BTA2	150p	41	40	256
BTB2	50p	47	55	592
BTC2	200p	39	38	223
BTD2	Blank sample	33	35	274
BTE2	100p	40	44	162

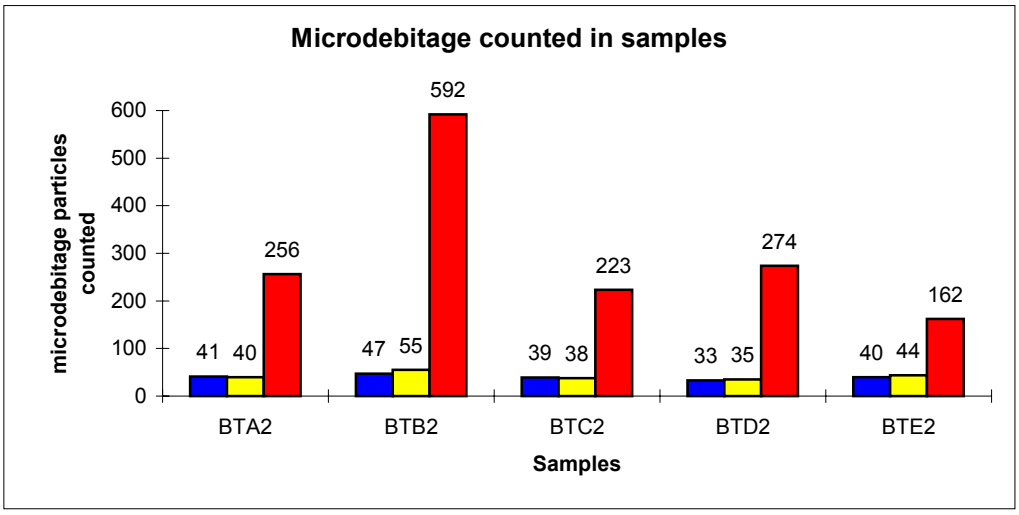


Figure 4.5.2.1. Counts of microdebitage in sample BT-A2 to BT-E2 (500-250µm).

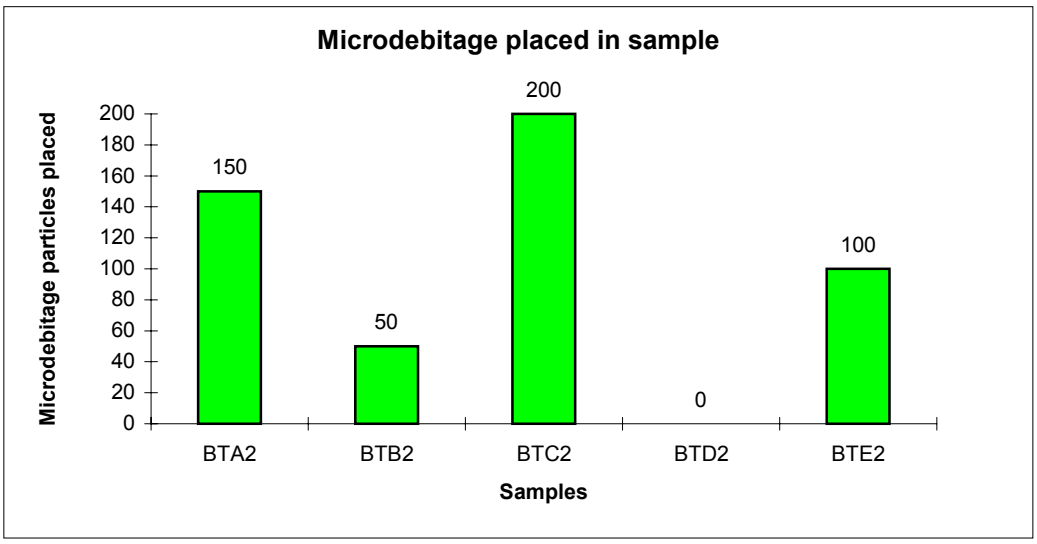


Figure 4.5.2.2. Approximate number of microdebitage grains placed in samples BT-A2 to BT-E2 (500-250µm).

4.5.3 Results of the SEM/EDX counts on 1000-500µm size range

Samples of material in the 1000-500µm size range were viewed at a magnification of 40x. The visual recognition of quartz environmental features was difficult at this magnification, and consequently the counting may have been distorted.

In the roundness test for this size sub-sample of Mutawintji topsoil (BH-C1A), 224 particles per 10,000 were angular. The blank sample used as control in this size range (BTB1) is composed of the same material (BH-C1A). Three hundred and forty two particles were counted as having naturally occurring features similar to microdebitage of the same size range (table 4.5.3.1).

This size is the largest in the blind test samples and contains a large amount of agglomerated material, which was later identified as sandstone aggregates with clays and silica cement. Some of the aggregated particles containing quartz grains with aeolian features may have been naturally occurring in the sediment, while aggregates with broken grains may have originated from the manufacturing process of the experimental rock engravings (figure 4.5.1). The samples were composed of approximately 10,000 particles of Mutawintji sediment topsoil (BH-C1A) with particles of microdebitage (BH-E1A) of the same size range.

The amount of microdebitage counted in the samples and the amount of microdebitage placed in the samples is remarkably different. This was the case even after the number of naturally occurring angular particles in the blank sample (BTB1) (figure 4.5.3.1 and figure 4.5.3.2) decreased the count. This distortion may have been caused by the low magnification used, which was not sufficient to recognise the more subtle features of microdebitage. Also the large amount of aggregated material, which may have been mistaken for microdebitage, may have been a contributing factor. Further, the inexperience in recognising microdebitage features in the early stages of the test may have also contributed to the error (Appendix 6 tables A6.5-A6.9). A re-count of part of the samples should be undertaken at higher magnification and with extensive use of the EDX probe.

Table 4.5.3.1. Counts of microdebitage in sample BT-A1 to BT-E1 (1000-500µm).

Sample	Microdebitage placed	Possible microdebitage	Probable microdebitage	Microdebitage counted
BTA1	100p	108	103	541
BTB1	Blank sample	77	91	342
BTC1	150p	70	75	178
BTD1	50p	68	73	207
BTE1	200p	78	72	384

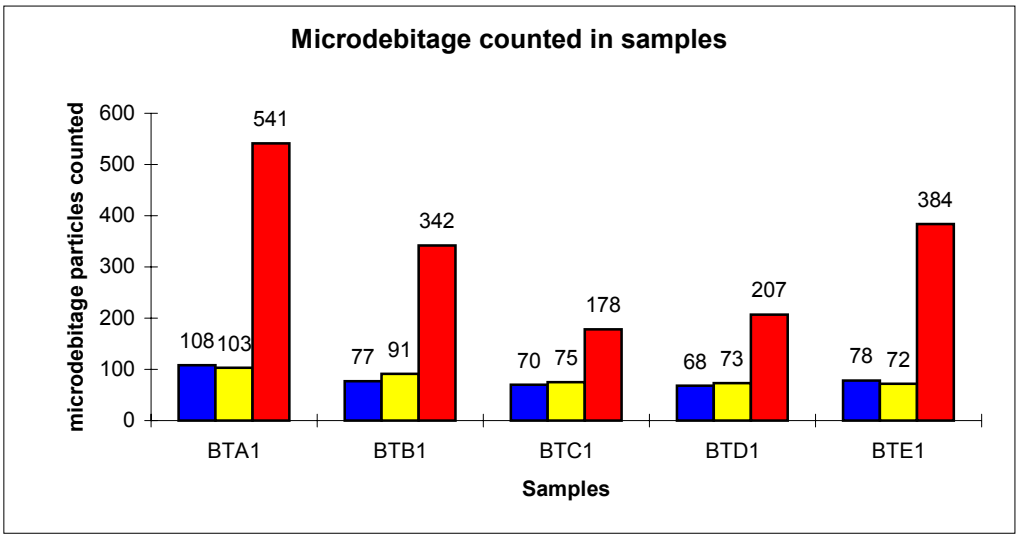


Figure 4.5.3.1. Counts of microdebitage in sample BT-A1 to BT-E1 (1000-500µm).

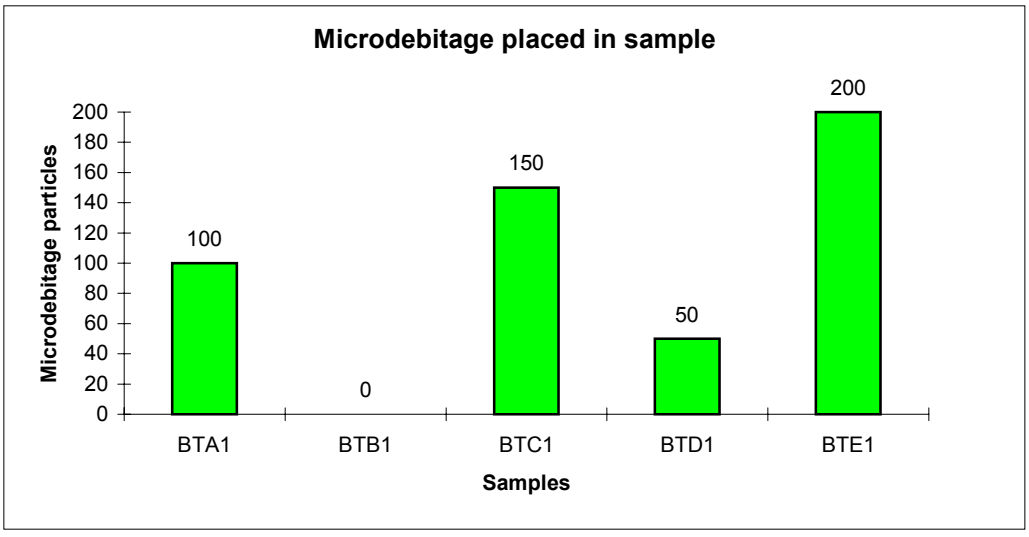


Figure 4.5.3.2. Approximate number of microdebitage grains placed in samples BT-A1 to BT-E1 (1000-500µm).

4.6 Errors and corrections

Revising part of the blind test samples took approximately 100 hours. The problems encountered in the first test were partly eliminated in this re-assessment. To understand the errors encountered and rectify the original test, some revision was necessary. Five stubs for each series of the 1000-500µm samples, three stubs for each of the 500-250µm series, and the stubs of the 250-125µm series, were re-examined by SEM.

The problems encountered with the blind test were based on the design of the test itself:

1. For use with a SEM, the number of grains and the number of stubs were too large. This problem stems from the sample size chosen; Fladmark (1982) was the only reference to amounts of microdebitage in soil samples.
2. The weight of the microdebitage and the *background* sediment particles were not calibrated to the actual proportion of non-quartz particles in the samples. The actual number of microdebitage particles in each sample may have been overestimated by using Fladmark's (1982) standard weights for 10,000 particles.
3. The 10,000 particles samples were not calibrated by Fladmark (1982) to the proportion of non-quartz particles in the samples and to relative humidity in the sample, and nor was it done for this test.
4. By chance, the first sample examined under SEM was a blank control sample. This made it extremely difficult to discern microdebitage at the beginning of the test.
5. Not all particles of microdebitage have all the described surface features. It was during the test that a method was devised for the separation of primary and secondary features for the distinction of microdebitage from other similar material together with the use of EDX.
6. Visual recognition has an inherited, subjective, bias error, which, although constant, is not quantifiable by the subject.
7. The magnification used was too low for effectively observing the

grain surface features.

8. Large amounts of sandstone matrix and clay aggregates were found in the samples. Difficulties were encountered in discerning those naturally occurring in the sediment and those produced during the making of the engravings.

The difficulty in determining an optimum sample for the test has been a limiting factor. In hindsight, the test, originally designed for light microscopy, was not suitable for the SEM microanalysis. This research has evaluated the reliability of the work of others, and has adapted methodologies and techniques that were not always compatible.

In an attempt to rectify these problems, part samples were taken and re-counted. Some of the counting problems, mainly the visual recognition of features, were not difficult to rectify. The accuracy in counting the microdebitage grains was limited by the proportion of non-quartz particles in the samples. In hindsight, the microdebitage particles for the test should have been counted rather than weighed before setting onto the SEM stubs.

As noted in the tables of data, there was a problem with recognition of the particles. The raw data in Appendix 6 illustrates that the number of microdebitage particles counted decreased after the first samples, notably due to problems in identifying microdebitage in the early stages of the test. With time and experience, it became more evident that the amount of microdebitage counted was higher in the earlier samples than the later. This problem has been partially rectified by a subsequent re-assessment of the particle numbers by re-counting the microdebitage in a portion of each of the samples (see Appendix 6, tables A6.20-A6.23). The re-assessment in this second test produced better results. The samples were observed at a larger magnification 120-250x, and a better and fuller use of the EDX assisted identification of microdebitage and its features. The resultant particles counted in each part sample were averaged and multiplied by the number of stubs per sample.

4.6.1 Review of the SEM/EDX counts on 250-125µm size range

The results of the revision of a part sample of this size fraction are illustrated in table 4.6.1.3, and figures 4.6.1.1 and 4.6.1.2. These figures indicate that there is an association between the microdebitage counted and the microdebitage placed in the sample. The difference in counts may be related to the proportion of non-quartz particles in the samples.

The original magnification for this size fraction in the first test was 100x. The revision used a magnification of 250x, enhancing the visual recognition capacity. The greater use of EDX assisted in accessing chemical information to distinguish loose clay particles (many of which were broken and resembled microdebitage). The sample presented mostly loose material with little agglomeration of clays or sandstone matrix.

Table 4.6.1.1 Counts of microdebitage in samples BT-A3 to BT-E3 (250-125µm).

Sample	Possible microdebitage	Probable microdebitage	Microdebitage counted	Microdebitage in Blind test
BT-A3	16	13	104	96
BT-B3	12	14	282	219
BT-C3	12	17	189	254
BT-D3	11	9	138	165
BT-E3 (blank)	12	5	20	93

Table 4.6.1.1 illustrates the actual particles counted in the samples. The entirety of these samples was revised as they were contained in one stub per sample. There is a considerable difference between the microdebitage counted in the part sample and the amount counted in the blind test. It is possible that the counts acquired in the early stages of the blind test were not as accurate as the later.

Table 4.6.1.2. Counts of microdebitage by subtracting the naturally occurring particles with microdebitage features in samples BT-A3 to BT-D3 (250-125µm).

Samples	Microdebitage placed	Possible microdebitage	Probable microdebitage	Microdebitage counted
BTA3	50p	4	8	84
BTB3	200p	0	9	262
BTC3	150p	0	12	169
BTD3	100p	-1	4	110

Table 4.6.1.2 illustrates the number of particles available in each sample without the count of particles with microdebitage features naturally occurring in the blank sample. The microdebitage counted is derived by averaging the count of the revised stubs and multiplying by the number of stubs in the sample (see Appendix 6 tables A6.22).

Table 4.6.1.3. Revised counts of microdebitage in samples BT-A3 to BT-E3 (250-125µm).

Sample	Microdebitage placed	Possible microdebitage	Probable microdebitage	Microdebitage counted
BTA3	50p	16	13	104
BTB3	200p	12	14	282
BTC3	150p	12	17	189
BTD3	100p	11	9	138
BTE3	Blank sample	12	5	20

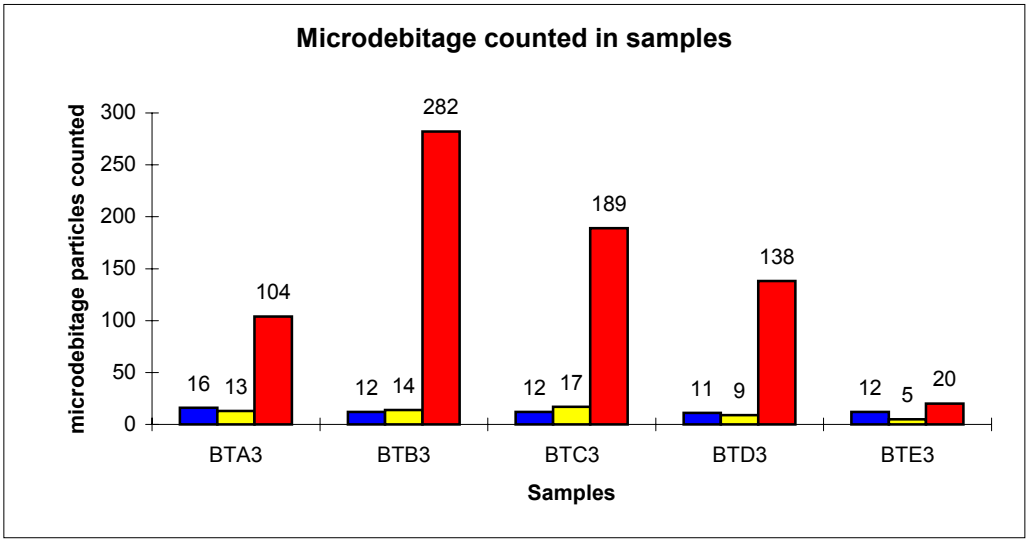


Figure 4.6.1.1. Revised counts of microdebitage in samples BT-A3 to BT-E3 (250-125µm).

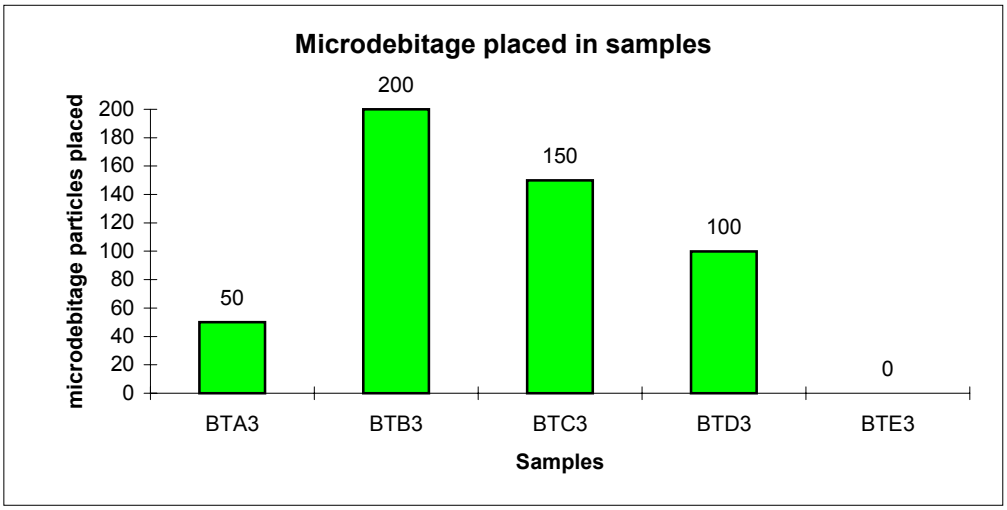


Figure 4.6.1.2. Approximate number of microdebitage grains placed in samples BT-A3 to BT-E3.

4.6.2 Review of the SEM/EDX counts on 500-250µm size range

This analysis represents three stubs out of eight in the original samples (table 4.6.2.1). The particles were observed at a magnification of 150x, while the blind test for this size fraction used a magnification of 60x. Table 4.6.2.1 illustrates the actual particles counted in the samples. This count is seen against the amount of microdebitage in the same stubs observed during the blind test. Table 4.6.2.3 and figures 4.6.2.1 and 4.6.2.2 represent the revised count with numbers averaged and multiplied for the entire sample.

Table 4.6.2.1. Counts of microdebitage in revised part samples BT-A2 to BT-E2 (500-250µm).

Sample stub	Possible microdebitage	Probable microdebitage	Microdebitage counted	Microdebitage in blind test
BT-A2/5	6	4	21	31
BT-A2/2	3	3	23	44
BT-A2/1	4	3	32	36
total	**13**	**10**	**76**	(3 of 8 stubs)
BT-B2/4	3	3	13	103
BT-B2/2	3	4	14	147
BT-B2/3	4	3	13	83
total	**10**	**10**	**27**	(3 of 8 stubs)
BT-C2/2	7	6	59	36
BT-C2/4	5	5	38	4
BT-C2/1	3	4	52	83
total	**15**	**15**	**149**	(3 of 8 stubs)
BT-D2/2	2	0	0	28
BT-D2/4	1	1	3	50
BT-D2/3	1	0	1	91
total	**4**	**1**	**4**	(3 of 8 stubs)
BT-E2/2	6	4	18	28
BT-E2/7	4	3	13	24
BT-E2/3	7	4	15	29
total	**17**	**11**	**46**	(3 of 7 stubs)

Table 4.6.2.2. Counts of microdebitage by subtracting the naturally occurring particles with microdebitage features in revised samples BT-A2, B2, C2 and BT-E2 (500-250µm).

Sample	Microdebitage placed	Possible microdebitage	Probable microdebitage	Microdebitage counted
BTA2	150p	23	18	191
BTB2	50p	47	50	95
BTC2	200p	29	32	386
BTE2	100p	28	17	96

Table 4.6.2.2 (above) shows the number of particles available in each sample without the particles naturally occurring in the blank sample. The microdebitage counted is derived by averaging the revised stubs count and multiplying by the number of stubs in the sample (see Appendix 6 tables A6.21).

Table 4.6.2.3. Revised counts of microdebitage in samples BT-A2 to BT-E2 (500-250µm).

Sample	Microdebitage placed	Possible microdebitage	Probable microdebitage	Microdebitage counted
BTA2	150p	34	26	202
BTB2	50p	58	58	106
BTC2	200p	40	40	397
BTD2	Blank sample	11	8	11
BTE2	100p	39	25	107

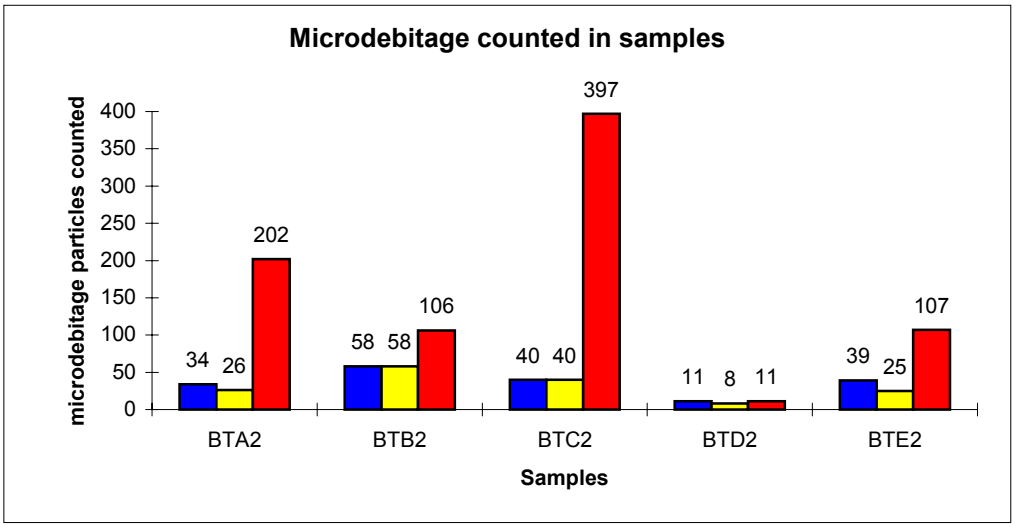


Figure 4.6.2.1. Revised counts of microdebitage in samples BT-A2 to BT-E2 (500-250µm).

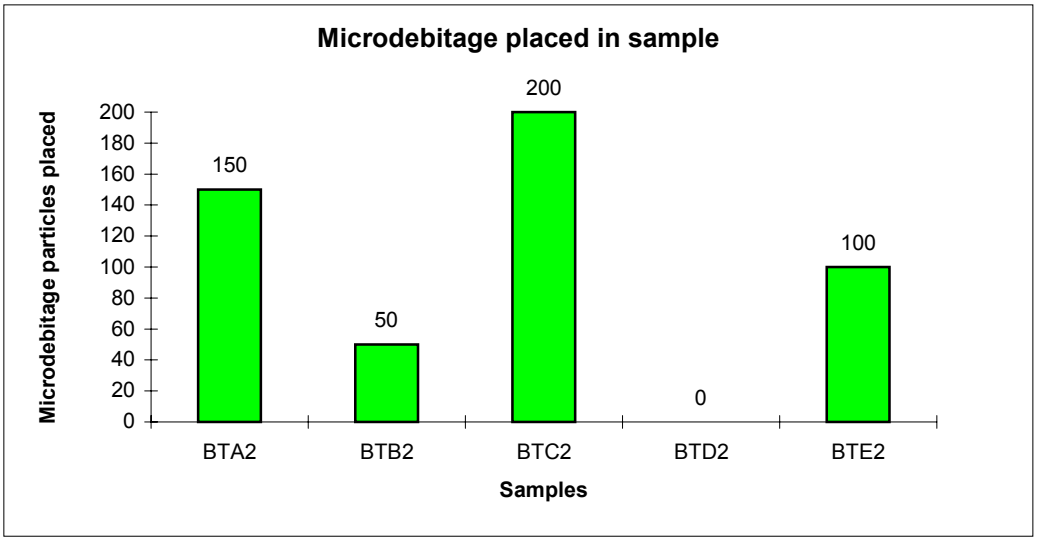


Figure 4.6.2.2. Approximate number of microdebitage grains placed in samples BT-A2 to BT-E2.

4.6.3 Review of the SEM/EDX counts on 1000-500µm size range

Table 4.6.3.1 represents the amount of microdebitage found in 1/7th of the total of 32 to 34 stubs per sample. The amount of microdebitage in the five stubs per sample was averaged and then multiplied by the total sample stubs. The amount of microdebitage counted is compared to the amount counted for the same stubs on the original blind test (table 4.6.3.3, and figures 4.6.3.1 and 4.6.3.2). For this revision of sample stubs, a magnification of 120x was used as opposed to the original 40x. This made the process of identification easier and more reliable.

Table 4.6.3.1 Counts of microdebitage in revised part samples BT-A1 to BT-E1 (1000-500µm).

Sample stub	Possible microdebitage	Probable microdebitage	Microdebitage counted	Microdebitage in Blind test
BT-A1/5	1	1	3	32
BT-A1/3	0	1	3	17
BT-A1/1	1	2	6	32
BT-A1/15	2	1	3	13
BT-A1/8	1	0	2	22
total	**5**	**4**	**17**	(5 of 33 stubs)
BT-B1/24	1	0	2	7
BT-B1/28	1	1	1	5
BT-B1/26	2	1	0	9
BT-B1/25	2	0	1	6
BT-B1/23	2	1	1	8
total	**8**	**3**	**5**	(5 of 34 stubs)
BT-C1/21	0	1	4	3
BT-C1/4	2	1	4	12
BT-C1/30	1	1	4	4
BT-C1/18	0	1	2	2
BT-C1/3	2	1	8	10
total	**5**	**5**	**22**	(5 of 32 stubs)
BT-D1/4	2	1	5	6
BT-D1/7	1	1	1	6
BT-D1/9	1	2	4	3
BT-D1/11	2	1	4	6
BT-D1/12	0	0	3	7
total	**6**	**4**	**19**	(5 of 33 stubs)
BT-E1/1	1	1	3	14
BT-E1/15	2	2	7	15
BT-E1/20	2	1	5	8
BT-E1/5	1	1	6	17
BT-E1/13	2	2	5	13
total	**8**	**7**	**26**	(5 of 34 stubs)

Table 4.6.3.2 depicts the number of particles available in each sample without the particles naturally occurring in the blank sample. The microdebitage counted is derived by averaging the revised stubs count and multiplying by the number of stubs in the sample (see Appendix 6 tables A6.20). The "microdebitage in blind test" column shows the amount of microdebitage recognised in those stubs in the earlier blind test. The difference between the two may be accounted for by the difficulty of recognising the features at lower magnification and at a glance (40x).

This revised test used a magnification three times greater than the blind test (120x), which markedly enhanced visual recognition capacity. The great use of EDX assisted in accessing chemical composition of the particles and in separating loose clay particles (many of which were broken and resembled microdebitage) from microdebitage and clay agglomerates. The sample presented mostly loose material with little agglomeration of clays or sandstone.

Table 4.6.3.2. Counts of microdebitage by subtracting the naturally occurring particles with microdebitage features in revised samples BT-A1, C1, D1, and BT-E1 (1000-500µm).

Sample	Microdebitage placed	Possible microdebitage	Probable microdebitage	Microdebitage counted
BTA1	100p	0	13	78
BTC1	150p	5	12	107
BTD1	50p	-22	13	78
BTE1	200p	-21	28	142

Table 4.6.3.3 shows the amount of microdebitage found in the samples corrected by subtracting the amount of particles with the same features available naturally in the Mutawintji sediment (BH-C1).

In this size range, five stubs out of an average of thirty-three were re-sampled. The revision, using SEM and EDX combined, aided in sorting microdebitage with sandstone matrix attached, from naturally available sandstone aggregates in the topsoil. This was achieved by magnifying the quartz grain aggregates to verify the existence of features.

Naturally occurring aggregates in the topsoil samples (BH-C1) of 1000-500µm size range have rounded grains with aeolian features. The sandstone aggregates

dislodged by the engraving process produced features on the grains consistent with the loose and broken quartz grains from the experimental microdebitage.

Table 4.6.3.3. Revised counts of microdebitage in samples BT-A1 to BT-E1 (1000-500µm).

Sample	Microdebitage placed	Possible microdebitage	Probable microdebitage	Microdebitage counted
BTA1	100p	33	33	112
BTB1	Blank sample	54	20	34
BTC1	150p	32	32	141
BTD1	50p	39	33	112
BTE1	200p	54	48	176

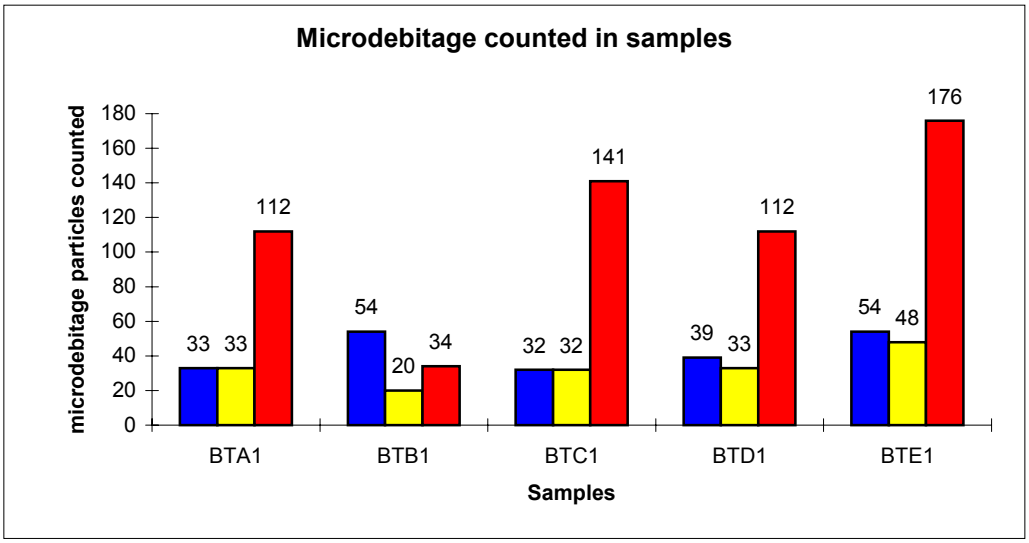


Figure 4.6.3.1. Revised counts of microdebitage in samples BT-A1 to BT-E1 (1000-500µm).

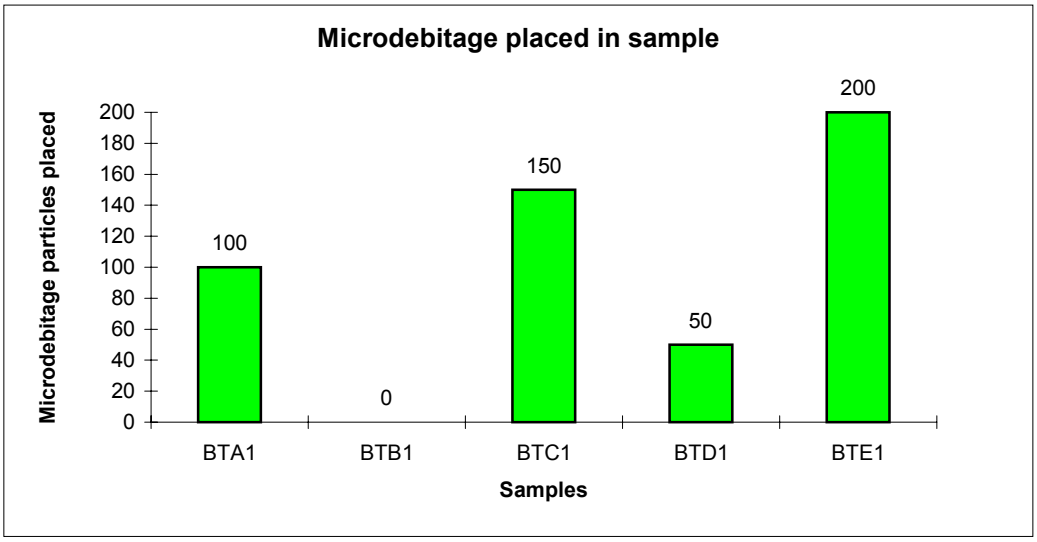


Figure 4.6.3.2. Approximate number of microdebitage grains placed in samples BT-A1 to BT-E1.

4.7 Review of the SEM/EDX counts—result

Results from the revised counts illustrates that the difference between the approximate amount of microdebitage placed in the sample and the amount counted is minimal, once the particles with microdebitage features naturally available in the blank samples were subtracted from the microdebitage counts (tables 4.7.1-4.7.3).

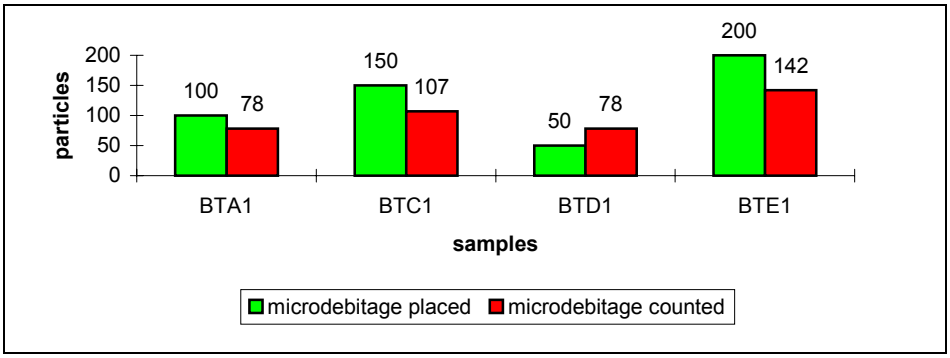
The larger amount of microdebitage, although reflecting the same between-sample trend as the approximate amount placed in the sample, is possibly due to an error in the proportion of non-quartz particles in the samples of the microdebitage and the soil sample. Fladmark (1982) proposed weights for 10,000 particles of sediment, which were followed in this research. The proportion of non-quartz particles in the samples should have been calibrated by counting and weighing the particles prior to fixing them on SEM stubs. This would have given standard proportions for the tests.

The revision of the counting procedure and the method has been generally successful in replicating the same pattern between the amount of microdebitage particles placed in the samples and the amount counted. It is possible that there are differing patterns of errors in each of the size fractions. However, the problem of the proportion of non-quartz particles in the samples could not be overcome unless a fresh test were undertaken in which the particles were counted and then placed on the stubs.

The problems encountered with the proportion of non-quartz particles in the samples could not be determined precisely. This caused difficulties in determining the exact amount of particles on each stub. Further difficulties in recognising quartz grains features in the early stages of the project have contributed to the variations in accuracy of the microdebitage counts. Greater accuracy in counting microdebitage was achieved in the revision than in the blind test once a higher magnification was adopted, and further experience in recognising features was achieved. The error percentages from the approximate microdebitage placed in the samples and the counted are outlined below.

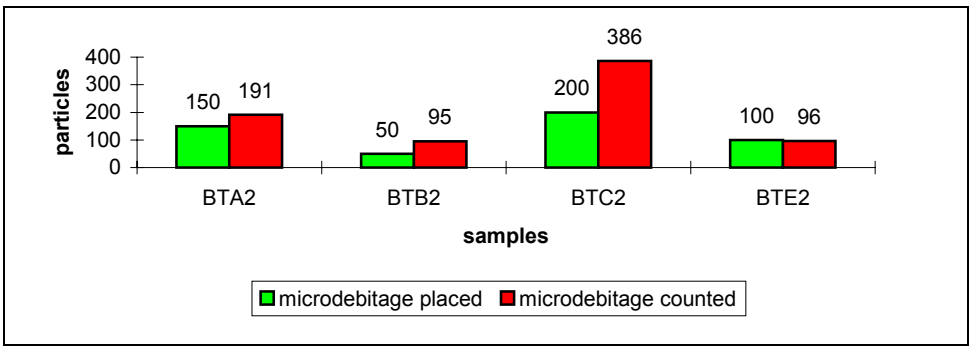
Graph 4.7.1. illustrates the difference between the placed and counted particles. The percentage variation between the approximate amount placed and counted are BTA1= -22%; BTC1= -28.6%; BTD1= +56%; and BTE1= -29%.

Graph 4.7.1. Counts by subtracting the naturally occurring particles in 1000-500µm.



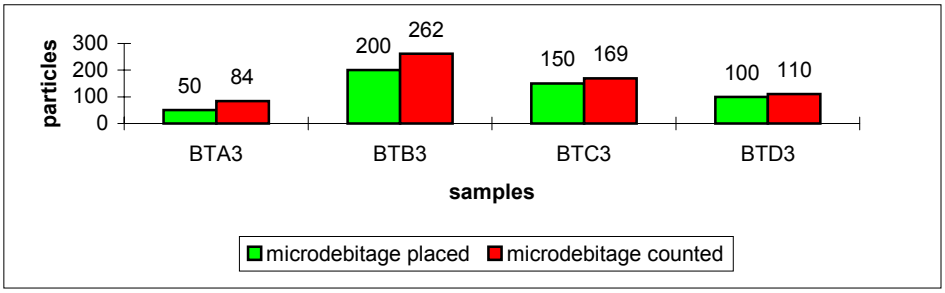
Graph 4.7.2. illustrates the difference between the placed and counted particles. The percentage variation between the approximate amount placed and counted are BTA2= +27.3%; BTB2= +90%; BTC2= +93%; and BTE2= -4%.

Graph 4.7.2. Counts by subtracting the naturally occurring particles in 500-250µm.



Graph 4.7.3. illustrates the difference between the placed and counted particles. The percentage variation between the approximate amount placed and counted are BTA3= +60%; BTB3= +31%; BTC3= +12.6%; and BTD3= +10%.

Graph 4.7.3. Counts by subtracting the naturally occurring particles in 250-125µm



The results of the tests have indicated that within a large sample (ca. 10,000 particles) it is possible to identify microdebitage in mixed sediments. The revision of the blind test has produced a closer relation between the *counts* and *expected* microdebitage in the samples, in which the final numbers of microdebitage particles counted were closer to the predicted approximation, based on the proportion of non-quartz particles in the samples. This was achieved once the counts were calibrated and adjusted by subtracting the particles defined as microdebitage in the blank samples (tables 4.7.1 to 4.7.3).

The 1000-500µm and the 500-250µm size fractions had a large proportion of sandstone matrix with broken and unbroken grains, while the 250-125µm fractions had a large proportion of unconsolidated clay particles and agglomerated clays.

The use of surface features has been enhanced by the roundness index tests. The test itself has produced the two general variables for a rapid distinction between aeolian grains and microdebitage: the aeolian grains fall within the rounded category while microdebitage falls within the highly angular category.

Sub-angular and sub-rounded grains with microdebitage surface features were observed and counted as possible and probable microdebitage. The grains may have been derived by the fracturing of only a portion of the grain during the production of microdebitage, retaining most of the grain as rounded. These grains may have also been dislodged from the sandstone matrix at the same time retaining surface features from the original environment.

The chi-squared test has been used as an independent measurement of how similar or different a sample is from the target population. In this case, the target sample is the grains placed in the sample and the variable is the grains counted (table 4.7.1). The total grains counted in each size category has been paired with the target count. The chi-squared test identified that all the samples were different at 95% probability. The chi-squared test was not applied to the blind test and the revised test as some cells have a value of zero.

Table 4.7.1. Chi-squared test between samples in the same size range.

Sample	Target grains placed in samples	Subtracted naturally occurring grains.	D*f*	X^2 value for series	95% probability
BTA1	100	78	4	9.4077*	different
BTB1					
BTC1	150	107			
BTD1	50	78			
BTE1	200	142			
BTA2	150	191	4	1.7987*	different
BTB2	50	95			
BTC2	200	386			
BTD2					
BTE2	100	96			
BTA3	50	84	4	6.4203*	different
BTB3	200	262			
BTC3	150	169			
BTD3	100	110			
BTE3					

* The chi-squared test value is for the entirety of the size range, without the blank.

Table 4.7.1 demonstrates that the counts in the revised test were considerably different from the approximate number of particles placed in the sample. This error may relate to the use of weight rather than particle numbers in the preparation of the samples. It is possible that a replication of the blind test, with controlled amounts of microdebitage placed in the sample, would produce better results.

The test results of the revised counts, although encouraging in its association between the particles placed and counted in the samples, is not supported by the chi-squared test . A chi-squared test on samples from the subtracted naturally occurring grains does not substantiate an association between the material counted and placed in each sub-sample.

Chapter five

"In Australia the earliest radiocarbon dates come from the Swan River near Perth. A date of 39,500 BP, almost at the limit of radiocarbon techniques, was obtained from carbonised wood and associated with almost a thousand small chert artefacts. Many believe that early finds are still to be made. Thermoluminescence (TL) dates from the Malakunanja rock shelter in northern Arnhem Land suggest initial occupation by 60,000 BP.... While some technical questions still surround the TL dating of sediments none of the current sceptics finds it difficult to accept that such age for the initial colonisation of greater Australia is possible"

Clive Gamble (1993:215).

Conclusions and archaeological implications

The use of microdebitage analysis for spatial patterning of archaeological sites has been a standard methodology since the early 1980s. In the geosciences, quartz grain surface features have been used since the early 1960s for identifying material provenance and analysing environmental changes. Both methodologies are well established and applied widely in their respective disciplines.

The analyses undertaken in this thesis have been based on material derived from the manufacture of rock engravings. This research has based the recognition of microdebitage features on the understanding that materials with of high silica content have a tendency to fracture in the same manner. Archaeologists have observed features on ancient lithic flaking remnants that are consistent, regardless of the siliceous raw material used. Material such as quartz, quartzite, chert, siltstone, mudstone, obsidian and many other stone types with high silica content have a tendency to produce the same surface features when struck to produce lithic tools or rock engravings.

Consistently mentioned in the archaeological literature, microdebitage has been identified and used to ascertain tool flaking areas in archaeological sites by employing spatial analysis. Microdebitage analysis is understood and employed to extract human occupational information and data from the sedimentary deposits of archaeological sites. The approach of this research to the analysis of microdebitage is innovative, as it employs techniques that are used mostly for the analysis of quartz grains in pottery.

The methods used were applied and modified from the geological study of quartz grain origin and provenance. The use of SEM rather than light microscopy is an improvement upon established archaeological techniques that were of limited value when dealing with quartz microdebitage in sandy deposits. There is no doubt that the surface features produced on quartz microdebitage from the manufacture of stone tools, and the features on microscopic quartz debris from the manufacture of rock engravings, are the same. Both forms of microdebitage were produced in the same manner, namely, rock-on-rock percussion. As Fladmark (1982: 205) said, it may be concluded that:

> *"Microdebitage is defined as all lithic manufacture residue less than 1mm in maximum dimension"* (cf. Chapter 2 page 10).

This research has collated methodologies that differ slightly from their original applications. The method used by Fladmark (1982) applies microdebitage analysis to archaeological deposits that contain lithic debris (quartz among others) from the making of stone tools. Krinsley and Doornkamp (1973) apply their knowledge of quartz grain environmental features to the investigation of quartz grains in sediments using SEM/EDX analyses. The amalgamation of these two methods and applications has contributed to this experimental research on the recognition of features on rock engraving debris or microdebitage. Microdebitage derived by lithic tool manufacture from archaeological sites is similar to, if not exactly the same as, the material used for this research. This allows for the existence of microdebitage from rock engravings and the possibility of recovery. Further, the possibility to extract more information than is already available from rock engraving sites and other archaeological deposits may be a valuable resource for the discipline as a whole.

Quaternary dating methods like AMS and OSL have been proven useful and reliable in dating sedimentary deposits in geosciences and archaeology. The most recent advances made by Murray and Roberts (1997) and Murray *et al.* (1997) on single aliquot OSL dating provide the potential to date quartz microdebitage directly. The dating of the *artefact* then becomes a reality for rock engraving sites. The added possibility of analysing rock engraving sites temporally and spatially

through microdebitage analysis has the potential to enhance information on stylistic changes through time, or to link stylistic form and time through the long distances between sites.

5.1 Microdebitage analysis, synthesis and critique

The evaluation of this research can be summarised as encouraging. The tests applied to the quartz grains, in hindsight, could have been better designed. However, the results do reflect the possibility that quartz microdebitage in rock engraving sites can be detected in the deposits and sediments. Microdebitage analysis is not a new technique and has been successfully employed in the field of lithic technology.

Experimental microdebitage can be distinguished from the soil *background*. The addition of sedimentary material to experimental microdebitage has given a first hand view of what types of features can be expected to be found on quartz grains broken during the manufacture of ancient engravings on sandstone. It is not known if the research can be used for sediments of different environments from those selected for the tests, nor if it could be successfully tested in the field conditions of an archaeological site. However, this work has provided some parameters for the search of microdebitage in these conditions.

This research was broadly divided in three parts which followed the questions as set out in Chapter 1 (section 1.4):

1. *What features occur on "non cultural " quartz grains?*

All environments produce recognisable features on the surface of quartz grains. The degree of change in original features depends on the weathering conditions of the depositional environment. For example, grains from the sand dune at Pagewood should have retained some features of subaqueous conditions and some of aeolian environment, as they were subjected to both before sedimentation in the dune. In the case of material from the Mutawintji sediment, the parent rock is sandstone, with incorporated quartz grains from sediments in the ocean floor. The grains were dislodged from the rock by weathering, and

released into an aeolian environment adding to the roundness produced by the original environment. Features on the grain surface were consistent with the aeolian environment in which they were re-deposited.

2. *What features occur on quartz grains derived from the rock engraving process? Are they different from other quartz grains?*

Rock engraving microdebitage has features consistent with Krinsley and Doornkamp's (1973) definition as *experimentally broken quartz*. Most of the features are also consistent with broken quartz grains from a glacial environment. The microdebitage used for this thesis was freshly derived from the manufacture of rock engravings. It did not exhibit any signs of diagenetic changes that would probably occur if the material remained in the environment for a length of time. Microdebitage from rock engravings of some antiquity would be subject to some degree of diagenesis however; the grains would probably retain most of the microdebitage features.

The high angularity and unusual shapes makes quartz microdebitage grains very different from the quartz grains derived from the environments analysed. The roundness index on microdebitage allows the possibility of recognising microdebitage against quartz grains from aeolian and arid environments.

3. *Can quartz grains derived from the rock engraving process be identified under natural conditions?*

Quartz microdebitage has been identified by Fladmark (1982) in archaeological deposits. Quartz microdebitage derived from rock engraving has features that compare with Fladmark's study. The test undertaken in this thesis used a *background* of aeolian quartz grains to emulate an environment in which microdebitage may be found. The choice of sample size was determined by Fladmark's research in which a small proportion of microdebitage can be located in a much larger proportion of sediment. The tests indicate that with observations of surface features and roundness index characteristics, allowing for some degree of diagenesis, it is possible to identify microdebitage under natural

conditions. However, this can only be done if the naturally available quartz grains do not have similar characteristics as microdebitage (eg a glacial environment or rock engravings carved or pecked on rocks with very angular quartz grains).

The techniques used in this research were designed for the recognition of microdebitage against other sedimentary material. The amounts of material used and the time spent analysing has far exceeded original estimates. Hull (1983) considered microdebitage analysis too time consuming for the results achieved. However, Hull's (1983) estimates were based on light microscopy alone, and the application of that technique was generally directed towards a more accurate picture of the spatial dimension in archaeological sites. The microdebitage used in Hull's study (1983) was part of larger debitage accumulations, and directed towards the understanding of living spaces.

The research undertaken in this thesis was to investigate the possibility of applying analytical techniques to quartz microdebitage produced during the manufacture of rock engravings. Unlike spatial studies on archaeological sites, which have larger lithic debitage available (such as flakes, cores and tools); microdebitage is probably the only remnant from the making of rock engravings.

This research has been useful in understanding the difficulties of applying new techniques to archaeological material, and to the future development of techniques to be performed in the field.

Because of time constraints, this work has been restricted to demonstrating in laboratory experiments that it is possible to identify microdebitage from quartz grains of differing environmental provenance. It is likely that microdebitage can be found in archaeological sites containing rock engravings, provided the sedimentary quartz grains have shapes and features different from those identified for microdebitage.

5.2 Microdebitage in archaeological investigations

This research confirmed that quartz grain features are different according to the environment. Experimental microdebitage is different from the quartz grains available in the soil.

Microdebitage analysis has been used for surface and sub-surface spatial patterning of archaeological sites (for example, Kroll and Price, 1991; Fladmark, 1982; Nicholson, 1983; Hull, 1983, 1987). It is within archaeological investigations of spatial patterning that the research in this thesis can be extremely useful. Kroll and Price (1991) believe that:

> "The interpretation of archaeological spatial patterns ...is as old an endeavour as Paleolithic archaeology itself. Since the earliest findings of prehistoric artefacts, prehistorians have tried to interpret the spatial associations and arrangements of materials in their depositional context. A major concern in the last century—the establishment of human antiquity—relied on the analysis of spatial relationships, specifically the co-occurrence of ancient bones and stone artefacts in stratified deposits... It is only since the 1950s that the quantity of such information has greatly increased. In the last thirty years, significant strides have been made in the analysis and interpretation of intrasite spatial data" (Kroll and Price, 1991: 1).

The experimental approach undertaken in this thesis may be useful in determining the temporal patterning of sites as well. Notwithstanding the benefits of new types of data added to the archaeology of rock art, this type of analysis is not confined to rock engraving sites of great antiquity. These investigations can be useful in determining if engraving or chiselling of rock has been done *in situ* or at other sites. The possibility of investigating the source of material for tools or the block of stone for a column could also be achieved. Other applications of these methods can help in the identification of aspects of material analysis and provenance of prime lithic materials (Shackley, 1998; Jahren *et al*., 1997) and applications of microdebitage analysis (Storck, 1997; Underbjerg, 1998). The application of statistical packages to spatial analysis in geoarchaeology (Doornkamp and King, 1971; Ebdon, 1985; Thomas, 1979) can be of great

assistance in preparing predictive models for finding microdebitage and assessing its archaeological potential.

In addition to the availability of microdebitage for site spatial analysis (Fladmark, 1982; Hull, 1983), the research in this thesis envisaged the use of microdebitage for direct and indirect Quaternary dating of rock engravings. These processes can be used also for the analysis of stone tools and its associated debitage, and can be applied to any other lithic manufacturing, and processing site.

The dating of human activity and associated archaeological deposits has, in recent years, added more accurate dates to archaeological investigations. The use of quartz microdebitage, combined with OSL dating, can add to this. OSL is the prime dating method for quartz grains in sediments. Quartz microdebitage can be isolated in the laboratory under red light conditions as any other quartz grain can be. Further, there should not be any problems in cleaning the samples in dark conditions (Dr Richard Roberts, OSL Laboratory, LaTrobe University, *pers. comm*.) The analysis of sediments and archaeological deposits, especially rock engraving sites, can benefit from this type of analysis.

The research undertaken in this thesis has developed a new use for these methodological tools. For archaeological investigations in general, the use of microdebitage analysis may not be confined to spatial patterning, but can be used for temporal patterning. In the case of rock engraving sites, or any other site that involves the use of tools for engraving rock, this technique can be useful in attempting to retrieve both temporal data and sourcing of material. It may also assist in determining if the artefacts were produced *in situ,* or imported from other places (if the microdebitage is buried subsequently to its production).

Investigations of archaeological sites involve, of necessity, the analysis of stratigraphic deposits. Such sediments have been studied for the purpose of information retrieval on the material remains of previous cultures. The research in this thesis has the potential to add to this by applying quartz microdebitage analyses to the study of tool making, art, and building in antiquity.

For the purposes of heritage management, the methods outlined in this research may be used for the retrieval information with minimal impact and invasiveness, and can be used for site surveying and monitoring in inaccessible and culturally sensitive areas.

5.3 Potential use for microdebitage in the archaeology of rock art

It is envisaged that these methods will be developed and modified (if needed) for field application, and possibly for dating of archaeologically significant sedimentary deposits. The archaeology of rock art includes a lacuna concerning the context of its manufacture. This research can assist in the investigation and understanding of the nature of the lacuna. It is envisaged that the analysis of microdebitage can be useful if applied to hypothesis building and to existing research. The implications of identifying quartz tool industries in Australia gives the potential to discover microdebitage derived from quartz and quartzite tools (as described by Flood, 1997). Evidence on the use of quartz as a raw material for engraving tools has been suggested by Flood (1997), who noted that quartz and quartzite tools have been used in Australia for the making of rock engravings.

5.4 Field applications and techniques

The application of the techniques developed in this thesis is to a large extent dependant on the type of information required by the investigator. With some modification, the techniques applied to microdebitage in this study can be used.

The ultimate implications for this research is to deliver a workable field method for the extraction of microdebitage for direct dating of rock engravings. Much of the field application for this research has been developed by Fladmark (1982) — microdebitage analysis, Krinsley and Doornkamp (1973)—quartz grain environmental textures, and Murray and Roberts (1997)—single quartz aliquot OSL dating. The combined work of these scholars is the best approach for the successful application of the methodologies discussed within this thesis.

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Appendix one

Laboratory method for the preparation of soil samples

(After Fladmark, 1982: 217-218).

Simplified laboratory procedures

The following procedures are intended to allow the microscopic examination of site sediments and soils for microdebitage. The pre-treatment procedures are derived from Shackley (1975).

1. Obtain 80-100 g bulk of sample sediments. Ensure that exposed surfaces of the sample area are fresh. Use a clean towel and place the sample in a clean labelled plastic bag. Make sure that no experimental Faking is going on anywhere within several hundred metres of the sampling site, and if the collector has recently been involved in experimental flaking, that his hands and clothing are clean. No screening should be going on nearby at the time of sampling, nor should sampling be conducted on a dusty, windy day. Make sure that a natural control sample of sediment is obtained.

2. Air dry samples.

3. Extract all coarse material (pebbles, large flakes, bone fragments, roots or other organic matter). Gently crush the sample in a soil mortar, or desegregate in a Calgon solution, if necessary.

4. Screen samples through 1.0, 0.5, 0.25, 0.125, and 0.063 mm soil sieve sizes. Make sure that the sieves are as clean as possible for each repeated analysis, or, preferably, use disposable nylon sieves.

5. Record and discard any items remaining in the 1.0 mm screen (by definition any material caught in this screen is not microdebitage), and weigh the contents of the other screens.

6. Place a small, randomly obtained sample of the 0·5 or 0·25mm fraction on a microscopic slide and examine at X 40, to determine amount of organic, carbonate or ferric contamination. If microdebitage would be readily visible without further pre-treatment proceed to step 14; if pre-treatment is necessary, proceed to step 7.

7. Place individual screened samples in 500-ml flasks and cover with 30-50% hydrogen peroxide solution, to remove organic constituents by wet combustion.

8. Dilute with fresh water, stand for 2-3 min and decant the clear liquid. Repeal 3-4 times. While repeated decanting results in some loss of very small particles, these will be mainly in a size range beyond the limits of study by standard optical microscopes.

9. Decant and decalcify in 30% HCl.

10. Repeat step 8.

11. Cover the sample in the flask with a 15-20% solution of oxalic acid, add a small strip of sheet aluminium, and boil gently for 15-20 min, to remove ferric oxides.

12. Repeat step 8.

13. Filter, air dry, and weigh the sample.

14. Homogenize the sample, and split off sub-sample for microscopic examination. When working with samples standardized at l0, 000 particles in each size class, a natural quartz sand with a small percentage of heavy minerals may be sub-sampled at the following rates: 0.5 mm-5.0 g; 0.25 mm-0.75 g; 0.125 mm-0.06 g; 0.063 mm-0.02 g.

15. Spread the weighed fraction on a standard glass microscope slide, with edges built-up to prevent spillage. A strip of cardboard glued around the edges of the slide is sufficient.

16. Microscopically scan the slide in even increments of the *x* and *y* axes to cover the entire surface with a minimum of overlap. Magnification of x 40 is most useful for 0.5, 0.25, and 0.125mm fractions; with x 100 used for the 0.063 fraction. While higher magnifications would allow closer examination of mineralogical characteristics, the high-relief of non-thin-sectioned particles makes use of low power magnifications with the greatest depth of field most practicable. Use a hand counter or electronic calculator to record the count of observed microdebitage in each sample.

Appendix two

Sediment sample cleaning experiments for the removal of clays and iron oxide

Each of the samples is derived from 10g of bulk soil sample BH-C1, without screening.

Sample 1

(a) Sample cleaned and wet sieved with standard dispersant at 63µm.

Sample 2

(a) Sample placed in a 500ml lab bottle with 200ml of double dispersant.
(b) Placed bottle on slow spinning wheel for 48 hours.
(c) After 48 hours, wet screened at 63µm with dispersant.
(d) In a beaker sample boiled at 90°C with 50% H_2O_2 for 20 minutes and washed with H_2O.
(e) Treated with 30% HCl left overnight.
(f) Sample washed and decanted with H_2O.
(g) Sample gently boiled in a flask with a 20% solution of oxalic acid and a strip of sheet aluminium for 15-20 minutes to remove iron oxides.
(h) Sample oven dried at 60°C overnight.

Sample 3

(a) Sample placed in a 500ml lab bottle with 200ml of double dispersant.
(b) Placed bottle on slow spinning wheel for 24 hours.
(c) After 24 hours, wet screened at 63µm with dispersant and cleaned with H_2O_2.
(d) In a beaker sample treated with 50% H_2O_2 for 5 minutes and washed with H_2O.
(e) Treated with 30% HCl for 5 minutes.
(f) Sample washed and decanted with H_2O.
(g) Sample gently boiled in a flask with a 20% solution of oxalic acid and a strip of sheet aluminium for 15-20 minutes to remove iron oxides.
(h) Sample oven dried at 60°C overnight.

Sample 4

(a) Sample placed in a 500ml lab bottle with 200ml of standard dispersant.
(b) Placed bottle on slow spinning wheel for 48 hours.
(c) After 48 hours, wet screened at 63µm with dispersant and cleaned with H_2O_2.
(d) In a beaker sample boiled at 90°C with 50% H_2O_2 for 20 minutes and washed with H_2O.

(e) Treated with 30% HCl left overnight.
(f) Sample washed and decanted with H_2O.

(g) Sample gently boiled in a flask with a 20% solution of oxalic acid and a strip of sheet aluminium for 15-20 minutes to remove iron oxides.
(h) Sample oven dried at 60°C overnight.

Sample 5

(a) Sample placed in a 500ml lab bottle with 200ml of standard dispersant.
(b) Placed bottle on slow spinning wheel for 24 hours.
(c) After 24 hours, wet screened at 63µm with dispersant and cleaned with H_2O_2.

(d) Treated with 50% HCl for 5 minutes.
(e) Sample washed and decanted with H_2O.

(f) Sample gently boiled in a flask with a 20% solution of oxalic acid and a strip of sheet aluminium for 15-20 minutes to remove iron oxides.
(g) Sample oven dried at 60°C overnight.

Sample 6

(a) Sample cleaned and wet sieved with standard dispersant at 63µm.
(b) Placed in ultrasonic bath with H_2O for 20 minutes.

(c) Cleaned with 100% H_2O_2 left in bath for 1 hour.

(d) Treated with 30% HCl for 5 minutes.
(e) Sample washed and decanted with H_2O.

(f) Sample gently boiled in a flask with a 20% solution of oxalic acid and a strip of sheet aluminium for 15-20 minutes to remove iron oxides.
(g) Sample oven dried at 60°C overnight.

Appendix three

Soil sample preparation for scanning electron microscopy (SEM)

1. Air-dry sample for at least 24 hours.

2. Weigh 100-120g of sample, and break clumps gently using mortar and pestle.
- This weight range gives sufficient material for analysis. Do not grind the sample in the mortar as it may damage the features on the quartz particles.

3. Place sample in beaker with dispersant solution of tetra-potassium pyrophosphate ($K_4P_2O_7$) in distilled water for 12 hours (1.65g $K_4P_2O_7$ x 1000ml H_2O). Do not place sample in an ultrasonic bath, it may damage the grain surfaces.
- Dispersant aids in the desegregation of clay size particles, making it easier to screen out this component of the sample (under 63µm). Ultrasonic bath may damage the features of the particles.

4. Wet sieve the sample in 63µm standard soil screen with H_2O until solution becomes clear.
- Wet sieving eliminates clay particles more efficiently than dry sieving. Determining features of clay particles (under 63µm) is difficult. Microdebitage and natural environmental material under 1mm in size may retain high angularity for longer periods of time.

5. Place sample in a beaker and add 120ml of hydrogen peroxide (H_2O_2) for three hours. If organic material persists, gently heat the sample at 90°C for two hours over a hot plate, stirring occasionally. Wash sample in a 63µm screen with water to clean out the remaining organic solution.
- Hydrogen peroxide eliminates most of the organic matter in the sample by wet combustion.

6. Transfer the washed sample from the sieve into a beaker, and desiccate sample in oven at 60°C overnight.

7. Transfer and screen dry sample in standard soil sieves sizes 1000µm, 500µm, 250µm, 125µm, 63µm, by mechanical shaker for 5 minutes, or manual shaking until needed.
- To sort sample into size fractions.

8. Retain sample sizes: <1000µm, <500µm, <250µm, <125µm, <63µm, for SEM and light microscopy.

9. Weigh samples by size component.
- To ascertain loss and size percentages of sample composition. A marker of microdebitage may be an unusual size range in relation to soil "background" samples.

10. Place samples by size component on standard ∅1cm aluminium SEM stubs and coat with Au (of about 400Å). For energy dispersive x-ray analysis (EDX) use a heavy carbon coating.

- The ∅1cm stubs have been effective in holding sufficient particles for a "Powers' roundness index" analysis. The heavy Au coat prevents charging of the particles.

Appendix four

Electron microscopy and materials analysis

In scanning electron microscopy (SEM) "a tungsten electrode is heated to thermoionically emit primary electrons which are accelerated and focussed through a series of magnetic lenses towards the sample. When the primary electrons collide with the sample, secondary backscattered electrons are emitted. A detector detects and converts the secondary backscattered electron emissions to an electronic signal, which is converted to a video image. The entire process is contained in a vacuum to prevent atmospheric elements from interrupting the primary and secondary electron emissions (Morrobel-Sosa, 1998: 3)"(see also: van Essen (1979: 99-120); Oatley (1972); Hearle (1972:1-23); and Castle (1972: 105-137).

Energy Dispersive X-Ray Analysis (EDX), as detailed by Morrobel-Sosa (1998) "is used to determine the elemental composition of a material. To do this, EDX measures the characteristic radiation signature emitted from a material that is bombarded with electrons. Typically, a tungsten, or other refractory metal electrode, is heated to a high temperature so that electrons are emitted. These electrons are then accelerated towards the target material [in the sample] through a magnetic field. When the electrons collide with the surface of the target material two types of energies are produced. One type of energy, known as Bramstrallung radiation, is caused by the deceleration of electrons colliding with the surface. It is this high rate of deceleration that converts the electron's kinetic energy into x-ray fluorescence. When a high velocity electron collides with the surface of the target material the electron stops over distances measured in nanometres. The second type of energy produced is that generated by inner-electrons involved in transitions to lower energy levels. The transition energies vary from different samples and energy levels. These energies are measured by an EDX detector. The higher the concentration of a certain element (-X-) that occurs on the surface of the sample, the greater the intensity of that particular transmission (Morrobel-Sosa, 1998:4-5)". For greater detail on the function of

EDX detectors and microanalysis see: van Essen, (1979: 99-120); Belk, (1979:195-207); and Salter (1979: 145-151)

The application of SEM and EDX in geology has been of much help for the analysis of quartz grain surface features (see Krinsley and Doornkamp, 1973: 3). Reed (1996), advocates the use of the SEM and EDX because of the following methodological applications:

1. Specimen preparation is straightforward and entails the use of existing techniques of section-making and polishing with only minor modifications;
2. electron microprobe analysis [EDX] is non-destructive, unlike most other analytical techniques;
3. quantitative elemental analysis with accuracy in the region of 1% (for major elements) can be obtained routinely;
4. all elements above atomic number 10 can be determined with fairly uniform accuracy and sensitivity, and those between 4 and 10 with somewhat inferior sensitivity (H, He and Li are not detectable);
5. detection limits (typically in the region of 50 PPM) are low enough to enable minor and trace elements to be determined in many cases;
6. the time per analysis is reasonably short (usually between 1 and 5 minutes);
7. spatial resolution of the order of 1µm enables most features of interest to be resolved;
8. individual mineral grains can be analysed *in situ*, with their textural relationship undisturbed and visible to the analyst;
9. a high specimen throughput rate is possible, the time required for changing specimens is quite short." (Reed, 1996: 3).

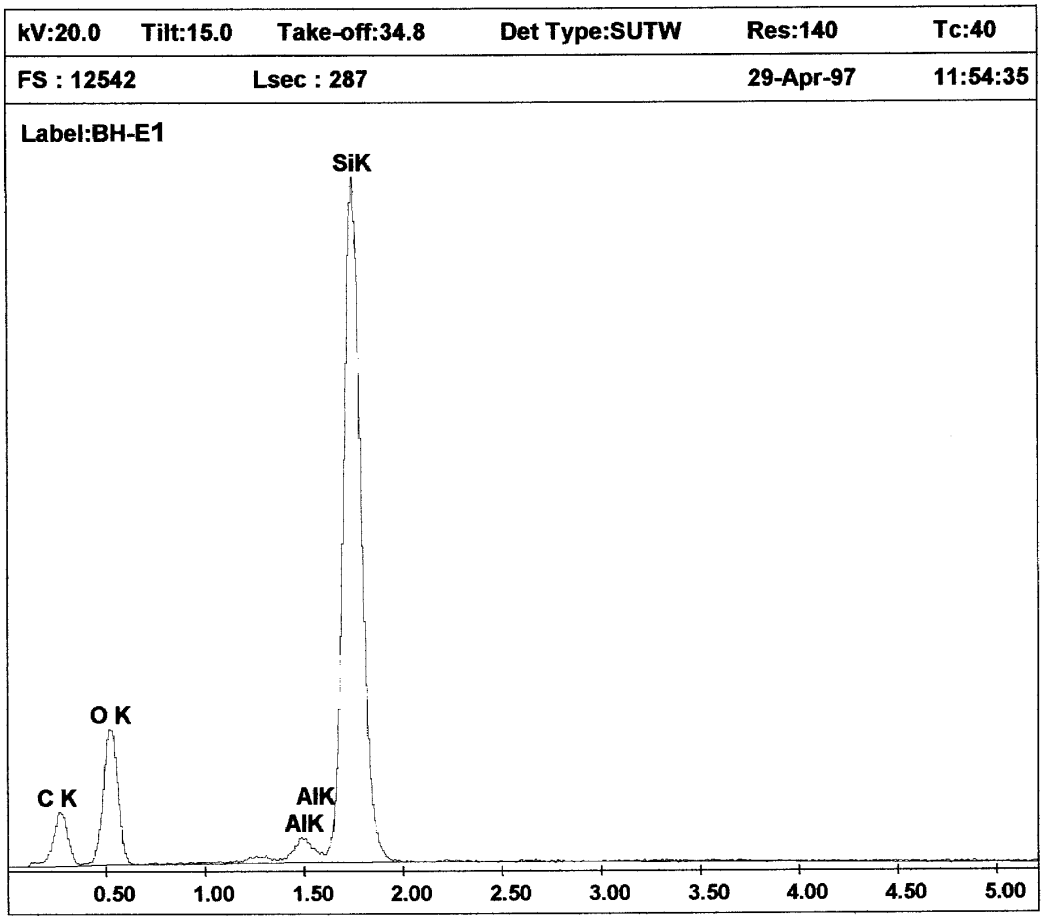
The SEM can be used in sedimentology for three dimensional viewing of "The morphology of individual sediment grains and intergrowths..."(Reed, 1996: 2), and the use of EDX analysis can be of great value in determining mineral characteristics and composition of materials. The recent application of the cathodoluminescence (CL) detector to SEM (SEM-CL) has improved the analysis of quartz grains for provenance and sourcing interpretation. Seyedolali, *et al*. (1997) has applied this technique to a variety of quartz grains from different environments. According to this study, patterns of luminescence on quartz grains appear to be an identifier for source material. The interest is that this research has revealed that environments and geological source produces minute stress fractures, not usually visible with the conventional SEM detectors. These fractures are used for identification and sourcing of quartz geological origin (Seyedolali, *et al*., 1997: 787-790). The application of SEM/EDX in archaeology was until recently confined of the sourcing of material from pottery sherds (Shackley, 1975; Garcia-Heras and Rincon, 1996).

Appendix five

Materials analysis of experimental tools and engravings

Material analysis of the engraving tools and sandstone slabs made at Broken Hill from material collected at Mutawintji (NSW Australia).

Graph A5.1. EDX analysis of sandstone from Mutawintji in experimental engraving E1.



EDAX ZAF Quantification (Standardless)
Element Normalized

Element	Wt %	At %	Z	A	F
C K	65.25	81.43	1.0202	0.1753	1.0000
AlK	1.20	0.67	0.9346	0.8908	1.0237
SiK	33.54	17.90	0.9619	0.9503	1.0000
Total	100.00	100.00			

Graph A5.1 shows the average chemical composition of sandstone in the experimental engraving E1, the oxygen has not been accounted for in the EDAX ZAF Quantification analysis (refer to figure 3.1.1.2a, page 50).

Figure A5.1 shows the polished section of the sandstone slab. The quartz grains can be seen as medium to coarse sand.

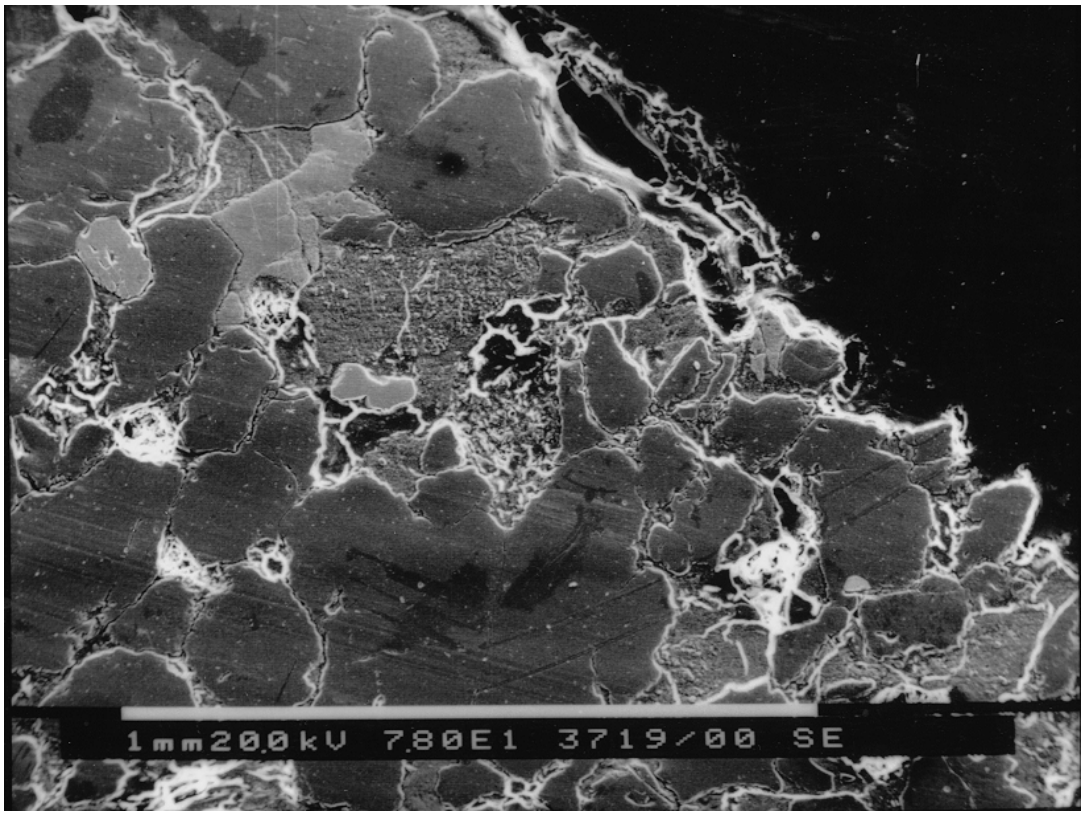


Figure A5.1. SEM Polished section of sandstone from the experimental engraving E1.

Figure A5.2 shows the broken grains as they are encased in the silica cementation and a clay matrix bond.

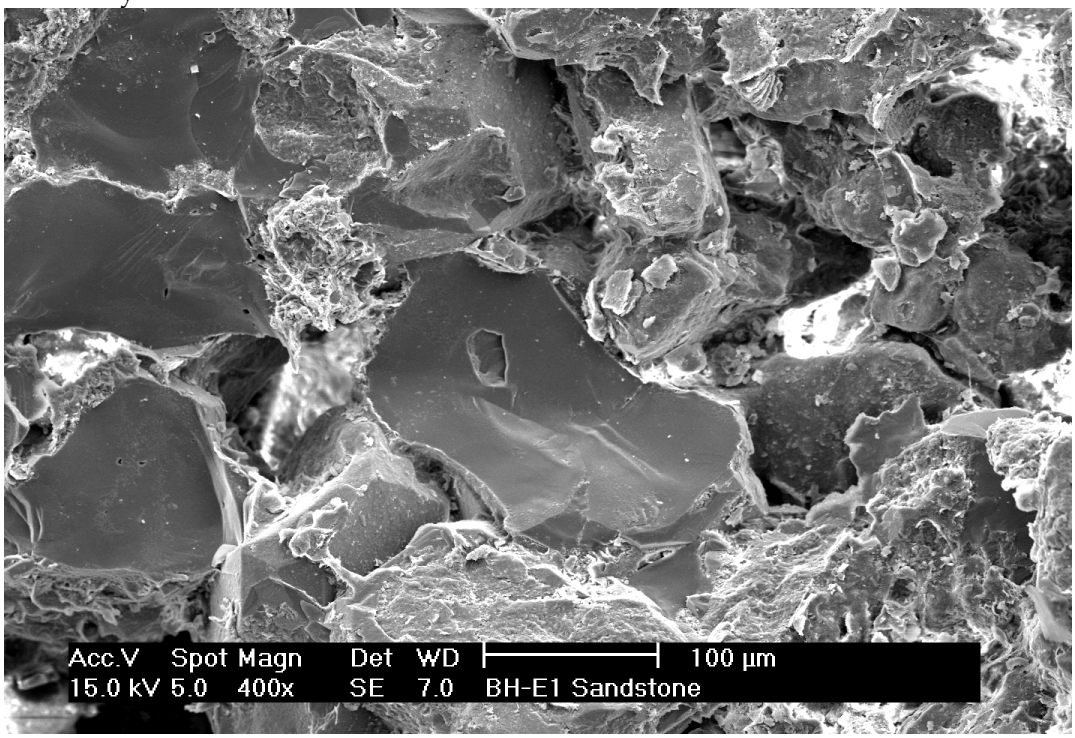
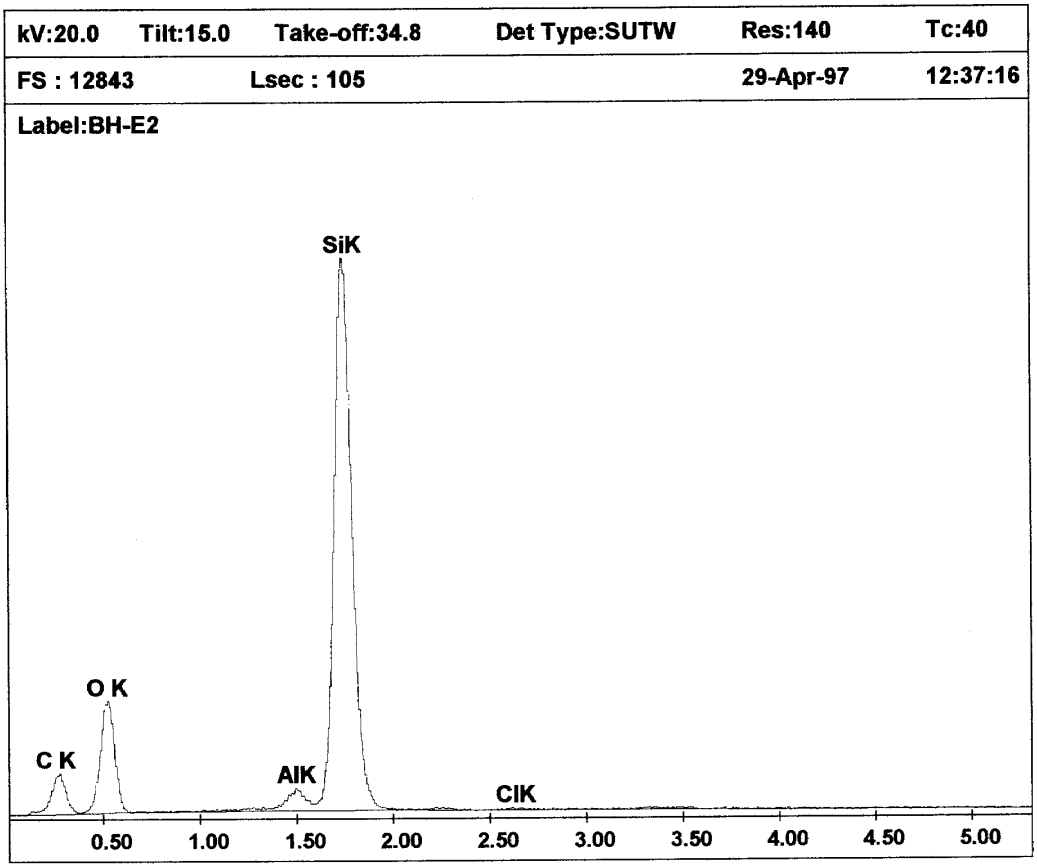


Figure A5.2. SEM Unpolished surface section of sandstone from the experimental engraving E1.

The unpolished surface in figure A5.2 has been achieved by breaking a thin piece of sandstone to expose the rough surface edges. The edge was not cut or sliced.

Graph A5.2. EDX analysis of sandstone from Mutawintji in experimental engraving E2.



EDAX ZAF Quantification (Standardless)
Element Normalized

Element	Wt %	At %	Z	A	F
C K	63.79	80.46	1.0211	0.1691	1.0000
AlK	1.28	0.72	0.9354	0.8917	1.0246
SiK	34.81	18.77	0.9628	0.9498	1.0000
ClK	0.13	0.05	0.9032	0.8324	1.0000
Total	100.00	100.00			

Graph A5.2 shows the average chemical composition of sandstone in the experimental engraving E2, the oxygen has not been accounted for in the EDAX ZAF quantification analysis (refer to figure 3.1.1.3a, page 51).

Figure A5.3 shows the polished section of the sandstone slab. The size of the quartz grains can be seen as medium to coarse sand.

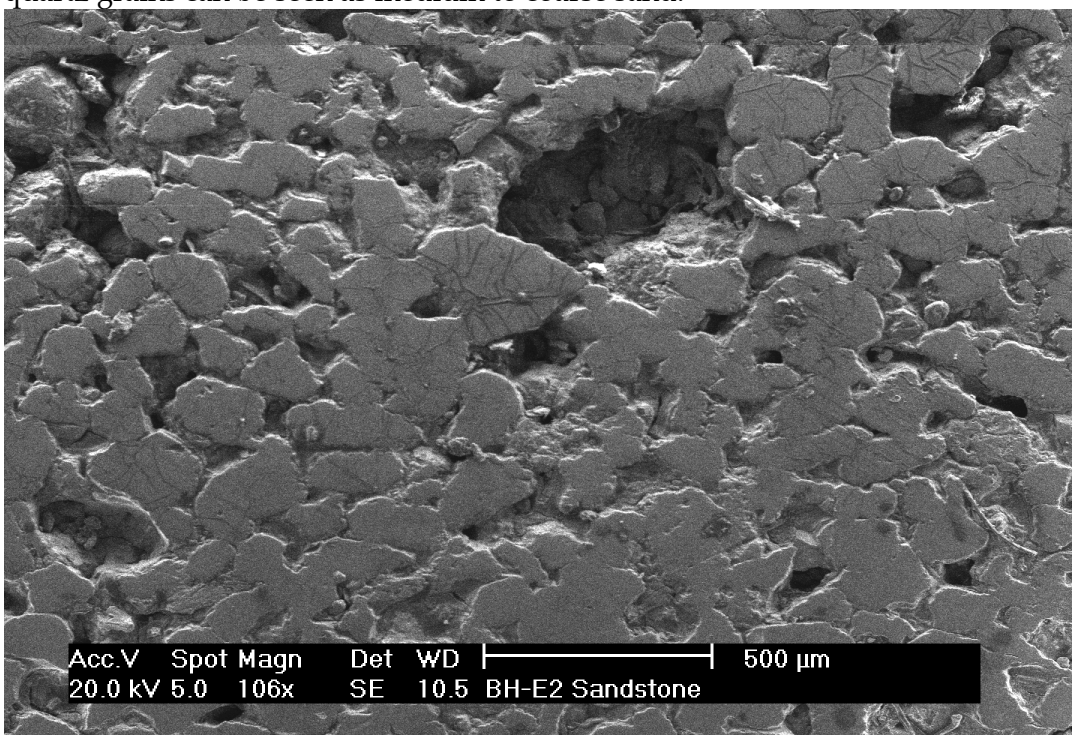


Figure A5.3. SEM Polished section of sandstone from the experimental engraving E2.

Figure A5.4 shows the broken grains as they are encased in the silica cementation and a clay matrix bond.

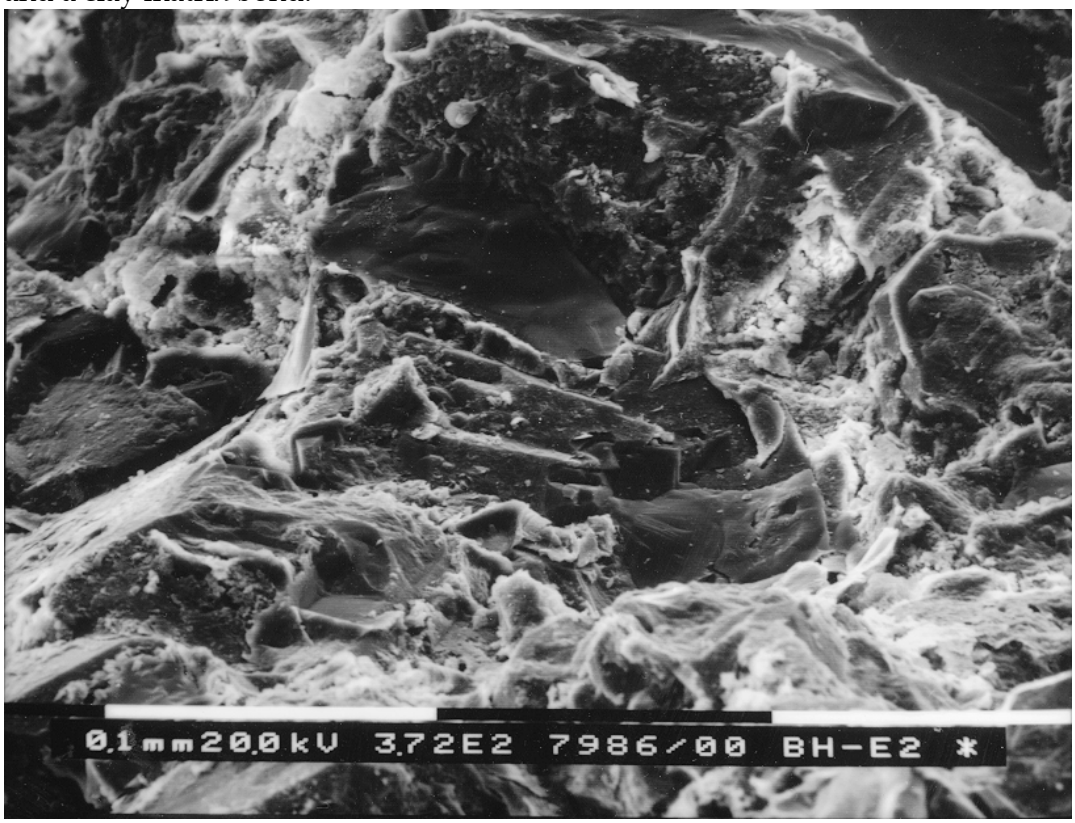
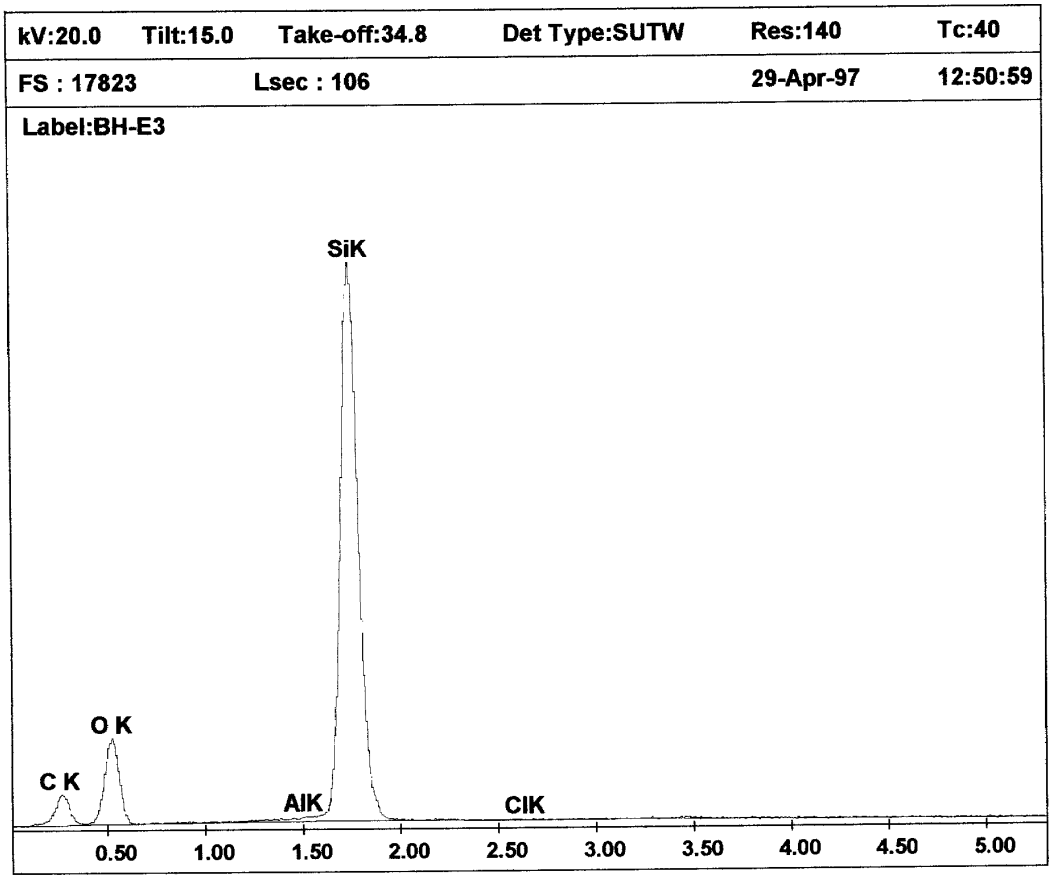


Figure A5.4. SEM Unpolished surface section of sandstone from the experimental engraving E2.

The unpolished surface in figure A5.4 has been achieved by breaking a thin piece of sandstone to expose the rough surface edges. The edge was not cut or sliced.

Graph A5.3. EDX analysis of sandstone from Mutawintji in experimental engraving E3.



EDAX ZAF Quantification (Standardless)
Element Normalized

Element	Wt %	At %	Z	A	F
C K	60.39	78.10	1.0229	0.1561	1.0001
AlK	0.32	0.19	0.9370	0.8939	1.0288
SiK	39.20	21.68	0.9644	0.9651	1.0000
ClK	0.09	0.04	0.9050	0.8146	1.0000
Total	100.00	100.00			

Graph A5.3 shows the average chemical composition of sandstone in the experimental engraving E3, the oxygen has not been accounted for in the EDAX ZAF quantification analysis (refer to figure 3.1.1.4a, page 52).

Figure A5.5 shows the polished section of the sandstone slab. The size of the quartz grains can be seen as medium to coarse sand.

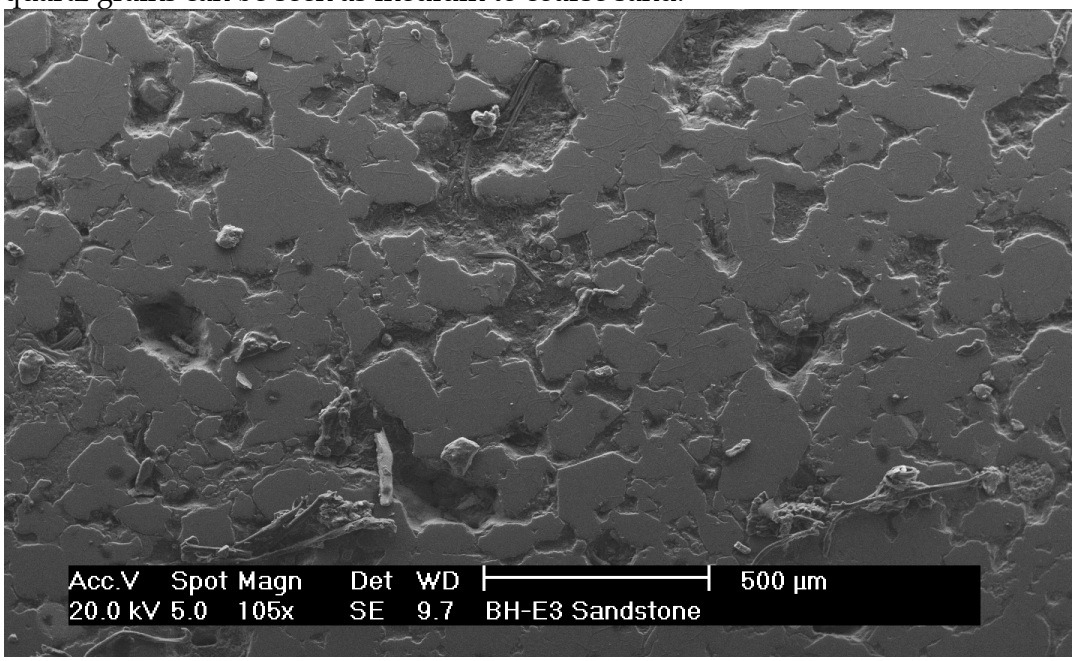


Figure A5.5. SEM Polished section of sandstone from the experimental engraving E3.

Figure A5.6 shows the broken grains as they are encased in the silica cementation and a clay matrix bond.

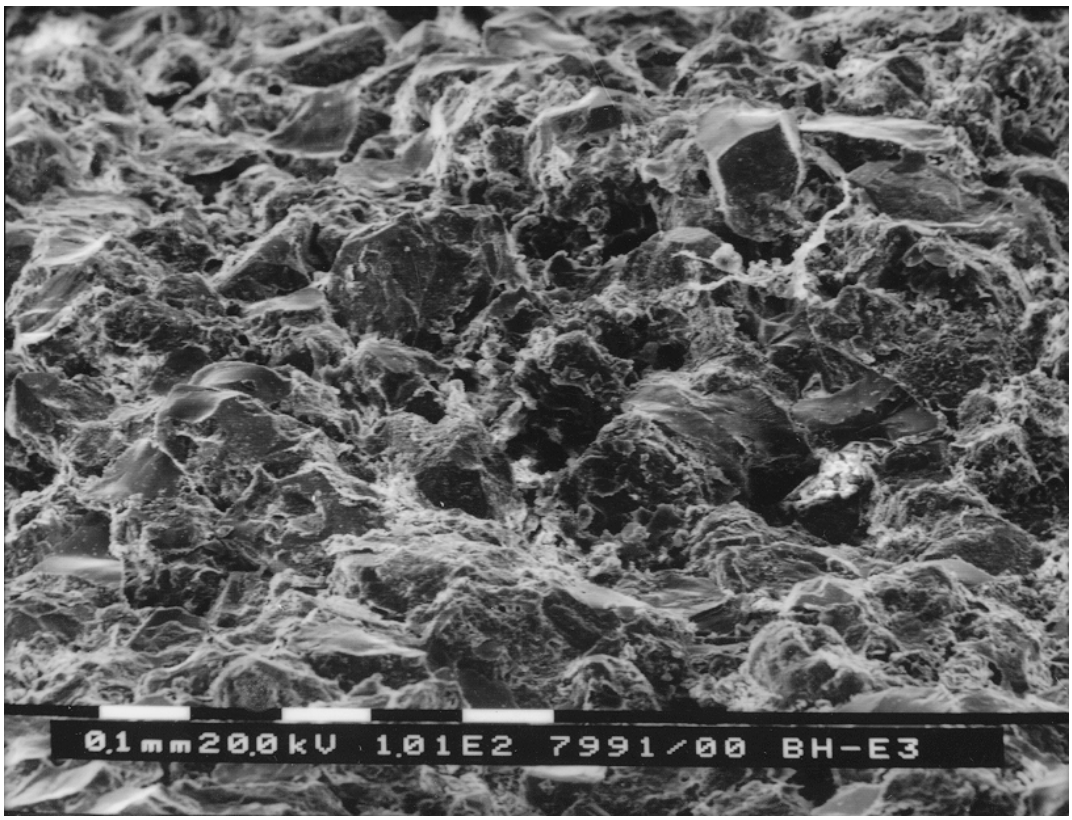
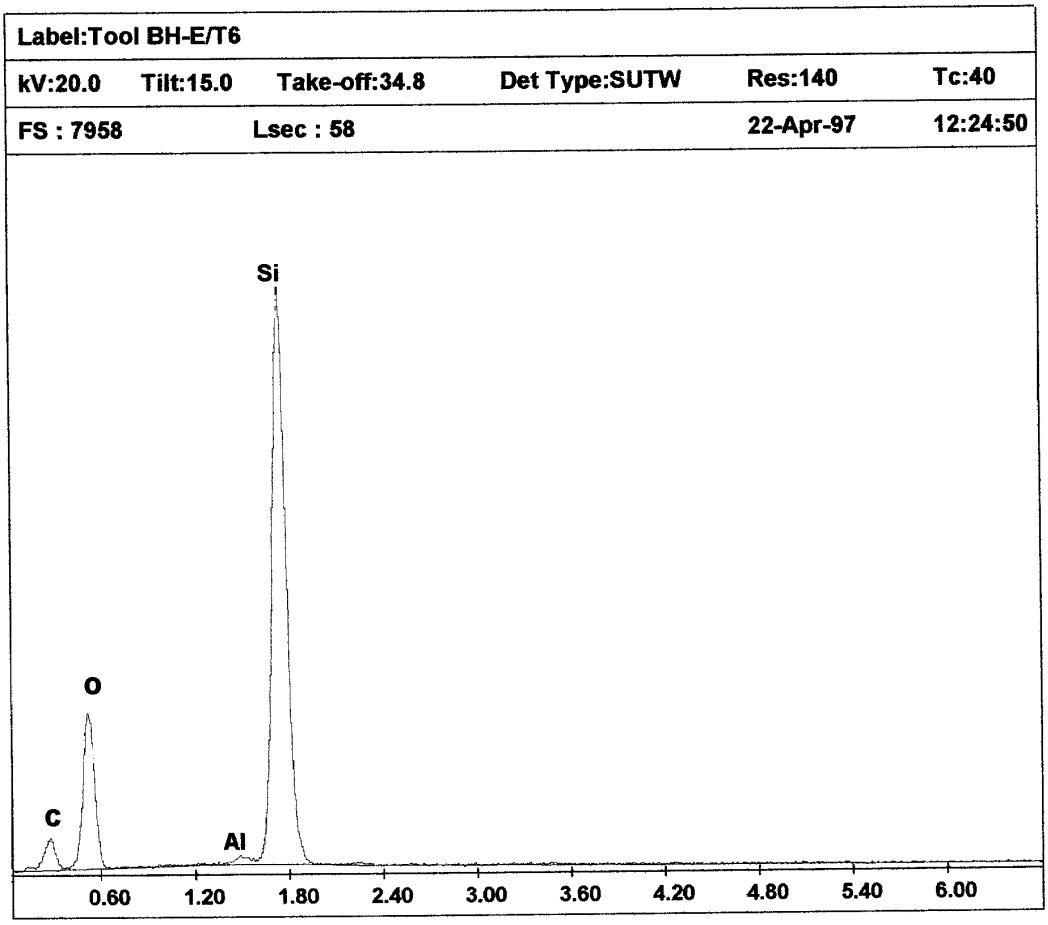


Figure A5.6. SEM Unpolished surface section of sandstone from the experimental engraving E3.

The unpolished surface in figure A5.6 has been achieved by breaking a thin piece of sandstone to expose the rough surface edges. The edge was not cut or sliced.

Graph A5.4. EDX analysis of quartzite tool T6 used in the making of engraving E1.



EDAX ZAF Quantification (Standardless)
Oxides

Element	Wt %	At %
Al2O3	1.35	0.80
SiO2	98.65	99.20
Total	100.00	100.00

Graph A5.4 shows the average chemical composition this quartzite cobble used in the making of experimental engraving E1, the oxygen has not been accounted for in the EDAX ZAF quantification analysis, only oxides have been calculated (refer to figure 3.1.1.2b, page 50).

Figure A5.7 shows the polished section of the quartzite cobble used as a tool in the making of experimental engraving E1. The quartz crystals can be seen as tightly bound in a silica cement binder.

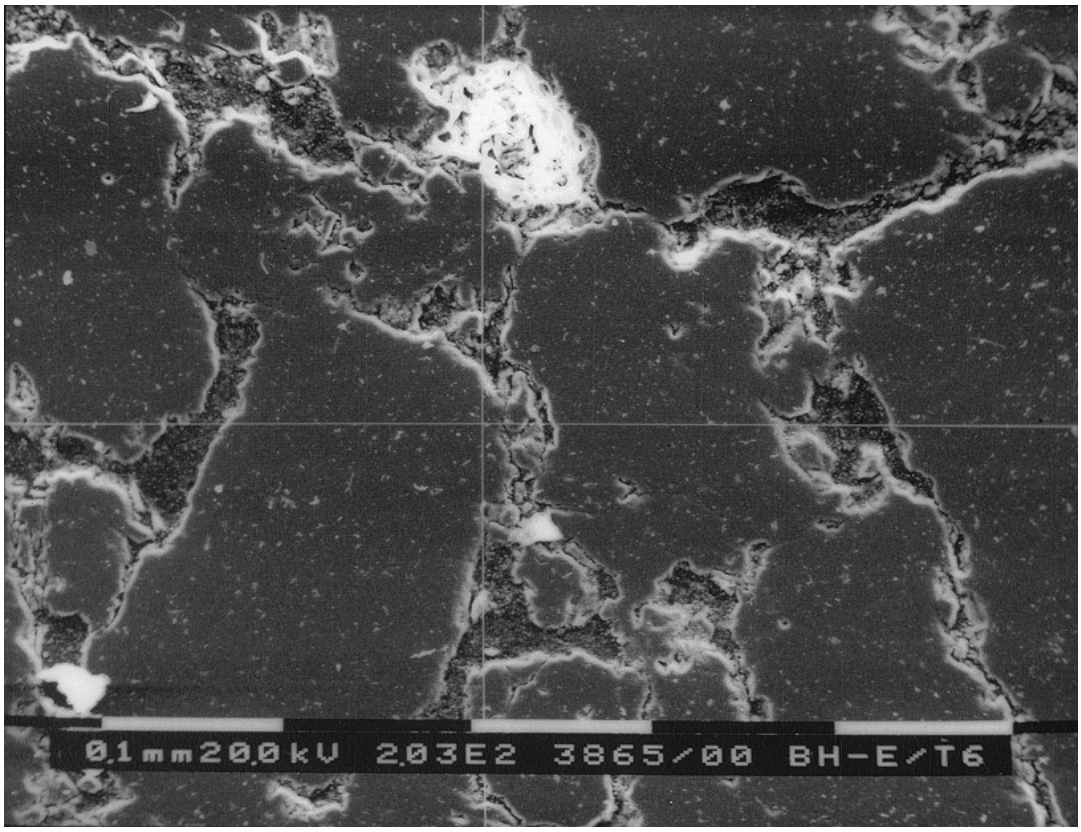
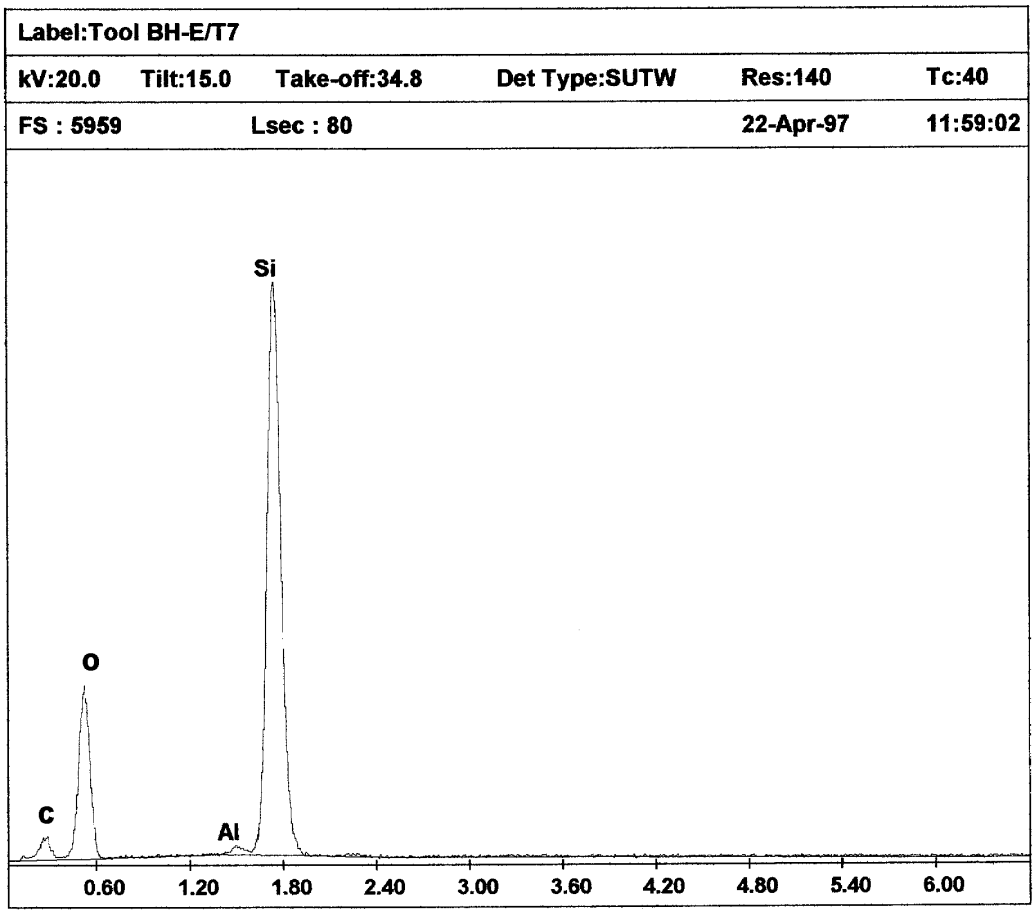


Figure A5.7. SEM Polished section of quartzite cobble T6 used in the making of engraving E1.

Graph A5.5. EDX analysis of quartzite tool T7 used in the making of engraving E2.



EDAX ZAF Quantification (Standardless)
Oxides

Element	Wt %	At %
Al2O3	1.20	0.71
SiO2	98.80	99.29
Total	100.00	100.00

Graph A5.5 shows the average chemical composition this quartzite cobble used in the making of experimental engraving E2, the oxygen has not been accounted for in the EDAX ZAF quantification analysis, only oxides have been calculated (refer to figure 3.1.1.3b, page 51).

Figure A5.8 shows the polished section of the quartzite cobble used as a tool in the making of experimental engraving E2. The quartz crystals can be seen as tightly bound in a silica cement binder.

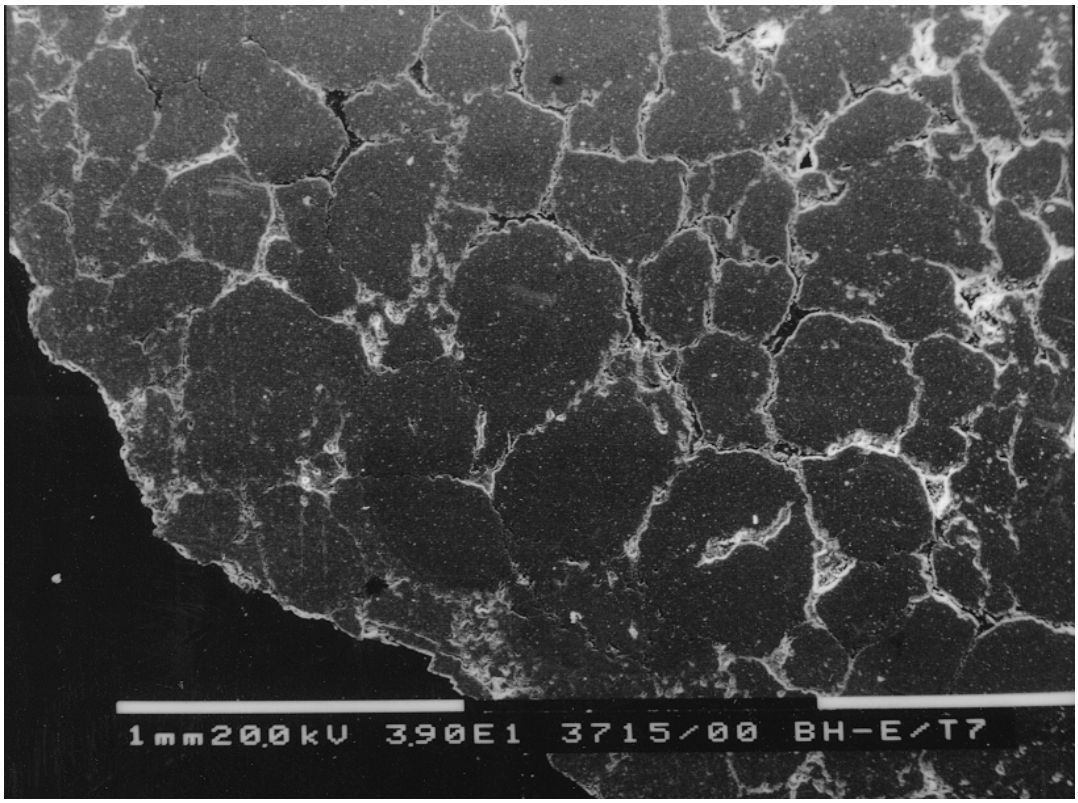
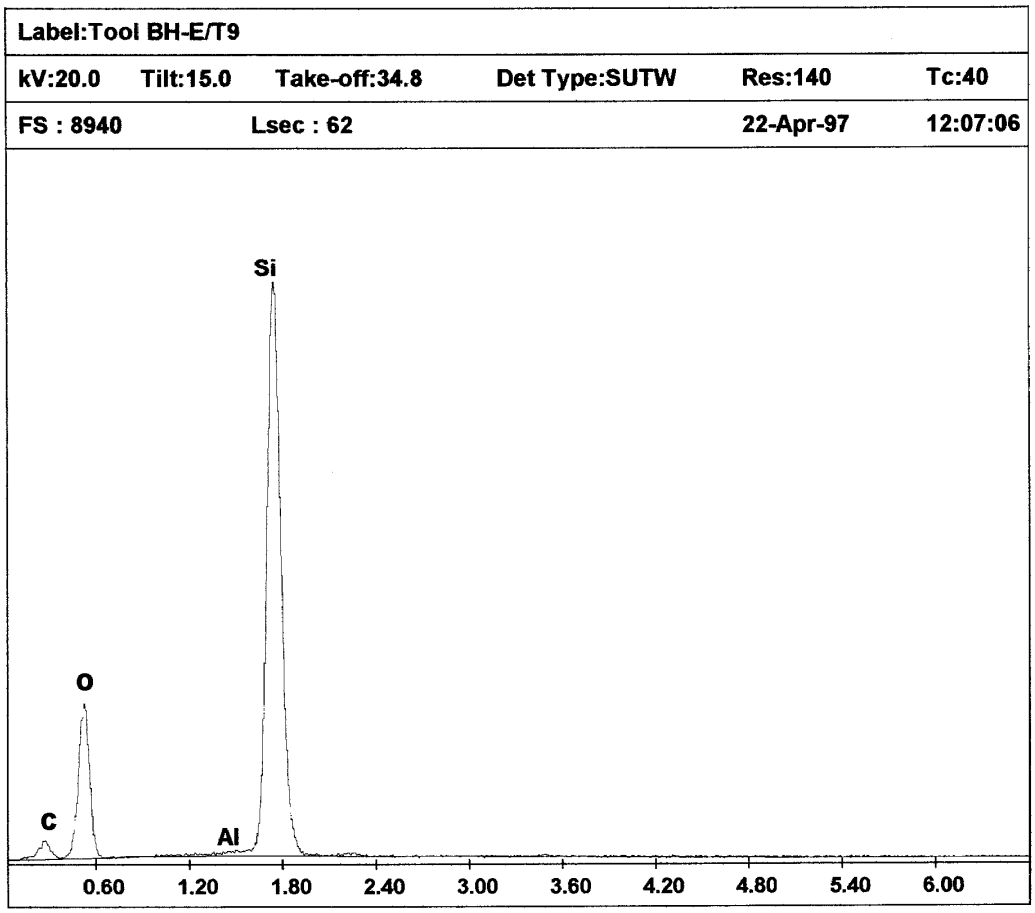


Figure A5.8. SEM Polished section of quartzite cobble T7 used in the making of engraving E2.

Graph A5.6. EDX analysis of quartz tool T9 used in the making of engraving E3.



EDAX ZAF Quantification (Standardless)
Oxides

Element	Wt %	At %
Al2O3	0.88	0.52
SiO2	99.12	99.48
Total	100.00	100.00

Graph A5.6 shows the average chemical composition this quartz cobble used in the making of experimental engraving E3, the oxygen has not been accounted for in the EDAX ZAF quantification analysis, only oxides have been calculated (refer to figure 3.1.1.4b, page 52).

Figures A5.9 and A5.10 shows the polished sections of the quartz cobble used as a tool in the making of experimental engraving E3. The quartz crystals can be seen as tightly bound in the matrix.

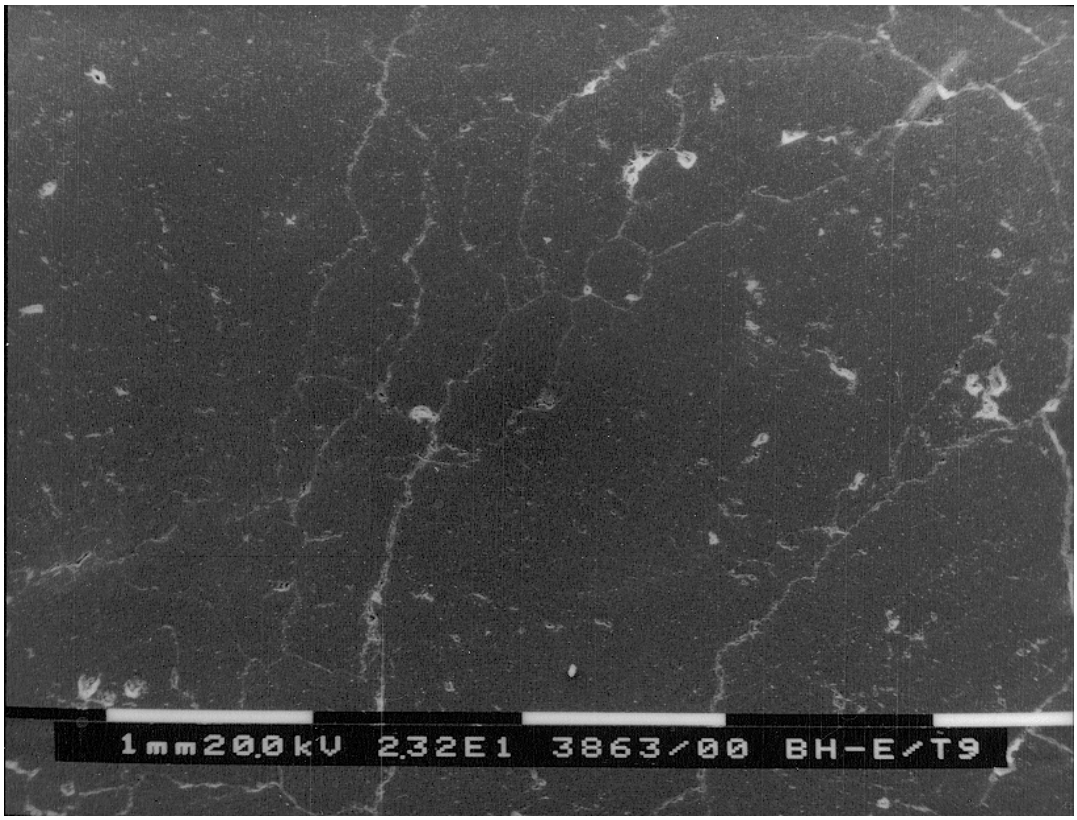


Figure A5.9. SEM Polished section of quartz cobble T9 used in the making of engraving E3.

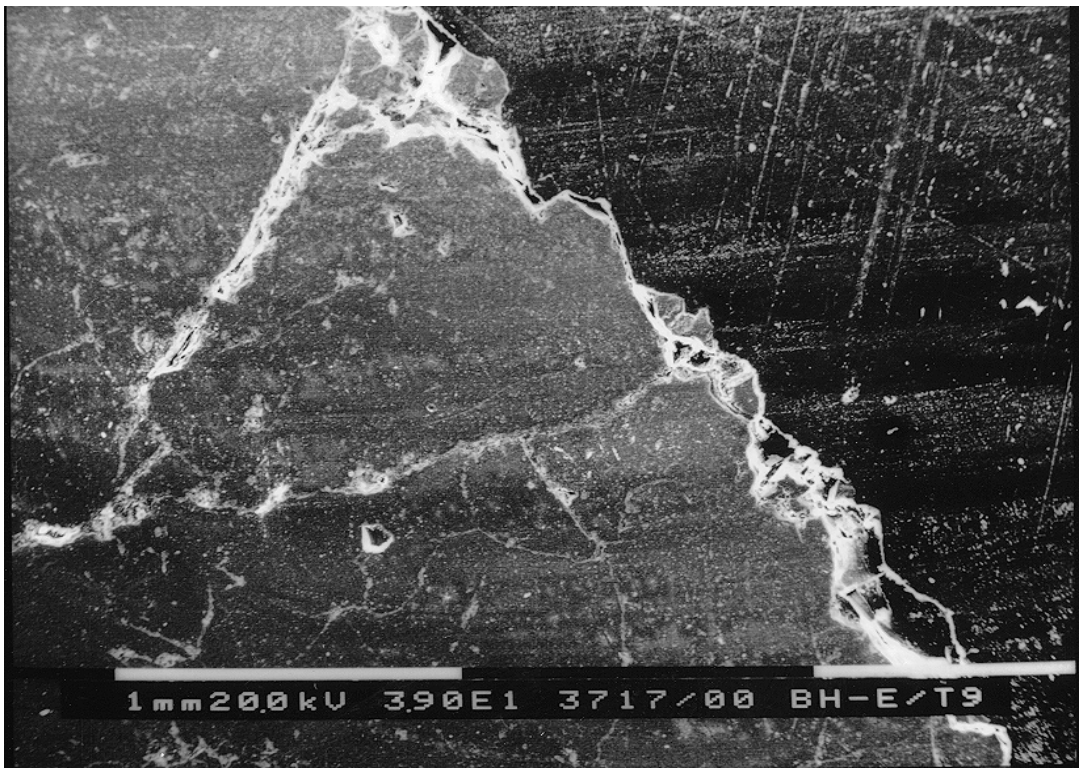


Figure A5.10. SEM Polished section of quartz cobble T9 used in the making of engraving E3.

Appendix six

Analyses data sheets and results

Roundness index

Table A6.1. Roundness index on samples of microdebitage from experimental engravings.

Sample	very angular	angular	sub-angular	sub-rounded	rounded	well rounded	total particles counted
BH-E1	226	107	34	11	10	5	393
BH-E1A	59	14	8	0	1	0	82
BH-E1B	41	29	6	2	0	0	78
BH-E1C	54	45	13	3	2	1	118
BH-E1D	72	19	7	6	7	4	115
BH-E2	284	109	39	27	6	1	466
BH-E2A	50	17	10	4	1	0	82
BH-E2B	92	33	12	9	1	0	147
BH-E2C	57	36	9	6	0	0	108
BH-E2D	85	23	8	8	4	1	129
BH-E3	268	148	56	30	8	1	511
BH-E3A	41	21	12	4	4	0	82
BH-E3B	106	54	19	9	0	0	188
BH-E3C	61	41	14	8	2	0	126
BH-E3D	60	32	11	9	2	1	115

Table A6.2. Roundness index on samples of sediment and sandstone from Sydney.

Sample	very angular	angular	sub-angular	sub-rounded	rounded	well rounded	total particles counted
SY-C1	5	21	76	112	101	39	354
SY-C1A	0	1	12	20	33	10	76
SY-C1B	0	2	10	34	28	21	95
SY-C1C	0	3	15	28	31	5	82
SY-C1D	5	15	39	30	9	3	101
SY-C2	1	14	62	118	76	45	316
SY-C2A	1	5	27	60	23	13	129
SY-C2B	0	0	10	20	36	25	91
SY-C2C	0	9	25	38	17	7	96
SY-C2D	*na*	*na*	*na*	*na*	*na*	*na*	*na*
SY-C3	363	110	26	6	1	0	506
SY-C3A	*na*	*na*	*na*	*na*	*na*	*na*	*na*
SY-C3B	92	62	13	0	0	0	167
SY-C3C	102	27	11	6	1	0	147
SY-C3D	69	21	2	0	0	0	92

Table A6.3. Roundness index on samples of microdebitage from experimental engravings.

Sample	very angular	angular	sub-angular	sub-rounded	rounded	well rounded	total particles counted
BH-E1	226	107	34	11	10	5	393
BH-E1A	59	14	8	0	1	0	82
BH-E1B	41	29	6	2	0	0	78
BH-E1C	54	45	13	3	2	1	118
BH-E1D	72	19	7	6	7	4	115
BH-E2	284	109	39	27	6	1	466
BH-E2A	50	17	10	4	1	0	82
BH-E2B	92	33	12	9	1	0	147
BH-E2C	57	36	9	6	0	0	108
BH-E2D	85	23	8	8	4	1	129
BH-E3	268	148	56	30	8	1	511
BH-E3A	41	21	12	4	4	0	82
BH-E3B	106	54	19	9	0	0	188
BH-E3C	61	41	14	8	2	0	126
BH-E3D	60	32	11	9	2	1	115

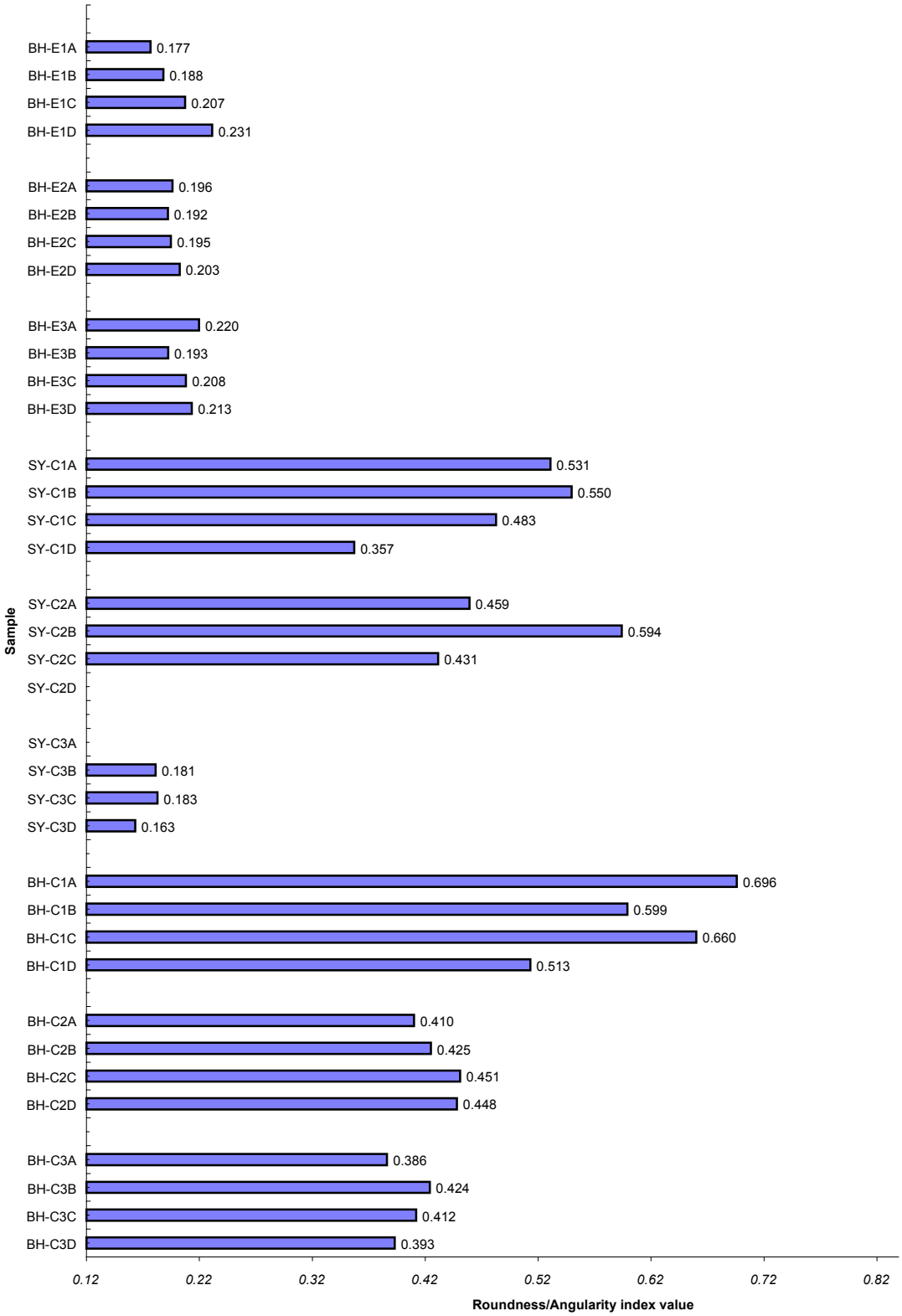
Table A6.4. Roundness index calculations of the mean value of samples.

Sample	0.145	0.210	0.300	0.420	0.595	0.850	total particles	0.145	0.210	0.300	0.420	0.595	0.850							Mean
BH-E1	226	107	34	11	10	5	393	57.51	27.23	8.65	2.80	2.54	1.27	0.08	0.06	0.03	0.01	0.02	0.01	0.204
BH-E1A	59	14	8	0	1	0	82	71.95	17.07	9.76	0.00	1.22	0.00	0.10	0.04	0.03	0.00	0.01	0.00	0.177
BH-E1B	41	29	6	2	0	0	78	52.56	37.18	7.69	2.56	0.00	0.00	0.08	0.08	0.02	0.01	0.00	0.00	0.188
BH-E1C	54	45	13	3	2	1	118	45.76	38.14	11.02	2.54	1.69	0.85	0.07	0.08	0.03	0.01	0.01	0.01	0.207
BH-E1D	72	19	7	6	7	4	115	62.61	16.52	6.09	5.22	6.09	3.48	0.09	0.03	0.02	0.02	0.04	0.03	0.231
BH-E2	284	109	39	27	6	1	466	60.94	23.39	8.37	5.79	1.29	0.21	0.09	0.05	0.03	0.02	0.01	0.00	0.196
BH-E2A	50	17	10	4	1	0	82	60.98	20.73	12.20	4.88	1.22	0.00	0.09	0.04	0.04	0.02	0.01	0.00	0.196
BH-E2B	92	33	12	9	1	0	147	62.59	22.45	8.16	6.12	0.68	0.00	0.09	0.05	0.02	0.03	0.00	0.00	0.192
BH-E2C	57	36	9	6	0	0	108	52.78	33.33	8.33	5.56	0.00	0.00	0.08	0.07	0.03	0.02	0.00	0.00	0.195
BH-E2D	85	23	8	8	4	1	129	65.89	17.83	6.20	6.20	3.10	0.78	0.10	0.04	0.02	0.03	0.02	0.01	0.203
BH-E3	268	148	56	30	8	1	511	52.45	28.96	10.96	5.87	1.57	0.20	0.08	0.06	0.03	0.02	0.01	0.00	0.205
BH-E3A	41	21	12	4	4	0	82	50.00	25.61	14.63	4.88	4.88	0.00	0.07	0.05	0.04	0.02	0.03	0.00	0.220
BH-E3B	106	54	19	9	0	0	188	56.38	28.72	10.11	4.79	0.00	0.00	0.08	0.06	0.03	0.02	0.00	0.00	0.193
BH-E3C	61	41	14	8	2	0	126	48.41	32.54	11.11	6.35	1.59	0.00	0.07	0.07	0.03	0.03	0.01	0.00	0.208
BH-E3D	60	32	11	9	2	1	115	52.17	27.83	9.57	7.83	1.74	0.87	0.08	0.06	0.03	0.03	0.01	0.01	0.213
SY-C1	5	21	76	112	101	39	354	1.41	5.93	21.47	31.64	28.53	11.02	0.00	0.01	0.06	0.13	0.17	0.09	0.475
SY-C1A	0	1	12	20	33	10	76	0.00	1.32	15.79	26.32	43.42	13.16	0.00	0.00	0.05	0.11	0.26	0.11	0.531
SY-C1B	0	2	10	34	28	21	95	0.00	2.11	10.53	35.79	29.47	22.11	0.00	0.00	0.03	0.15	0.18	0.19	0.550
SY-C1C	0	3	15	28	31	5	82	0.00	3.66	18.29	34.15	37.80	6.10	0.00	0.01	0.05	0.14	0.22	0.05	0.483
SY-C1D	5	15	39	30	9	3	101	4.95	14.85	38.61	29.70	8.91	2.97	0.01	0.03	0.12	0.12	0.05	0.03	0.357
SY-C2	1	14	62	118	76	45	316	0.32	4.43	19.62	37.34	24.05	14.24	0.00	0.01	0.06	0.16	0.14	0.12	0.490
SY-C2A	1	5	27	60	23	13	129	0.78	3.88	20.93	46.51	17.83	10.08	0.00	0.01	0.06	0.20	0.11	0.09	0.459
SY-C2B	0	0	10	20	36	25	91	0.00	0.00	10.99	21.98	39.56	27.47	0.00	0.00	0.03	0.09	0.24	0.23	0.594
SY-C2C	0	9	25	38	17	7	96	0.00	9.38	26.04	39.58	17.71	7.29	0.00	0.02	0.08	0.17	0.11	0.06	0.431
SY-C2D	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.000*

Table A6.4. Roundness index calculations of the mean value of samples

Sample	0.145	0.210	0.300	0.420	0.595	0.850	total particles	0.145	0.210	0.300	0.420	0.595	0.850							Mean
SY-C3	363	110	26	6	1	0	506	71.74	21.74	5.14	1.19	0.20	0.00	0.10	0.05	0.02	0.00	0.00	0.00	0.171
SY-C3A	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.000*
SY-C3B	92	62	13	0	0	0	167	55.09	37.13	7.78	0.00	0.00	0.00	0.08	0.08	0.02	0.00	0.00	0.00	0.181
SY-C3C	102	27	11	6	1	0	147	69.39	18.37	7.48	4.08	0.68	0.00	0.10	0.04	0.02	0.02	0.00	0.00	0.183
SY-C3D	69	21	2	0	0	0	92	75.00	22.83	2.17	0.00	0.00	0.00	0.11	0.05	0.01	0.00	0.00	0.00	0.163
BH-C1	0	13	60	367	92	13	545	0.00	2.39	11.01	67.34	16.88	2.39	0.00	0.01	0.03	0.28	0.10	0.02	0.442
BH-C1A	0	3	31	72	27	1	134	0.00	2.24	23.13	53.73	20.15	0.75	0.00	0.00	0.07	0.23	0.12	0.01	0.426
BH-C1B	0	3	15	75	17	0	110	0.00	2.73	13.64	68.18	15.45	0.00	0.00	0.01	0.04	0.29	0.09	0.00	0.425
BH-C1C	0	1	10	126	28	6	171	0.00	0.58	5.85	73.68	16.37	3.51	0.00	0.00	0.02	0.31	0.10	0.03	0.455
BH-C1D	0	6	4	94	20	6	130	0.00	4.62	3.08	72.31	15.38	4.62	0.00	0.01	0.01	0.30	0.09	0.04	0.453
BH-C2	4	21	42	398	64	16	545	0.73	3.85	7.71	73.03	11.74	2.94	0.00	0.01	0.02	0.31	0.07	0.02	0.434
BH-C2A	1	6	13	102	8	1	131	0.76	4.58	9.92	77.86	6.11	0.76	0.00	0.01	0.03	0.33	0.04	0.01	0.410
BH-C2B	0	7	13	100	19	1	140	0.00	5.00	9.29	71.43	13.57	0.71	0.00	0.01	0.03	0.30	0.08	0.01	0.425
BH-C2C	1	4	6	100	17	7	135	0.74	2.96	4.44	74.07	12.59	5.19	0.00	0.01	0.01	0.31	0.07	0.04	0.451
BH-C2D	85	23	8	8	4	1	129	65.89	17.83	6.20	6.20	3.10	0.78	0.10	0.04	0.02	0.03	0.02	0.01	0.203
BH-C3	1	60	64	426	45	8	604	0.17	9.93	10.60	70.53	7.45	1.32	0.00	0.02	0.03	0.30	0.04	0.01	0.405
BH-E3A	1	16	12	94	4	0	127	0.79	12.60	9.45	74.02	3.15	0.00	0.00	0.03	0.03	0.31	0.02	0.00	0.386
BH-C3B	0	6	11	117	11	3	148	0.00	4.05	7.43	79.05	7.43	2.03	0.00	0.01	0.02	0.33	0.04	0.02	0.424
BH-C3C	0	8	21	131	14	1	175	0.00	4.57	12.00	74.86	8.00	0.57	0.00	0.01	0.04	0.31	0.05	0.00	0.412
BH-C3D	0	30	20	84	16	4	154	0.00	19.48	12.99	54.55	10.39	2.60	0.00	0.04	0.04	0.23	0.06	0.02	0.393

In table A6.4, the mean index value was determined by calculating the "percentage of total sample in each roundness class, multiply this percentage by the class midpoint and sum values obtained. From this summed value, obtain mean roundness value " (Briggs, 1977: 118).



Graph A6.1 Mean roundness index value for all the samples.

Blind Test

Table A6.5. Blind test microdebitage counts of sample BTA1.

BT-A1	Possible	Probable	Microdebitage	DATE
1	2	7	32	31-Mar-98
2	2	5	36	31-Mar-98
3	2	3	17	06-May-98
4	2	3	11	16-Jun-98
5	6	5	32	30-Mar-98
6	3	3	16	19-May-98
7	3	2	23	19-May-98
8	6	5	22	31-Mar-98
9	3	2	6	16-Jul-98
10	3	4	14	19-May-98
11	6	5	22	31-Mar-98
12	4	5	11	04-May-98
13	5	3	30	06-May-98
14	4	3	16	06-May-98
15	6	3	13	26-Mar-98
16	3	3	16	06-May-98
17	3	1	13	01-Jun-98
18	3	2	14	28-Jul-98
19	2	1	10	27-May-98
20	5	2	16	06-May-98
21	2	3	19	06-May-98
22	1	1	12	16-Jun-98
23	2	3	12	19-May-98
24	3	3	14	06-May-98
25	4	2	18	19-May-98
26	2	3	11	19-May-98
27	3	3	22	06-May-98
28	4	3	14	06-May-98
29	5	4	11	28-Apr-98
30	2	3	10	27-May-98
31	2	3	9	27-May-98
32	2	3	9	27-May-98
33	3	2	10	09-Jun-98
Total	108	103	541	

Table A6.6. Blind test microdebitage counts of sample BTB1.

BT-B1	Possible	Probable	Microdebitage	DATE
1	6	4	24	28-Apr-98
2	2	3	21	28-Jul-98
3	3	3	18	29-Jul-98
4	3	4	11	29-Jul-98
5	1	3	14	29-Jul-98
6	2	3	20	29-Jul-98
7	1	2	13	29-Jul-98
8	3	2	15	29-Jul-98
9	3	4	14	03-Aug-98
10	1	2	11	03-Aug-98
11	3	3	16	03-Aug-98
12	2	4	10	03-Aug-98
13	3	3	6	03-Aug-98
14	2	4	12	03-Aug-98
15	1	2	5	03-Aug-98
16	3	3	6	03-Aug-98
17	1	1	6	03-Aug-98
18	1	3	7	03-Aug-98
19	2	3	8	10-Aug-98
20	3	2	10	10-Aug-98
21	2	1	8	10-Aug-98
22	3	3	8	10-Aug-98
23	2	4	8	10-Aug-98
24	2	2	7	10-Aug-98
25	1	2	6	10-Aug-98
26	3	3	9	11-Aug-98
27	3	3	4	11-Aug-98
28	2	3	5	11-Aug-98
29	3	1	4	11-Aug-98
30	2	2	5	11-Aug-98
31	1	3	9	11-Aug-98
32	2	2	8	11-Aug-98
33	2	1	7	11-Aug-98
34	3	3	7	11-Aug-98
Total	77	91	342	

Table A6.7. Blind test microdebitage counts of sample BTC1.

BT-C1	Possible	Probable	Microdebitage	DATE
1	5	4	14	28-Apr-98
2	2	3	16	29-Jul-98
3	2	3	10	04-Aug-98
4	2	4	12	04-Aug-98
5	1	1	5	04-Aug-98
6	3	3	7	04-Aug-98
7	2	3	6	04-Aug-98
8	3	2	10	04-Aug-98
9	2	2	5	04-Aug-98
10	4	3	10	04-Aug-98
11	1	2	5	04-Aug-98
12	3	2	8	04-Aug-98
13	3	3	4	05-Aug-98
14	3	2	3	05-Aug-98
15	2	2	4	05-Aug-98
16	2	3	4	05-Aug-98
17	3	2	5	05-Aug-98
18	1	1	2	05-Aug-98
19	2	3	5	05-Aug-98
20	2	1	4	05-Aug-98
21	1	1	3	05-Aug-98
22	3	3	3	05-Aug-98
23	2	2	5	05-Aug-98
24	1	2	2	05-Aug-98
25	1	2	2	05-Aug-98
26	2	3	4	10-Aug-98
27	1	1	4	10-Aug-98
28	3	3	4	10-Aug-98
29	2	2	2	10-Aug-98
30	1	2	4	10-Aug-98
31	2	3	3	10-Aug-98
32	3	2	3	10-Aug-98
Total	70	75	178	

Table A6.8. Blind test microdebitage counts of sample BTD1.

BT-D1	Possible	Probable	Microdebitage	DATE
1	4	3	7	04-Apr-98
2	3	2	13	23-Jun-98
3	2	1	5	23-Jun-98
4	1	2	6	23-Jun-98
5	2	2	6	23-Jun-98
6	2	3	9	23-Jun-98
7	2	2	6	23-Jun-98
8	2	2	9	06-Jul-98
9	2	3	4	06-Jul-98
10	1	2	3	06-Jul-98
11	2	3	6	06-Jul-98
12	1	2	7	06-Jul-98
13	4	5	12	07-Jul-98
14	2	1	5	07-Jul-98
15	2	3	7	07-Jul-98
16	1	1	4	22-Jul-98
17	3	3	5	22-Jul-98
18	2	2	7	22-Jul-98
19	2	2	3	22-Jul-98
20	1	1	5	22-Jul-98
21	2	2	5	22-Jul-98
22	3	3	1	22-Jul-98
23	2		1	22-Jul-98
24	1	2	6	22-Jul-98
25	1	2	4	22-Jul-98
26	3	2	8	22-Jul-98
27	3	2	5	22-Jul-98
28	1	3	4	27-Jul-98
29	1	3	5	27-Jul-98
30	2	1	9	27-Jul-98
31	3	3	15	27-Jul-98
32	2	2	4	03-Aug-98
33	3	3	11	23-Jun-98
Total	68	73	207	

Table A6.9. Blind test microdebitage counts of sample BTE1.

BT-E1	Possible	Probable	Microdebitage	DATE
1	4	4	14	04-Jun_98
2	2	3	13	05-Apr-98
3	2	2	9	01-Jun-98
4	2	1	5	13-Jul-98
5	3	2	17	16-Jun-98
6	2	3	6	13-Jul-98
7	2	2	12	09-Jun-98
8	5	3	14	05-Mar-98
9	2	1	13	05-Mar-98
10	1	2	6	01-Jun-98
11	3	4	19	05-Mar-98
12	1	2	12	22-Jun-98
13	3	2	13	26-Mar-98
14	2	3	14	27-Apr-98
15	4	4	15	26-Mar-98
16	1	2	4	4-May-98
17	2	0	7	09-Jun-98
18	1	1	6	09-Jun-98
19	2	5	21	4-May-98
20	4	3	8	4-May-98
21	2	2	19	27-Jul-98
22	1	2	12	27-Jul-98
23	3	3	21	4-May-98
24	1	2	16	27-Jul-98
25	1	1	8	27-Jul-98
26	3	2	6	28-Jul-98
27	2	1	10	28-Jul-98
28	2	3	16	28-Jul-98
29	1	1	9	28-Jul-98
30	2	2	5	28-Jul-98
31	2	3	7	28-Jul-98
32	1	2	6	28-Jul-98
33	1	3	12	28-Jul-98
34	2	2	9	28-Jul-98
Total	72	78	384	

Table A6.10. Blind test microdebitage counts of sample BTA2.

BT-A2	Possible	Probable	Microdebitage	DATE
1	4	3	36	30-Mar-98
2	4	5	44	05-Apr-98
3	5	5	20	27-Apr-98
4	6	7	36	5-May-98
5	4	5	31	5-May-98
6	4	3	19	16-Jun-98
7	9	6	37	30-Mar-98
8	5	6	33	09-Apr-98
Total	41	40	256	

Table A6.11. Blind test microdebitage counts of sample BTB2.

BT-B2	Possible	Probable	Microdebitage	DATE
1	3	3	73	28-Apr-98
2	11	9	147	18-Mar-98
3	4	6	83	31-Mar-98
4	9	11	103	31-Mar-98
5	6	8	36	4-May-98
6	4	5	43	16-Jun-98
7	5	6	75	06-Apr-98
8	5	7	32	26-Apr-98
Total	47	55	592	

Table A6.12. Blind test microdebitage counts of sample BTC2.

BT-C2	Possible	Probable	Microdebitage	DATE
1	8	6	54	27-Apr-98
2	5	6	36	04-Mar-98
3	6	5	28	04-Mar-98
4	4	4	4	22-Jul-98
5	4	4	14	16-Jun-98
6	2	2	5	22-Jun-98
7	5	5	46	09-Jun-98
8	5	6	36	08-Jun-98
Total	39	38	223	

Table A6.13. Blind test microdebitage counts of sample BTD2.

BT-D2	Possible	Probable	Microdebitage	DATE
1	6	7	41	26-Apr-98
2	5	8	28	26-Apr-98
3	5	6	91	26-Mar-98
4	7	4	50	26-Mar-98
5	3	2	2	22-Jun-98
6	1	2	30	22-Jun-98
7	3	3	18	22-Jun-98
8	3	3	14	9-Jun-98
Total	33	35	274	

Table A6.14. Blind test microdebitage counts of sample BTE2.

BT-E2	Possible	Probable	Microdebitage	DATE
1	6	4	19	28-Apr-98
2	5	4	28	23-Apr-98
3	9	10	29	6-Apr-98
4	6	8	19	27-Apr-98
5	6	4	18	28-Apr-98
6	4	9	25	28-Apr-98
7	4	5	24	26-Apr-98
Total	40	44	162	

Table A6.15. Blind test microdebitage counts of sample BTA3.

BT-A3	Possible	Probable	Microdebitage	DATE
1	8	10	96	20-Jan-98

Table A6.16. Blind test microdebitage counts of sample BTB3.

BT-B3	Possible	Probable	Microdebitage	DATE
1	19	18	219	19-Jan-98

Table A6.17. Blind test microdebitage counts of sample BTC3.

BT-C3	Possible	Probable	Microdebitage	DATE
1	12	12	254	8-Apr-98

Table A6.18. Blind test microdebitage counts of sample BTD3.

BT-D3	Possible	Probable	Microdebitage	DATE
1	13	13	165	19-Jan-98

Table A6.19. Blind test microdebitage counts of sample BTE3.

BT-E3	Possible	Probable	Microdebitage	DATE
1	12	10	93	19-Jan-98

Blind test revision

Table A6.20. Revision of microdebitage counts of samples BTA1-BTE1.

Sample	Possible	Probable	Microdebitage	DATE
BTA1/5	1	1	3	5/3/99
BTA1/3	0	1	3	5/3/99
BTA1/1	1	2	6	5/3/99
BTA1/15	2	1	3	5/3/99
BTA1/8	1	0	2	30/3/99
Total	4	5	15	
BTB1/24	1	0	2	5/3/99
BTB1/28	1	1	1	24/5/99
BTB1/26	2	1	0	24/5/99
BTB1/25	2	0	1	24/5/99
BTB1/23	2	1	1	24/5/99
Total	8	3	5	
BTC1/21	0	1	4	22/1/99
BTC1/4	2	1	4	25/3/99
BTC1/30	1	1	4	24/5/99
BTC1/18	0	1	2	24/5/99
BTC1/3	2	1	8	24/5/99
Total	5	5	22	
BTD1/4	2	1	5	22/1/99
BTD1/7	1	1	1	22/1/99
BTD1/9	1	2	4	22/1/99
BTD1/11	2	1	4	22/1/99
BTD1/12	0	0	3	22/1/99
Total	6	5	17	
BTE1/1	1	1	3	24/5/99
BTE1/15	2	2	7	6/5/99
BTE1/20	2	1	5	6/5/99
BTE1/5	1	1	6	6/5/99
BTE1/13	2	2	5	6/5/99
Total	8	7	26	

Table A6.21. Revision of microdebitage counts of samples BTA2-BTE2.

Sample	Possible	Probable	Microdebitage	Date
BTA2/5	6	4	21	3/3/99
BTA2/2	3	3	23	23/3/99
BTA2/1	4	3	32	23/3/99
Total	13	10	76	
BTB2/4	3	3	13	25/3/99
BTB2/2	3	4	14	30/3/99
BTB2/3	4	3	13	30/3/99
Total	10	10	40	
BTC2/2	7	6	59	16/2/99
BTC2/4	5	5	38	24/5/99
BTC2/1	3	4	52	24/5/99
Total	15	15	149	
BTD2/2	2	0	0	5/4/99
BTD2/4	1	1	3	5/4/99
BTD2/3	1	0	1	5/4/99
Total	4	1	4	
BTE2/2	6	4	18	12/12/98
BTE2/7	4	3	13	14/12/98
BTE2/3	7	4	15	13/12/98
Total	17	11	46	

Table A6.22. Revision of microdebitage counts of samples BTA3-BTE3.

Sample	Possible	Probable	Microdebitage	Date
BTA3	16	13	104	7/1/99
BTB3	12	14	282	7/1/99
BTC3	12	17	189	7/1/99
BTD3	11	9	138	7/1/99
BTE3	12	5	20	7/1/99

Table A6.23. Revision of microdebitage total counts, all samples.

Sample	Possible	Probable	Microdebitage	Particles placed
BTA3	16	13	104	50p
BTB3	12	14	282	200p
BTC3	12	17	189	150p
BTD3	11	9	138	100p
BTE3	12	5	20	CONTROL
BTA2	34	26	202	150p
BTB2	58	58	106	50p
BTC2	40	40	397	200p
BTD2	11	8	11	CONTROL
BTE2	45	29	122	100p
BTA1	33	33	112	100p
BTB1	54	20	34	CONTROL
BTC1	32	32	141	150p
BTD1	39	33	112	50p
BTE1	54	48	176	200p