

## THE RELATIONSHIP BETWEEN LITHOLOGY, FLAKING PROPERTIES AND ARTEFACT MANUFACTURE FOR AUSTRALIAN SILCRETES\*

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*Mechanical properties of Australian silcrete strongly influenced raw material selection and artefact manufacture. Microcrystalline silcrete, with high compressive and tensile strength, is suitable for blade tools requiring fine retouch. Fine-grained silcrete (high compressive strength but lower tensile strength) was often used for blade-based implements, but is more susceptible to edge fracturing. Medium-grained silcrete has poor flaking properties (low compressive and tensile strength) and was often used for flake manufacture. Thus material determinism can explain much of the variability in silcrete artefact morphology and assemblage composition. Silcrete compressive strength is positively correlated with percentage of microcrystalline matrix and negatively correlated with average grain size, so hand lens examination of a silcrete sample can give a good indication of its likely flaking quality.*

**KEYWORDS:** SILCRETE, MICROSTRUCTURE, FRACTURE MECHANICS, COMPRESSIVE STRENGTH, FLAKING PROPERTIES

### INTRODUCTION

In Australian prehistoric research, there is a strong tradition of material determinism in artefact studies. Raw material differences are often used to explain variability in the morphology of lithic artefacts and assemblage composition, and particular lithologies have been related to particular manufacturing techniques and artefact types (e.g., O'Connell 1977; White and O'Connell 1982; Hiscock 1986; Draper 1987; Holdaway 1995; Hayden 1998; Mulvaney and Kamminga 1999; Holdaway and Stern 2004; Shiner *et al.* 2007). This reflects the fact that a stone knapper with access to materials of differing flaking properties will inevitably select the better-quality material for the manufacture of morphologically more complex and technologically more demanding tools (Mellars 1996, 137). As a result, an understanding of how artefact lithologies break—that is, fracture mechanics—constitutes the heart of lithic analysis (Odell 2000). Controlled fracture mechanics experiments (Domanski and Webb 1992, 2000; Domanski *et al.* 1994; Doelman *et al.* 2001) have shown that fracture toughness in particular is an objective measure of raw material quality.

Silcrete is a very widespread artefact lithology in Australia; it is found in lithic assemblages from coast to coast, and is the most common lithic material in the arid and semi-arid zones (White and O'Connell 1982; Mulvaney and Kamminga 1999). Its popularity was probably due partly to its abundance, but must also reflect its flaking properties, which were poorly known. Silcrete therefore offers an ideal opportunity to assess the importance of flaking properties in raw material choice, in particular because there are several different types of silcrete that are

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likely to vary substantially in properties such as fracture toughness. Consequently, this paper defines in detail the mechanical properties of silcrete from five prehistoric quarries scattered across the Australian continent, and relates these properties to flaking quality and its influence on stone tool manufacture and maintenance, as shown by the composition of stone tool assemblages near the quarries. The relationship between the microscopic structure of silcrete and its flaking properties is also examined.

#### FRACTURE MECHANICS

To understand the flaking properties of silcrete, it is necessary to consider the mechanics of fracture propagation in artefact materials.

In homogeneous, isotropic, fine-grained siliceous lithologies, normally favoured for the manufacture of stone tools by flaking, the direction of flake detachment is determined only by the stress distribution during the flaking event, and is controlled by a stoneknapper through the location, magnitude and angle of the force applied (Faulkner 1972; Cotterell and Kamminga 1987). The fracture zone at the crack tip is small and the fracture surface is smooth and conchoidal, and forms a feather fracture termination (Cotterell and Kamminga 1987; Whittaker *et al.* 1992). The direction of the fracture path is determined by the stiffness of the developing flake; long, thin, parallel-sided flakes can be detached from an isotropic blade core (Cotterell *et al.* 1985; Cotterell and Kamminga 1987). If the flaking face is flattish the fracture will diffuse outwards, but a median ridge on the flaking face will prevent this and guide the fracture over a considerable distance (Faulkner 1972).

The resistance to fracture propagation is determined by the atomic/molecular bonding energy along the fracture path. The quartz silicon – oxygen bond is very strong; weaker impurities such as clay, iron oxide and organic matter will generally decrease the compressive strength, and also cause the fracture surface to be rougher (Lawn and Wilshaw 1975; Whittaker *et al.* 1992). However, small isolated particles of weaker impurities within a uniform microcrystalline groundmass do not have a significant effect on the compressive strength because they blunt, rather than assist, microcrack growth (Atkinson and Meredith 1987; Domanski *et al.* 1994).

In coarser-grained siliceous materials, the main fracture propagates both as transgranular (cleavage) and intergranular (grain boundary) cracks (Mardon *et al.* 1990; Whittaker *et al.* 1992). Intergranular fracturing consumes less energy, because external surface atoms are not bonded to the maximum number of nearest neighbours (Faulkner 1972; Davidge 1979). There is natural barrier to both intergranular and cleavage crack propagation at a grain boundary, because the crack needs to either change direction along a new grain boundary or nucleate a new cleavage crack in the next grain. Fine-grained materials, which fracture predominantly along grain boundaries, are stronger than coarse-grained lithologies of the same composition, in which fracturing is predominantly transgranular (Davidge 1979; Mardon *et al.* 1990). Coarser-grained lithologies are made even weaker by the often greater concentration of impurities and strain energy at the larger grain boundaries, decreasing the grain boundary fracture energy (Davidge 1974).

Defects such as large quartz grains (e.g., 2 mm across) will make the fracture path unstable, often causing an abrupt change in the direction of fracture and resulting in step and hinge fracture terminations, particularly during removal of smaller flakes a few millimetres wide (Cotterell and Kamminga 1987; Hiscock 1993). In general, the high frequency of step fracture terminations in coarser granular materials makes them unsuitable for detachment of narrow flakes and sharpening of working edges (Kuhn 1990).

## SILCRETE

Silcretes are strongly indurated siliceous materials resulting from low-temperature surface or near-surface silicification of weathered bedrock, regolith and/or unconsolidated sediments; they are not produced by metamorphic, igneous or moderate-to-deep burial diagenetic processes (Nash and Ulliyott in press). Silcretes are very resistant to weathering, so as a result they frequently outcrop prominently as low cliff lines. Chemically and mineralogically, silcretes are comparatively simple materials, as they are highly siliceous (>95% silica in most samples) and composed predominantly of quartz. A content of 85% silica provides an arbitrary lower limit (Summerfield 1983).

Flint and chert (of marine or replacement origin), metamorphic quartzite and silicified sandstone not formed near the ground surface should not be confused with silcrete, although mistakes of interpretation have been made in the archaeological literature (e.g., Sullivan and Simmons 1979). Silcrete may not be easily distinguishable from other siliceous rocks without careful examination of the associated field evidence; *in situ* silcrete invariably occurs as near-surface layers or blocks. Re-evaluation of some Australian and American siliceous artefact materials initially identified as 'silicified sediment', 'orthoquartzite' or 'quartzite' has identified them as silcrete (e.g., Finlayson and Webb in press).

Silcrete contains both a detrital component inherited from the host material (dominated by quartz with minor heavy minerals) and secondary silica precipitated during silcrete formation (dominated by quartz with generally minor chalcedony and/or opal; Nash and Ulliyott in press).

Silcrete micromorphology is very variable, largely reflecting the grain size of the host material (from mud to gravel). Summerfield (1983) recognized four silcrete types based on microfabric: grain-supported, floating (>5% skeletal grains floating in a matrix), matrix (<5% skeletal grains) and conglomeratic (containing pebbles >4 mm across). For archaeological use, a simpler grain-size classification that does not require thin-section examination has been proposed: microcrystalline, fine-grained and medium-grained silcrete (Doelman *et al.* 2001; Holdaway *et al.* 2004, 2006). Microcrystalline silcrete consists of an extremely fine-grained quartz matrix with scattered silt-sized quartz clasts; it has a matrix or floating silcrete microfabric, and there are almost no visible grains in hand specimen. Fine- and medium-grained silcrete comprise, respectively, dominantly fine-sand-sized (<0.25 mm) and medium-sand-sized (0.25–0.5 mm) quartz clasts, surrounded by either a matrix of microcrystalline quartz or quartz/chalcedony cement; the sand grains are easily visible in hand specimen. Medium-grained silcrete is typically grain-supported; fine-grained silcrete may have a grain-supported or floating microfabric. Coarser-grained varieties of silcrete also occur—for example, containing coarse-sand-sized (>0.5 mm) and/or pebbly clasts—but these were rarely used as artefact materials.

Silcrete has been reported from all continents except Antarctica. It is most widespread in Australia, but is also common in southern Africa and Europe, particularly England and France (Nash and Ulliyott in press).

## SILCRETE IN AUSTRALIA

Silcretes occur scattered across a large part of the Australian continent (Stephens 1971; Young 1985); two distinct geographical associations have been differentiated: inland and eastern (Webb and Golding 1998).

The inland silcretes occur extensively through the central arid regions of Australia (Wopfner 1978; Webb and Golding 1998). They have been subdivided into pedogenic and groundwater types (Nash and Ulliyott in press). Pedogenic silcretes occur usually as surface or near-surface layers 0.5–2.0 m thick outcropping as low cliff lines around the edges of mesas and cuestas, and are characterized by irregular bases that merge with the underlying sediments. These silcretes comprise nodular, columnar and/or massive layers that are the product of precipitation within the soil profile. By contrast, groundwater silcretes are massive with sharp upper and lower boundaries, and lack pedogenic features such as nodules and columns. These silcretes are less common and generally occur topographically lower in the landscape. They probably reflect silicification at the water table.

Eastern silcretes are common in the more humid parts of Australia east of the Great Dividing Range, from Tasmania to north Queensland (Young 1985; Webb *et al.* 1994). They resemble the inland groundwater silcretes and lack pedogenic features. They generally show a close spatial relationship to basalts, and are commonly known as ‘sub-basaltic’ silcretes; they may be genetically related to the basalts (Webb and Golding 1998).

In the Australian archaeological record, silcrete is found in lithic assemblages over large areas of the continent, reflecting its availability (White and O’Connell 1982; Mulvaney and Kamminga 1999). In western New South Wales, where much of the plains are covered in silcrete gravels (‘gibber’), silcrete is probably the most common material used for flaked artefacts (Allen 1998; Hiscock and Allen 2000; Doelman *et al.* 2001; Shiner *et al.* 2005; Holdaway *et al.* 2006).

## METHODOLOGY

### *Silcrete samples*

The most common silcrete types used for artefacts in Australia (microcrystalline, fine-grained and medium-grained) were sampled from five well-known prehistoric quarries that span both inland and eastern silcretes (Fig. 1) and are associated with nearby lithic assemblages. Thin sections of the silcretes were described in detail (Table 1); percentages of different components were estimated using the point counting technique (Harwood 1988).

It is difficult to compare the silcrete samples examined in this study with many published descriptions of artefact silcrete, because terminology is frequently inconsistent and records in the archaeological literature often lack petrological details, even those that can be readily discerned using a hand lens; for example, average clast size (if present) and the percentage of matrix and/or cement.

### *Mechanical testing*

Altogether, 22 different samples and 502 individual specimens from the five quarries (Fig. 1) were tested for mechanical properties (Young’s modulus, compressive strength, tensile strength and fracture toughness) and assessed for macroscopic uniformity. All tests were carried out on cylinders 15 mm in diameter; the length varied according to the test (36 mm, Young’s modulus and compressive strength; 7.5 mm, tensile strength; 21.75 mm, fracture toughness). Details of procedures are given in Domanski *et al.* (1994, 185–9).

Young’s modulus (also called the modulus of elasticity) is a measure of the resistance of a solid to being deformed by a load. The present study showed that this property shows little



Figure 1 The locations of the silcrete quarries.

variation among different rock types (see Tables 2 and 3 below), and consequently it will not be discussed further.

Compressive strength is a measure of a material's resistance to failure under compressive loading, and is an important measure of a material's stiffness; that is, the compressive and bending stress component of stiffness-controlled fracture propagation in the process of flake detachment from a core. Compressive strength tests are very sensitive to microstructural defects (Domanski *et al.* 1994).

Tensile strength is a measure of a material's resistance to failure under tensile loading, and was measured in the present study by the simple and reliable Brazilian test (Domanski *et al.* 1994). In this test the tensile fracture initiates from a pre-existing micro-flaw and propagates until the specimen fails, so the tensile strength is the energy required for the fracture initiation and propagation.

Fracture toughness is a measure of the resistance of a material to (catastrophic) fracture propagation (Lawn and Wilshaw 1975); it is an important measure of stiffness-controlled fracture propagation, but does not directly measure stiffness. In the present study, the accurate and precise short rod chevron notch fracture toughness test was used (Whittaker *et al.* 1992; Domanski *et al.* 1994). In this test the fracture propagates from a well-developed crack until

Table 1 *Silcrete petrology*

Sample number	Collection locality	Texture	Percentage of silica	Percentage of matrix	Percentage of cement	Percentage of voids	Matrix (mm)	Grain size		
								Quartz clasts		
								Minimum (mm)	Maximum (mm)	Average (mm)
193	Lake Mungo quarry	Medium-grained	78.0	49.6	0	0	<0.002	0.008	1.000	0.280
194	Lake Mungo quarry	Medium-grained	96.0	50.0	0	0	<0.002	0.006	1.200	0.250
195	Lake Mungo quarry	Medium-grained	95.0	51.3	0	0	<0.002	0.008	1.200	0.280
196	Lake Mungo quarry	Medium-grained	85.0	55.3	0	0	<0.002	0.006	1.900	0.320
197	Lake Mungo quarry	Fine- to medium-grained	91.0	53.3	0	0	<0.002	0.006	0.760	0.224
357	Olive Downs quarry	Microcrystalline	97.0	95.6	0	0	<0.002	0.008	0.060	0.024
358	Olive Downs quarry	Microcrystalline	97.3	95.3	0	0	<0.002	0.008	0.080	0.024
358**	Olive Downs quarry	Microcrystalline	95.9	93.6	0	0	<0.002	0.008	0.260	0.024
358*	Olive Downs quarry	Microcrystalline	77.9	91.6	0	0	<0.002	0.008	0.400	0.028
359	Olive Downs quarry	Microcrystalline	80.3	92.6	0	0	<0.002	0.010	0.260	0.016
359**	Olive Downs quarry	Microcrystalline	63.3	96.6	0	0	<0.002	0.006	1.900	0.024
370	Olive Downs quarry	Microcrystalline	96.2	97.2	0	0	<0.002	0.006	0.600	0.024
371	Olive Downs quarry	Microcrystalline	45.7	95.3	0	0	<0.002	0.006	0.600	0.024
365	Gorge quarry	Very fine-grained	99.0	49.5	0	0	<0.002	0.008	1.800	0.480
360	Gorge quarry	Medium-grained	99.0	49.5	0	0	<0.002	0.008	1.800	0.480
361	Gorge quarry	Medium-grained	99.3	55.3	0	0	<0.002	0.008	1.500	0.400
362	Gorge quarry	Medium-grained	98.3	55.3	0	0	<0.002	0.008	1.100	0.480
364	Gorge quarry	Medium-grained	97.3	55.6	0	0	<0.002	0.016	0.900	0.460
366	Gorge quarry	Medium-grained	97.6	56.6	0	0	<0.002	0.012	1.400	0.500
229	Kenniff Cave quarry	Fine-grained	98.6	0	5.9	2.3	<0.002	0.016	0.380	0.112
230	Kenniff Cave quarry	Fine-grained	97.2	0.6	14.3	0.6	<0.002	0.012	0.540	0.144
231	Kenniff Cave quarry	Fine-grained	95.9	0	4.6	3.0	<0.002	0.012	0.460	0.144
155	Green Gully quarry	Medium-grained	86.6	29.6	0	0	<0.002	0.012	2.640	0.260
156	Green Gully quarry	Medium-grained	95.0	34.3	0	0	<0.002	0.016	2.280	0.320
157	Green Gully quarry	Medium-grained	93.3	34.0	0	0	<0.002	0.012	3.100	0.300

Table 2 Mechanical properties of medium-grained silcrete. The average from a series of tests is presented as the median. The variability about the median presented as 95% uncertainties was calculated using the non-parametric asymmetric method of Rock et al. (1987)

Sample number	Collection locality	Texture	Modulus of elasticity (MPa)		Compressive strength (MPa)		Tensile strength (MPa)		Fracture toughness (MPa.mm <sup>1/2</sup> )			Ranking of uniformity
			No. of specimens	Median and 95% uncertainty	No. of specimens	Median and 95% uncertainty	No. of specimens	Median and 95% uncertainty	No. of specimens tested	No. of tests valid	Median and 95% uncertainty	
193	Lake Mungo quarry	Medium-grained	4	58 313 +938 -4 722	4	561.83 +122.35 -188.68	Untested		10	10	85.90 +9.02 -2.06	5
194	Lake Mungo quarry	Medium-grained	7	53 029 +3 022 -3 506	7	505.51 +237.92 -226.94	Untested		12	9	77.18 +3.12 24.05	6
195	Lake Mungo quarry	Medium-grained	7	58 049 +2 625 -11 419	7	496.36 +393.51 -273.84	Untested		15	12	85.99 +6.16 -3.80	5
196	Lake Mungo quarry	Medium-grained	29	57 878 +584 -652	10	512.33 +111.47 -205.99	12	49.70 +15.94 -7.54	14	11	80.45 +2.79 -2.19	8
196*	Lake Mungo quarry	Medium-grained		Untested		Untested	Untested		11	4	32.61 +12.62 -17.91	8
197	Lake Mungo quarry	Fine- to medium-grained	6	57 535 +3 394 -5 345	6	584.33 +36.28 -169.70	Untested		14	14	85.50 +1.85 -1.10	5
360	Gorge quarry	Medium-grained		Untested		Untested	Untested		15	13	51.08 +2.77 -4.60	5
361	Gorge quarry	Medium-grained		Untested		Untested	Untested		15	12	81.79 +7.76 -1.86	2
362	Gorge quarry	Medium-grained		Untested		Untested	Untested		13	12	66.10 +14.84 -3.77	5

Table 2 (Continued)

Sample number	Collection locality	Texture	Modulus of elasticity (MPa)		Compressive strength (MPa)		Tensile strength (MPa)		Fracture toughness (MPa.mm <sup>1/2</sup> )			Ranking of uniformity	
			No. of specimens	Median and 95% uncertainty	No. of specimens	Median and 95% uncertainty	No. of specimens	Median and 95% uncertainty	No. of specimens tested	No. of tests valid	Median and 95% uncertainty		
364	Gorge quarry	Medium-grained		Untested		Untested		Untested	12	11	51.74	+0.47 -5.08	1
366	Gorge quarry	Medium-grained		Untested		Untested		Untested	12	11	48.82	+1.98 -2.52	1
155	Green Gully quarry	Medium-grained	3	52 775 +897 -1 366	3	338.34 +39.26 -15.88		Untested	14	10	80.85	+2.94 -3.47	6
156	Green Gully quarry	Medium-grained	34	53 323 +2 490 -1 975	14	350.28 +15.28 -54.15	16	27.77 +10.66 -3.68	18	15	74.59	+4.34 -7.69	2
157	Green Gully quarry	Medium-grained	5	53 704 +1 050 -3 199	12	417.59 +19.35 -106.73		Untested	13	10	76.05	+7.28 -5.66	2

\*, Soft host material.

Table 3 Mechanical properties of microcrystalline and fine-grained silcrete. The average from a series of tests is presented as the median. The variability about the median presented as 95% uncertainties was calculated using the non-parametric asymmetric method of Rock et al. (1987)

Sample number	Collection locality	Texture	Modulus of elasticity (MPa)		Compressive strength (MPa)		Tensile strength (MPa)		Fracture toughness (MPa.mm <sup>1/2</sup> )			Ranking of Uniformity
			No. of specimens	Median and 95% uncertainty	No. of specimens	Median and 95% uncertainty	No. of specimens	Median and 95% uncertainty	No. of specimens tested	No. of tests valid	Median and 95% uncertainty	
357	Olive Downs quarry	Microcrystalline		Untested	5	582.12 +293.67 -205.24		Untested	12	12	67.16 +2.44 -5.36	1
358	Olive Downs quarry	Microcrystalline		Untested	5	862.90 +105.93 -125.15		Untested	13	13	65.27 +6.18 -2.19	2
358**	as above	Microcrystalline		Untested		Untested		Untested	11	11	62.40 +2.28 -14.55	As above
358*	as above	Microcrystalline		Untested		Untested		Untested	7	3	13.67 +7.89 -4.80	As above
359	Olive Downs quarry	Microcrystalline		Untested	5	443.45 +184.86 -44.30		Untested	15	15	53.93 +4.24 -3.03	2
359**	as above	Microcrystalline		Untested		Untested		Untested	8	8	42.64 +5.25 -5.52	As above
370	Olive Downs quarry	Microcrystalline		Untested	3	850.23 +124.97 -276.44		Untested	12	12	67.52 +2.16 -3.89	1
371	Olive Downs quarry	Microcrystalline		Untested		Untested		Untested	15	10	42.70 +6.53 -5.60	5
365	Gorge quarry	Very fine-grained		Untested	5	649.86 +132.43 -74.83		Untested	11	10	86.69 +9.73 -14.66	1
229	Kenniff Cave quarry	Fine-grained	5	54 375 +646 -2 334	5	554.00 +41.88 -177.12	16	39.16 +10.41 -4.24	12	12	47.71 +2.78 -3.39	8
229***	As above	Fine-grained	5	31 305 +2 990 -15 173	5	118.84 +24.33 -66.78	11	7.82 +1.67 -0.95			Untested	As above
230	Kenniff Cave quarry	Fine-grained		Untested		Untested		Untested	6	6	43.55 +6.25 -0.37	1
231	Kenniff Cave quarry	Fine-grained		Untested		Untested		Untested	2	2	49.74	1

\*, Soft host material; \*\*, pinkish material with clay, iron oxide and organic material; \*\*\*, weathered material.

the specimen fractures completely. The fracture toughness is the energy required for the fracture propagation.

The ratio of median compressive strength to median fracture toughness (here called the index of stiffness) was calculated from the test results. This index measures the directional stability of stiffness-controlled fracture propagation in detaching long parallel-sided flakes.

Previous studies on mechanical properties of artefact lithologies have been able to relate the results to the flaking properties of the materials. Glass Buttes obsidian of central Oregon, graded at 1.0 on Callahan's (1979) scale of workability, can be used as a reference material. It has low values of tensile strength (median 39 MPa) and fracture toughness (median 26 MPa.mm<sup>1/2</sup>), high compressive strength (median 745 MPa) and high macroscopic uniformity (Domanski *et al.* 1994, table 5). The low fracture toughness and the low tensile strength indicate that obsidian is very susceptible to edge fracturing in tool use. In comparison, microcrystalline siliceous lithologies such as flint, which were used for the systematic production of blades and demonstrate well-developed stiffness-controlled fracture propagation, have much higher values of fracture toughness and tensile strength, and similar values of compressive strength (more than 500 MPa), and macroscopic uniformity (Domanski and Webb 1992, 2000; Domanski *et al.* 1994; Doelman *et al.* 2001).

#### SILCRETE QUARRIES

Five prehistoric silcrete quarries were sampled: three are in inland pedogenic and groundwater silcrete (Lake Mungo, Olive Downs and Gorge), and two in eastern association (sub-basaltic) silcrete (Kenniff Cave and Green Gully). For each, the site is described, including its archaeology, followed by the lithology and mechanical properties of the silcrete, and the relationship between the tool types present and the mechanical properties.

##### *Inland silcrettes*

*Lake Mungo* Lake Mungo lies in the Willandra Lakes area of southwestern New South Wales (Fig. 1). The quarry lies on the western shore of the dry flat floor of the lake, where a low ridge is covered with large blocks and boulders of silcrete, and silcrete gravel occurs along the edge of the lake. Virtually all of the boulders show some evidence of human activity, and artefacts are found over the quarry area (Allen 1990; Williams 1991). Other exposures of silcrete quarried for artefacts occur nearby on the western shores of Lakes Chibnalwood and Leaghur. The Willandra Lakes region has a paucity of stone sources, so the presence of accessible stone raw materials has drawn Aboriginal people to the area throughout its history (Allen 1998).

Silcrete forms the bulk of raw material found at the archaeological sites in the Willandra Lakes region, with much smaller quantities of quartzite and sandstone. Of the silcrete artefacts, 95% were made from medium-grained silcrete and the remainder from fine-grained silcrete; both types of silcrete are found at the quarries (Allen 1998).

The silcrete samples used in the present study were collected at the quarry; they are predominantly dull yellow orange with a thin light grey weathering rind. Relatively large inclusions of light-grey clay-cemented material are evident on the uneven granular fracture surfaces. The Lake Mungo silcrete is medium-grained, and consists predominantly of well-sorted, subangular to subrounded quartz clasts, mostly medium-sand-sized, in a matrix of microcrystalline quartz; it has a grain-supported microfabric (Fig. 2 (A) and Table 1).

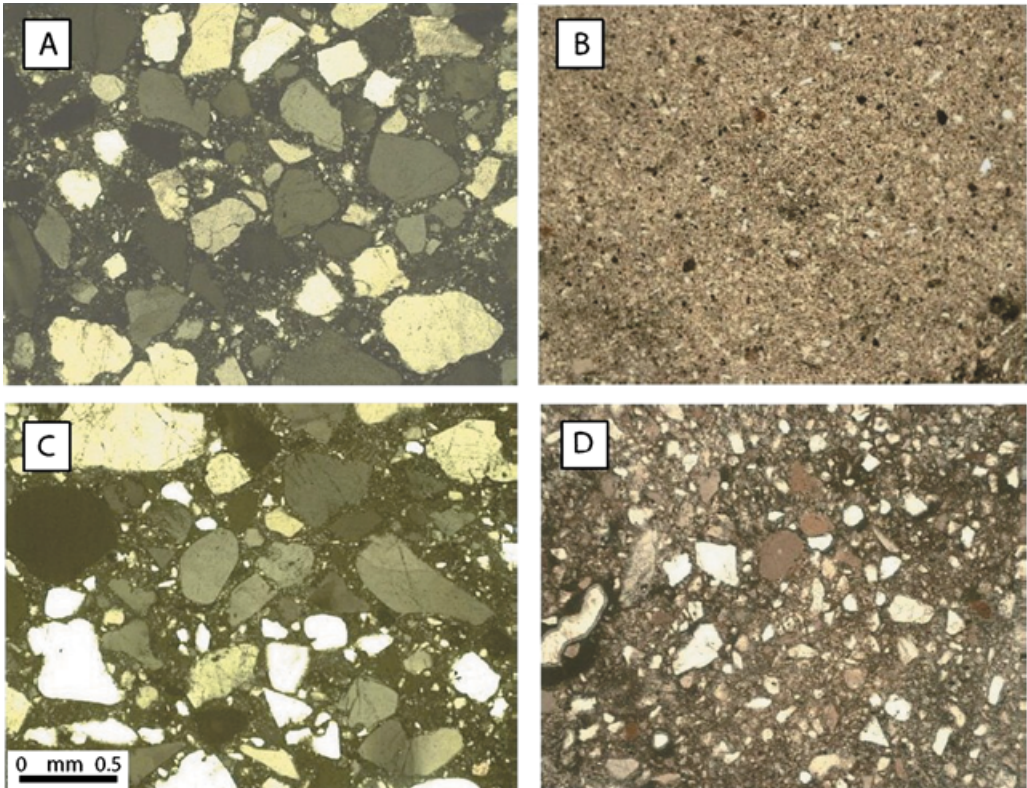


Figure 2 Thin-section micrographs of inland silcretes; the scale in C applies to all photos. (A) Lake Mungo (sample 196): well-sorted subangular to subrounded medium-sand-sized clasts in microcrystalline matrix. (B) Olive Downs (sample 358): microcrystalline matrix with scattered angular silt-sized clasts. (C) Gorge (sample 364): moderately sorted subangular to subrounded mostly medium-sand-sized clasts in microcrystalline matrix. (D) Gorge (sample 365): well-sorted subangular mostly very fine-sand-sized clasts in microcrystalline matrix.

The results of the mechanical tests (Table 2) show that the Lake Mungo medium-grained silcrete has poor flaking properties. The high fracture toughness (median  $85 \text{ MPa}\cdot\text{mm}^{1/2}$ ) reveals that it is difficult to knap, and inclusions of clay-cemented material represent major defects that markedly lower the fracture toughness (sample no. 196\*—median  $33 \text{ MPa}\cdot\text{mm}^{1/2}$ ). Lake Mungo silcrete has a low index of stiffness, so fracture propagation lacks directional stability and there will be a high frequency of step fracture terminations, also caused by the microstructural defects represented by medium-sand-sized quartz grains. As a result, the Lake Mungo silcrete is much less suitable for detachment of narrow flakes and resharpening of working edges.

However, these mechanical properties have less deleterious effects when detaching large wide flakes (Cotterell and Kamminga 1987; Hiscock 1993), so Lake Mungo medium-grained silcrete was often used for the hard hammer percussion manufacture of steep-step flaked artefacts such as horse-hoof cores and steep-edged scrapers (White and O'Connell 1982; Cotterell and Kamminga 1987; Allen 1998). In both Late Pleistocene and Holocene lithic assemblages of the Willandra Lakes, blocky horse-hoof cores and various scraper forms are common (Jones and Allen, in Bowler *et al.* 1970; Allen 1998; Hiscock and Allen 2000).

*Tibooburra (Olive Downs and Gorge quarries)* Within Sturt National Park in western New South Wales, 25 km east of Tibooburra (Fig. 1), pedogenic silcrete outcrops as a laterally continuous layer in low scarps (Watts 1978), and as extensive pavements of closely packed subspherical cobbles (called gibber). The silcrete occurs as microcrystalline, fine-grained and medium-grained varieties (Table 1; Doelman *et al.* 2001).

Of the numerous outcrops of silcrete in the area, only those with a massive appearance were quarried; quarries are mainly distributed in elevated positions at the crest of the escarpments and within the stream gullies. Two quarries in the Tibooburra area were sampled: Olive Downs (microcrystalline silcrete) and Gorge (fine- and medium-grained silcrete).

The Olive Downs silcrete shows conchoidal fracturing and is dominantly light brownish grey to dull orange in colour. This silcrete is microcrystalline, consisting predominantly of a microcrystalline quartz matrix through which are scattered angular clasts of mostly silt-sized quartz (Fig. 2 (B) and Table 1). There are occasional layers and patches of coarser quartz clasts (up to 2 mm across), partially silicified clay and very fine-grained iron oxide minerals and organic matter, and small cavities (up to 1 mm across).

At the Gorge quarry, two varieties of silcrete are present: fine- and medium-grained. The Gorge medium-grained silcrete has irregular granular fracture, and is a uniform light grey or greyish yellow. It has a grain-supported microfabric and consists of moderately sorted, subangular to rounded quartz clasts, mostly medium-sand-sized, in a microcrystalline quartz matrix (Table 1 and Fig. 2 (C)). Abundant small cavities (up to 3 mm across) and occasional large quartz grains (up to 2 mm across) are present.

The uniform light grey fine-grained silcrete at Gorge quarry shows conchoidal fracture surfaces. It has a grain-supported microfabric of well-sorted, subangular quartz clasts, mostly very fine-sand-sized (occasionally coarse-grained), in a matrix of microcrystalline quartz (Table 2 and Fig. 2 (D)). Some patches of chalcedonic silica are present.

The mechanical test results (Table 3) reveal that the Olive Downs microcrystalline silcrete has mechanical properties comparable to Australian flint (Doelman *et al.* 2001, table 1), in terms of fracture toughness (median 65 and 58 MPa.mm<sup>1/2</sup> respectively), compressive strength (medians 720 and 730 MPa, respectively) and index of stiffness (medians 11.0 and 13.0, respectively). This similarity reflects their petrology, an interlocking mosaic of very fine quartz crystals. Soft clay, iron oxide and organic inclusions substantially lower the compressive strength and fracture toughness of some samples (Table 3), and hence markedly decrease the flaking quality.

The Gorge medium-grained silcrete has a lower median fracture toughness than Olive Downs microcrystalline silcrete (52 and 65 MPa.mm<sup>1/2</sup> respectively), although there is considerable overlap (Table 2). It was not tested for compressive and tensile strength, but it probably has lower values of these properties compared to the microcrystalline silcrete, because almost all Australian medium-grained silcretes tested have low to moderate compressive and tensile strength (Table 2). In comparison, Gorge fine-grained silcrete has a relatively high fracture toughness (median 87 MPa.mm<sup>1/2</sup>) and low index of stiffness (7.5).

At the nearby Late Holocene Stud Creek site (~12 km south of Gorge quarry), the raw material available was dominated by medium-grained silcrete, with a smaller amount of microcrystalline silcrete and little fine-grained silcrete (Doelman *et al.* 2001; Holdaway *et al.* 2004). Within the surface scatters of stone artefacts at Stud Creek, microcrystalline silcrete was preferred for the manufacture of blades and for tools that require a greater degree of fine retouch (thumbnail scrapers) and high-edge holding properties (tula and burren adzes). Compared to medium-grained silcrete, microcrystalline silcrete was flaked more intensively, as indicated

by a smaller size of complete flakes, a higher ratio of flakes to cores and a smaller mean core volume of the cores. In comparison, the lower-quality medium-grained silcrete was generally used for expedient core and flake tools that required a smaller degree of retouch. This pattern of usage directly reflects the difference in mechanical properties of the two silcrete types; compared to the microcrystalline silcrete, the low to moderate fracture toughness of the medium-grained silcrete means that, like the Lake Mungo silcrete, it has relatively poor flaking properties, as it is less resistant to edge fracturing in tool use, less suitable for the manufacture of blades and less amenable to repeated resharpening. In addition, the larger quartz clasts present would result in a relatively high frequency of step fracture terminations, particularly during fine retouching.

#### *Eastern association (sub-basaltic) silcretes*

*Kenniff Cave* The Central Queensland Highlands (Fig. 1) form a low relief tableland dissected by steep-sided valleys. The sides of the gorges are cliffed near the base in Lower Jurassic sandstone; a second higher cliff represents overlying Tertiary basalts. Silcrete, referred to as 'grey billy', outcrops at a number of sites through the highlands (Finlayson and Webb in press), as discontinuous layers up to 3 m thick at the top of the sandstone, immediately beneath the basalt.

Kenniff Cave is located within a sandstone cliff on the south bank of Meteor Creek (Fig. 1). Silcrete occurs beneath the basalt capping the ridge, and silcrete scree chokes a section of Meteor Creek near the cave (Mulvaney and Joyce 1965). Within a few metres of Kenniff Cave is a silcrete quarry.

The Kenniff Cave silcrete is uniform and light grey with conchoidal fracture surfaces. It is fine-grained, grain-supported and consists of very well sorted subrounded to angular fine-sand-sized quartz clasts cemented by syntaxial overgrowths and very thin layers of chalcedony around small voids (Table 1 and Fig. 3 (B)); microcrystalline quartz matrix is virtually absent (<4%).

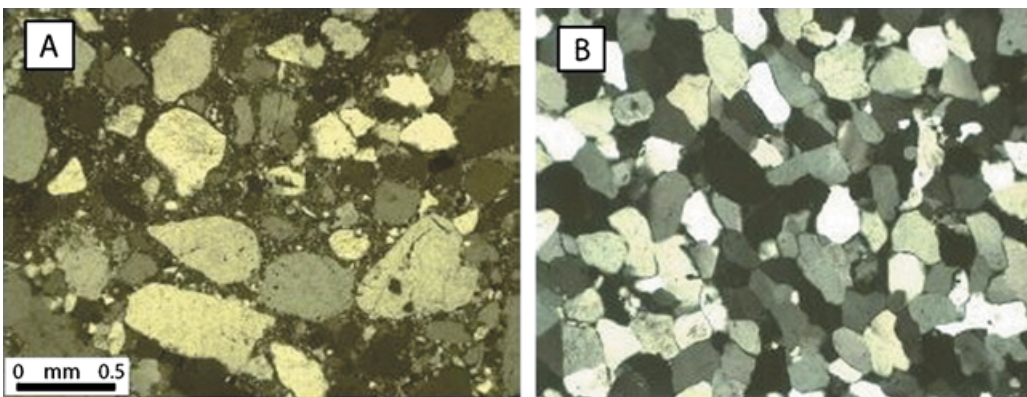


Figure 3 Thin-section micrographs of inland and eastern silcretes; the scale in A applies to both photos. (A) Green Gully (sample 156): moderately sorted angular to subangular mostly medium-sand-sized clasts in microcrystalline matrix. (B) Kenniff Cave (sample 229): very well sorted fine-sand-sized clasts cemented by syntaxial overgrowths and occasional very thin layers of chalcedony (not easily visible at this magnification).

The mechanical tests showed that Kenniff Cave fine-grained silcrete is a high-quality material, relatively easy to flake by percussion knapping techniques, as indicated by the low fracture toughness (median 48 MPa.mm<sup>1/2</sup>), comparable to that of Australian flint (median 58 MPa.mm<sup>1/2</sup>) and Tiboburra microcrystalline silcrete (median 65 MPa.mm<sup>1/2</sup>) (Table 3). Unweathered Kenniff Cave silcrete has a moderate compressive strength (median 550 MPa), a moderate index of stiffness (11.5) and a quite low tensile strength (median 39 MPa) (Table 3); the weathered material has markedly lower values of these mechanical properties. The values of compressive strength, index of stiffness and tensile strength of Kenniff Cave silcrete are lower than those of Australian flint and Tiboburra microcrystalline silcrete, but are much higher than for Australian medium-grained silcretes (Table 2). They indicate that Kenniff Cave silcrete has sufficient compression–bending stiffness to maintain the directional stability of fracture propagation. Furthermore, the small number and size of the largest quartz clasts (0.5 mm) indicate that they have little effect on the direction of fracture during fine retouching, and there would be a low frequency of step fracture terminations.

Mulvaney's excavation of Kenniff Cave revealed a three-part cultural history (Morwood 1981, 1984). The earliest phase, the core tool and scraper industry, entirely constituted varieties of flake scrapers. The small tool industry, which appeared in the mid-Holocene, saw the proliferation of micro-blade technology and backed artefacts, pirri points, eloueras, tula and burren adzes. At ~2500 BP the recent industry appeared, characterized by the Juan knife; several distinctive tool types, such as backed artefacts, dropped out of the assemblage.

Fine-grained silcrete (referred to as quartzite) was the predominant material used throughout the Kenniff Cave sequence (Mulvaney and Joyce 1965), both because of the close proximity of a source and its high quality. The mechanical properties show that this lithology is very amenable to the manufacture of not only the flake scrapers abundant in the early industry, but also the blade-based implements of the mid-Holocene assemblage, including tools that require delicate backing or semi-invasive retouching. The technological and typological changes evident in the cave deposits did not affect the lithology used, because the high-quality fine-grained silcrete locally available had sufficient versatility for the manufacture of both flake scrapers and blades/micro-blades.

However, at other Central Queensland Highlands sites, in particular Native Well (Morwood 1981, 1984), the mid-Holocene appearance of the small tool industry was accompanied by dramatic changes in raw material use, with an increase in the use of fine-grained and microcrystalline silcrete and chert, in response to the technological and the functional requirements of the new tool types. At the Native Well sites, tula and burren adzes were made exclusively of chert rather than fine-grained silcrete (Morwood 1981), probably because the silcrete was more prone to edge fracturing and less efficient in working hard wood, due to its relatively low tensile strength and fracture toughness.

The mid-Holocene proliferation of backed artefacts, tula adzes and points across Australia has been interpreted as a technological response to reduce risk associated with increased foraging, higher mobility and colonization of previously unoccupied regions, resulting from a drier unpredictable environment that began about 4000–5000 years BP in southern Australia (Hiscock 1994, 2002). The small delicate standardized flakes could be integrated into reliable and maintainable multipurpose composite tools.

A similar pattern of change in technology and raw material selection has been documented in southern Africa at the beginning of the last Ice Age, about 70 000 years ago (Ambrose and Lorenz 1992; Ambrose 2002). The invention of small blade technology and backed micro-liths was a response to the drier unpredictable environment, promoted by the availability of

fine-grained materials with suitable mechanical properties, obtained either through exchange or increased residential and logistical mobility.

*Green Gully* Near Keilor in central Victoria (Fig. 1), discontinuous lenses of silcrete up to 2 m thick outcrop in the banks of the Maribyrnong River; they have formed in Tertiary sediments directly beneath basalts (Joyce *et al.* 1983). Medium- and coarse-grained silcrete are common; fine-grained and microcrystalline silcrete are less abundant—the latter was called amorphous, opaline or cherty by Tunn (1998) and Witter and Simmons (1978).

Ten silcrete quarries have been recorded within the Maribyrnong River valley (Tunn 1998); samples were collected from one, at Green Gully. This silcrete has irregular granular fracture surfaces, and is brown to greyish yellow in colour. It is medium-grained with a grain-supported microfabric, consisting predominantly of moderately sorted, angular to subangular mostly medium-sand-sized quartz clasts in a microcrystalline quartz matrix (Table 1 and Fig. 3 (A)). The quartz clasts range from very fine-grained (0.012 mm across) to occasionally very coarse-grained (3 mm across).

The mechanical tests (Table 2) show that the Green Gully medium-grained silcrete has poor flaking and edge-holding properties and low reshaping qualities. The high fracture toughness (median 76 MPa.mm<sup>1/2</sup>) reveals that it is difficult to knap. The low compressive strength (median 350 MPa), the low index of stiffness (median 4.6) and the low tensile strength (median 28 MPa) indicate that it lacks the compression–bending stiffness necessary to maintain the directional stability of fracture propagation and will have a high frequency of step fracture terminations.

Two lithic assemblages have been identified in the Maribyrnong River valley (Mulvaney 1970; Witter and Simmons 1978; Munro 1998). The lower assemblage contains relatively small numbers of artefacts, mainly scrapers and notches, whereas the upper small tool industry emphasizes micro-blade production and contains backed artefacts, larger scrapers and notches. The striking feature of the younger assemblage is the frequent selection of microcrystalline and fine-grained silcrete for tools such as delicately retouched backed artefacts, even though these silcrete varieties are relatively uncommon at the quarries nearby. The poorer flaking properties of the coarser-grained silcrete made it less suitable for artefacts and tools requiring repeated reshaping, and it was used for less than 10% of the retouched pieces.

#### THE RELATIONSHIP BETWEEN THE MECHANICAL PROPERTIES AND MICROSTRUCTURE OF SILCRETE

A comparison of the mechanical properties of the silcrete samples in the present study with their microstructure shows that there is a close relationship. In particular, for silcretes that contain microcrystalline matrix there is a strong positive correlation ( $r^2 = 0.96$ ) between the amount of matrix and the compressive strength (Fig. 4 (A)). Microcrystalline silcrete with few impurities has a high compressive strength because of its very strong quartzose mineralogy and uniform very small grain size; fine-grained materials, which fracture predominantly along grain boundaries, are stronger than coarse-grained lithologies of the same composition, in which fracturing is predominantly transgranular (Davidge 1979; Mardon *et al.* 1990). Furthermore, cracks developed in any larger quartz clasts are effectively blunted by the much stronger microcrystalline quartz matrix. However, relatively large particles of weaker non-silica minerals (mostly clay and iron oxide) act to lower the compressive strength (Fig. 4 (A)).

There are moderate negative correlations between average grain size and compressive strength for both medium- and finer-grained silcretes, excluding the samples with a high

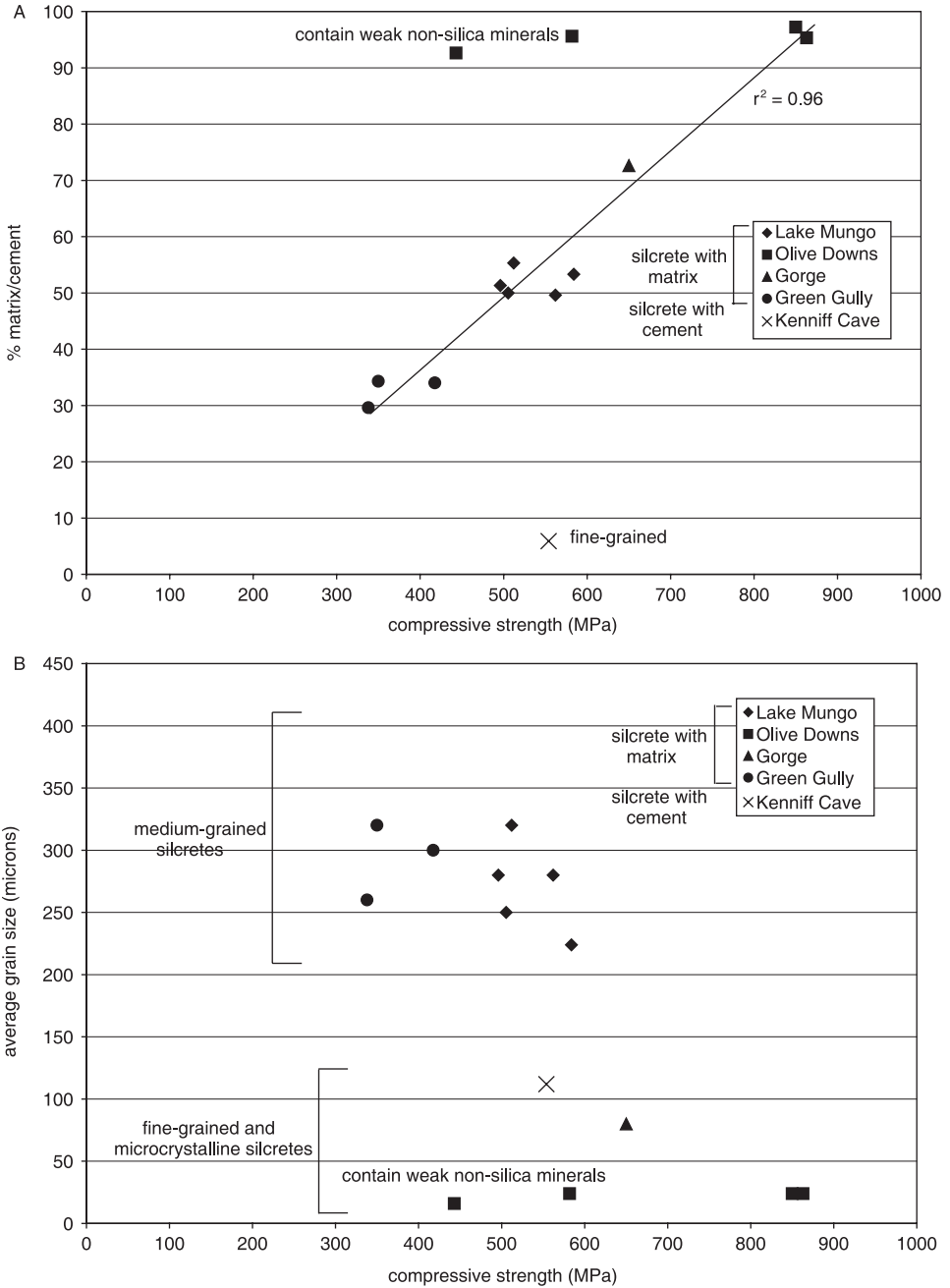


Figure 4 The relationship between compressive strength and texture—amount of matrix/cement (A) and grain size (B)—for Australian silcretes.

content of impurities (Fig. 4 (B)). This is expected from the general relationship between strength and grain size. The correlation is probably weakened by the considerable variations in the percentage of matrix and cement (Fig. 4 (A)).

Among the silcrete samples that have cement rather than matrix, the Kenniff Cave silcrete has a relatively weaker compressive strength. Experimental studies on granular lithologies containing little matrix or cement indicate that most tensile cracks initiate near the boundaries of larger grains (Gallagher *et al.* 1974; Zhang *et al.* 1990; Malan and Napier 1995), so a large contact area between adjacent particles results in a markedly lower compressive strength. The dominance of syntaxial overgrowth cement in the Kenniff Cave silcrete means that the majority of clasts are effectively in contact, accounting for its relatively low compressive strength. This effect overrides any increase in strength due to filling of microcracks and point defects in quartz clasts by the syntaxial overgrowth cement (Joesten 1991; Goldstein and Rossi 2002).

There is no relationship between fracture toughness and either percentage of matrix or grain size for the silcrete samples. Previous studies have found that for rocks of similar mineralogical composition, an increase in grain size generally results in a decrease in fracture toughness for grain sizes smaller than 0.2 mm (Huang and Wang 1985; Whittaker *et al.* 1992; Domanski and Webb 2000). This correlation is not present in the tested silcrete samples (Tables 2 and 3), probably because it is overridden by microstructural variability in sorting and percentage of microcrystalline quartz matrix, chalcedonic cement and/or voids. These microstructural heterogeneities may cause crack branching, dissipating the energy available for fracture propagation (Atkinson and Meredith 1987).

#### CONCLUSIONS

The present study highlights the importance of the compressive strength of silcrete in flake formation. Silcretes suitable for systematic production of blades have a high index of stiffness and a high compressive strength (>500 MPa), comparable to those of obsidian and flint (Domanski *et al.* 1994, table 4). The compressive strength of the different silcrete types is determined to a large extent by microstructure, so that compressive strength is positively correlated with percentage of microcrystalline matrix and negatively correlated with average grain size. Therefore, examination of a silcrete sample with the aid of a hand lens can give a good indication of its likely flaking quality.

The mechanical properties of the different silcrete types strongly influenced patterns of raw material selection as well as stone tool manufacture, maintenance and discard, and in effect the composition of stone tool assemblages.

Microcrystalline Olive Downs silcrete has mechanical properties comparable to those of Australian flint, reflecting the petrological similarity of the two lithologies, particularly the very fine groundmass of quartz crystals. The high values of compressive and tensile strength of microcrystalline silcrete give this lithology a high compression–bending stiffness, keep the fracture direction stable and prevent step fracture terminations, and therefore enable systematic production of long regular blades, micro-blades and the detachment of small flakes when retouching stone tools. The high strength also gives substantial edge-holding properties in working soft (meat, skin) and hard organic materials (wood, bone). A selection for high-quality microcrystalline silcrete is evident for the more curated tools (i.e., tula adzes) that required a greater degree of fine retouch and reshaping.

The fine-grained silcretes (Kenniff Cave) have mechanical properties comparable to those of microcrystalline silcrete and Australian flint, so they are also suitable for the manufacture

of blades and the production of blade-based implements that require fine retouching. The lower tensile strength of fine-grained silcrete compared to flint indicates that it is more susceptible to edge fracturing and therefore less suitable for the manufacture of tools for working hard organic materials (e.g., tula and burren adzes).

The medium-grained silcretes (Lake Mungo, Green Gully and Gorge) have poor flaking properties, reflected in their low compressive and tensile strength. As a result, medium-grained silcrete was much less suitable for the production of blades and retouched tools, and was often used for flake manufacture.

The choice of a silcrete lithology for manufacture of a particular artefact type was clearly influenced largely by its mechanical properties, although other factors, particularly proximity of source and availability of material, were also involved.

The mid-Holocene proliferation of tula adzes, backed artefacts and points, associated with fine pressure and delicate percussion retouching, necessitated the use of high-quality silcrete (microcrystalline or fine-grained) for these more curated tools (Flenniken and White 1985; Mulvaney and Kamminga 1999). Raw material procurement was characterized by greater selectivity and increasing emphasis on extending use-life of stone tools. Very fine-grained siliceous materials such as microcrystalline silcrete were favoured because they are suitable for fine flaking, have high edge-holding properties and are amenable to repeated resharpening (Cotterell and Kamminga 1987). At some sites, the mid-Holocene change in technology was accompanied by a change in the predominant artefact lithology; at sites where high-quality silcrete was already utilized for flakes and scrapers, no change in lithology was required for the production of more curated tools.

Thus material determinism clearly played a major role in silcrete raw material selection, artefact manufacture, maintenance and discard, and can explain much of the variability in silcrete artefact morphology and assemblage composition. Other components of variability in artefact morphology and assemblage composition are subordinate to the physical and mechanical properties of the raw material.

The primacy of the nature of the raw material in tool manufacture has also been noted in other parts of the world (e.g., Ambrose and Lorenz 1990; Ambrose 2002; Byrne 2004), and the editorial introduction to Speth (1977) noted that ‘the worker of siliceous rock ... is bound within a mechanical straitjacket because the restrictive nature of the raw material itself imposes severe limitations on the final form a piece may take and on the techniques which may be used to achieve it’.

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