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ABRASIVE AND IMPACT WEAR OF STONE USED TO MANUFACTURE AXES IN NEOLITHIC GREECE

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ABSTRACT

Excavations at the Neolithic settlement at Makriyalos in Northern Greece brought to light a large number of stone axe heads, the majority of which were manufactured from serpentinite and igneous rocks. Detailed study of the manufacturing traces on the archaeological implements identified that both percussive (pecking) and abrasive techniques (sawing and grinding/polishing) were employed for the production of the axes. There is limited evidence, however, of how these processes may have been undertaken.

The aim of this work was to build on previous research investigating sawing and polishing methods and the materials that may have been used in these tasks.

Modern samples of two types of serpentinite and a dolerite were collected from the environs of the archaeological site. These were tested for strength and porosity. Through archaeological research the materials available to Neolithic people were established and some testing was carried out to establish sliding speeds and loads and percussive impact velocities achievable by a human to feed into the tribological test design.

Pin-on-disc wear tests were carried out using quartz, chalcedony and sandstone as the pin material in wet and dry conditions to study sawing and polishing behaviour. Reciprocating tests were carried out using leather and combinations of lubricant (animal fat and water) and abrasive medium (sand) to study effects on polishing. Percussive impact tests were also carried out.

The tests indicated that with certain combinations of materials and test conditions, both sawing and polishing could be achieved. A series of stages for the polishing were identified which are in line with observations made by archaeologists.

INTRODUCTION

Work has been carried out previously to study the wear of different types of serpentinite to improve understanding of the methods that may have been used to manufacture stone axes from such stone in the Late Neolithic period (ca. 5400/5300 B.C. to ca. 4700/4500 B.C.) in prehistoric Greece [1]. A series of pin-on-disc wear tests were carried out sliding both sandstone and quartz against black/green serpentinite and pistachio green serpentinite. The wear behaviour observed was interpreted using data from strength and porosity measurements on the serpentinites.

This work revealed which combinations of materials would be well suited for cutting and polishing processes and how they were affected by the addition of water. The results are summarised in Table 1.

Serpentinite		Black/green	Pistachio green
Best option for:	Cutting	Dry quartz	Wet sandstone
	Polishing	Wet sandstone	Possibly dry sandstone

Table 1. Optimum Cutting and Polishing Combinations [1]

The aim of the present work was to take the original testing a step further by simulating different mechanical actions that were more in line with those that were most likely used in prehistory. Reciprocating and impact tests were planned as well as repeats of the pin-on-disc unidirectional sliding tests.

In this work greater emphasis was placed on understanding the materials that Neolithic people may have had access to, and, as a result, a greater range of tool and work piece materials were studied. Effort was also put into establishing more rigorously the human hand force and speed characteristics for the different mechanical actions involved in the production of stone axes, which were fed into the tribological tests.

BACKGROUND

Tribology and Archaeology

As mentioned in the previous work [1], the links between archaeology and tribological methods are key to establishing the materials, manufacturing processes and kinetics involved in the production of ancient artefacts. This includes the use of tribological test methods to replicate features observed in the archaeological assemblages (excavated objects), as illustrated, for instance, in the work by Astruc et al. [2], who used friction and scratch testing to replicate wear features seen on prehistoric chert tools and surface analysis to understand how tool surfaces were altered through contact with other materials. Similarly, Vargiolu et al. [3], developed a “drilling tribometer” to study abrasive techniques used in the production of stone vases made during the Bronze Age (3000 to 1000 B.C.) in Crete.

There are also a number of examples in the literature where tribologists and archaeologists have worked together using an “experimental archaeological approach” (see [4]).

This approach involves the study of tool use through the replication of prehistoric stone tools followed by the simulation of their use and the analysis of the resultant micro-wear on their surfaces. Archaeological examples are then studied to identify similar wear patterns and thus to infer the types of activities tools were used for [5]. Such studies include among others, the work of Anderson et al. [6], who used tribological techniques to analyse micro-wear traces observed on flint blades for threshing grain and cutting straw from sites in the Near East from the later Neolithic to the Early Bronze Age. Similarly Le Moine’s study of bone and antler tools [7] was carried out to demonstrate that distinctive patterns of wear on tool working faces depend on the activities tool were used for. For example bone and antler tools used to cut ice often show very different patterns of wear on the tool face compared with those used to cut wood.

Stone Axe Production in Neolithic Greece

The Greek Neolithic lasted over three millennia (ca. 6700/6500-3300/3100 BC) and is divided into four sub-phases: Early, Middle, Late Neolithic and Final Neolithic [8]. The period is characterized by sedentary farming communities that practised an agropastoral economy as suggested by archaeozoological and archaeobotanical evidence characterised principally by domesticated seed crops and livestock [9, 10]. During the Neolithic period the organisation of daily life was connected with the emergence of new diverse technologies (e.g., pottery, food-processing technologies, polished stone axes and grinding stone tools) and thus it is characterised by an expansion of materials used, objects (tools, ornaments and containers) produced and techniques employed in their production.

Similar to many North European examples (e.g. [11, 12]) the Neolithic communities of the Aegean, employed a wide variety of rock types for their stone axes that can be attributed to all three geological categories (metamorphic, sedimentary, and igneous) with metamorphic and igneous specimens being used more frequently [13, 14]. Systematic work on stone sources established that stone axes in Northern Europe circulated over long distances and played an important role in the exchange systems of Neolithic communities making stone axes highly valued objects (e.g. [15, 12, 11]). Similar, recent studies on raw material sourcing in the Aegean indicate diverse rock procurement mechanisms [16, 17]. The analysis of the large stone axe assemblage from Late Neolithic Makriyalos suggests that the acquisition of rocks for edge tools relied on both local and non-local sources which were acquired either through direct procurement or through some form of exchange mechanism [18].

Detailed study of the manufacturing traces on the archaeological implements showed that stone axes were produced through a combination of percussive (i.e. mainly coarse hammering and pecking) and abrasive techniques (i.e., grinding, polishing and sawing; the latter used mainly for the modification of tools) [13, 17]. Archaeological evidence, supported by ethnographic and experimental research, suggests that grinding/polishing was achieved by rubbing the surface of the stone tool against harder surfaces such as coarse-grained stones, gneiss and quartz sandstones. The grinding process would involve the use of abrasives of different textures, starting with coarser and moving to finer abrasives facilitated possibly by the use of water [5, 12, 18]. Grinding/polishing may have been further facilitated by the use of animal products such as leathers and animal fats [19, 20]. The use of dry or wet sand as a polishing agent has also been suggested by Bordaz [21]. This would have produced third body abrasion as the sand, water and any abraded rock fragments would form an abrasive slurry between the work piece and tool. The original study by Lewis et al. [1] found that sand and water was effective at polishing harder work piece materials, whereas dry conditions were better for softer work piece materials. The addition of water to softer materials weakened them, however, and made cutting operations easier.

ARCHAEOLOGICAL SPECIMENS

Similar to the initial study (Lewis et al., 2009) the basis for this current project was the stone axes discovered during excavations at the Neolithic settlement of Makriyalos, in Central Macedonia, Northern Greece [13, 22, 23], two examples of which are shown in Figure 1.

Detailed study of the Makriyalos stone axes in terms of rock selection and use, manufacturing techniques and use-wear patterns was conducted by Tsoraki for her doctoral research [13, 24]. The study identified that all three geological categories of rocks (metamorphic, igneous and sedimentary) were used by the Makriyalos Neolithic community for the production of their stone axes. There was, however, a clear preference for the use of different types of serpentinite including a pistachio green serpentinite and a dark black/green serpentinite, a common aspect throughout the Greek Neolithic. Igneous rocks are mainly represented by dolerite (the second most common rock type used), basalt and generally fine grained varieties of igneous rocks. Other rock types employed include: schist, marble, gneiss, gabbro, diorite [13, 24].

The majority of these tools were manufactured from different types of serpentinite including a pistachio green serpentinite and a dark black/green serpentinite [24].

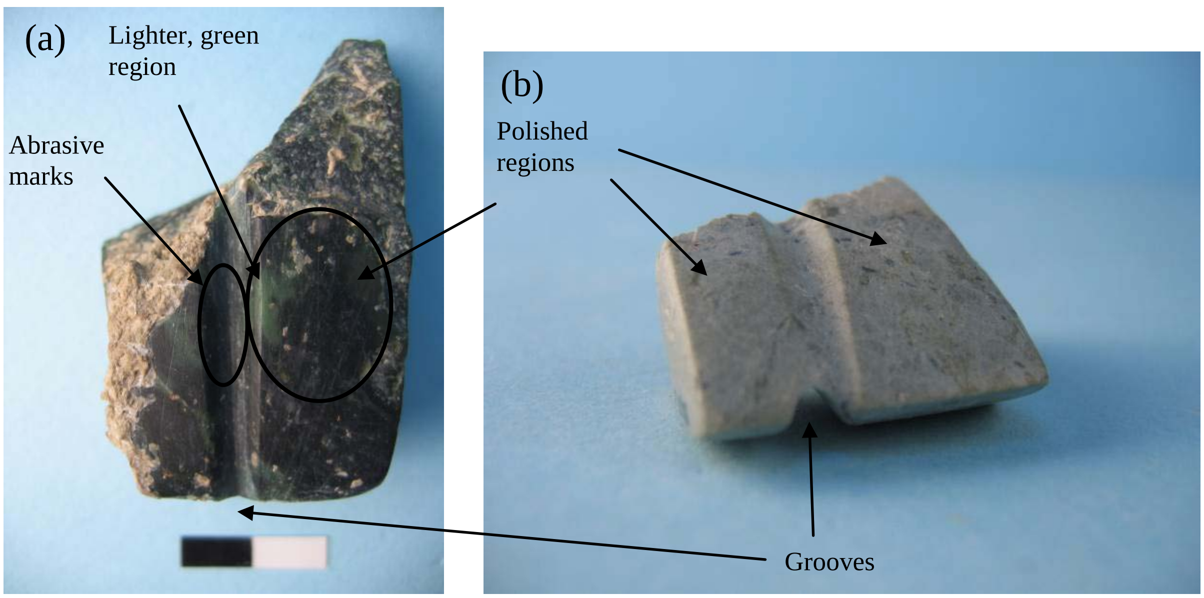

Figure 1. Makriyalos stone axes: (a) Black/Green Serpentinite (surviving dimensions: 5.5×3.5×2.1cm, groove width: 0.5cm) and (b) Pistachio Green Serpentinite (surviving dimensions: 3.4×3.2×2.1cm, groove width: 0.5 – 0.8cm) [18]

Serpentinite is a metamorphosed ultramafic rock where the ferromagnesian silicate minerals of olivine and pyroxene have been altered to serpentine minerals such as chrysotile (asbestos), antigorite, chlorite, serpentine and talc, which are rich in magnesium and iron, but poor in potassium and calcium [25]. Serpentinites are a highly variable group of rocks, ranging greatly in appearance and properties. This is mainly due to the varying composition of the original material and different temperature and pressure conditions under which the rock was formed. Most types are green in colour, although they may also be red, grey or black. Dolerite, also a mafic rock, contains augite and feldspar with relatively little silica (thin section samples of the rocks used in the experiments are described in the next section of the paper).

Various techniques were employed for the production and modification/maintenance of the Makriyalos stone axes: flaking (occasionally), pecking, grinding, polishing and sawing (mainly for modification of tools) [18]. Initially, the rough shaping of the rocks was achieved mainly by direct percussion activities such as coarse hammering and pecking. The tools used during this stage were hammerstones of different sizes made out of quartz and igneous rocks such as dolerite and diorite. The rough surfaces created by pecking were smoothed by using abrasive techniques (i.e. grinding) (Figure 1). The tools used during this stage were mainly stone slabs (i.e. grinding slabs) made of various stones such as sandstone, gneiss and schist. The manufacture of stone axes was finished with the application of polishing, an abrasive technique that created extremely smooth and often shiny surfaces. Sawing was used at Makriyalos for the modification of tools (Figure 1): to split tools in half, to correct the overall dimensions of tools and to repair faults [24].

The previous study [1] shed some light on how grinding/polishing and sawing may have been achieved, but more information was required on fine finishing techniques and the coarser methods used for initial shaping. Taking into account the manufacturing techniques visible on the archaeological assemblage and the materials identified in archaeological contexts, it was decided to expand on the testing carried out in the previous study as follows:

1. sliding wear tests (to study cutting and polishing) with a greater range of tool and work piece materials
2. reciprocating polishing tests with leather and a range of lubricants (animal fat)/abrasive pastes (made up with sand)
3. percussive impact wear tests where a steel ball repeatedly strikes the work piece material normal to its surface

It was also decided to carry out a rigorous characterisation of human force and speed capability for the reciprocating polishing and impact actions. Strength and porosity tests were also carried out to characterize the new work piece materials.

EXPERIMENTAL SPECIMENS

Modern samples of two types of serpentinite the same as those used in the first study [1] (designated new black/green and new pistachio serpentinite) and a dolerite sample were collected from the environs of the Neolithic site of Makriyalos. While they are very different in appearance and structure, they were chosen to represent variation encountered in the archaeological assemblage. The axe heads shown in Figure 1 are made from stone similar in appearance to these.

In order to provide data about the mineralogy and texture of the rocks used in the study, thin sections were prepared of representative samples of the dolerite and the pistachio green and black/green dolerite. These were examined using a petrological microscope using both plain polarised and cross polarised light conditions. A selection of the resulting photomicrographs are shown in Figure 2.

As Figure 2a shows, the dolerite consists of a medium grained equigranular mass of pyroxene (probably aegerite) and plagioclase feldspar. The rock is intersected by cracks, upto 0.5mm wide that are infilled with quartz. The presence of pyroxene and feldspar, which are strong minerals, and their interlocking texture gives rise to a very strong isotropic rock with a relatively high resistance to abraision.

The two serpentinites are very different from each other, in terms of both composition and structure. The pistachio green serpentinite, in Figure 2b consists of a foliated fine grained quartz and talc rich rock, probably with some chlorite, whereas the black/green serpentinite shown in Figure 2c is a medium grained, crudely foliated rock due to the alignment of the crystalline grains composing the rock. The grains themselves consist of crysotile with some small pyroxene crystals, calcite and zones containing frequent crystals of magnetite. There are systems of calcite filled cracks containing angular rock fragments. The foliated texture of both serpentinites gives rise to anisotropic rocks which have a tendency to split more easily along the foliation than in other directions. Both talc and chlorite are relatively weak minerals, which explains the lower strength of this rock compared with the other rocks examined.

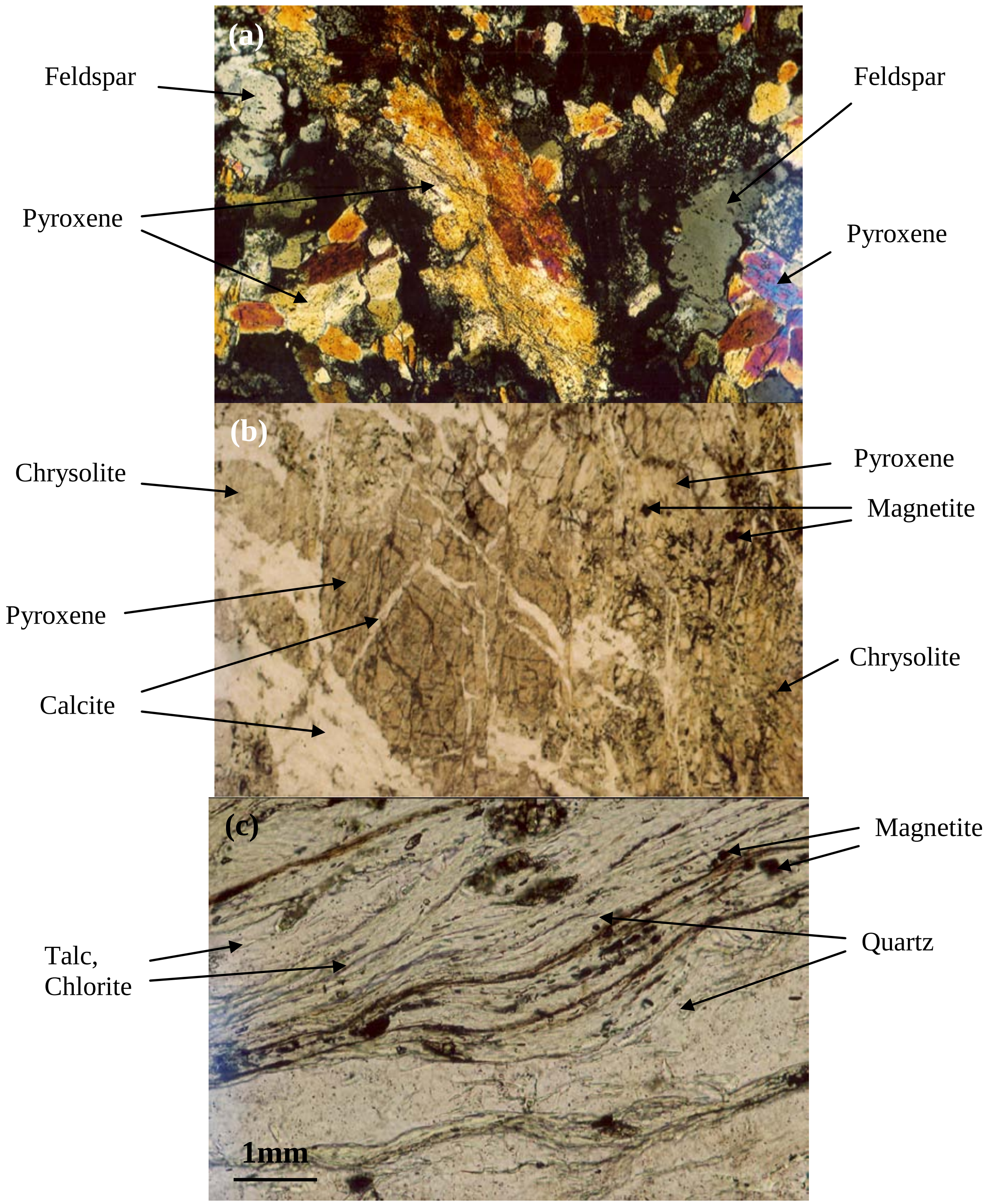

Figure 2. Photomicrographs of (a) Dolerite under Cross-Polarised Light; (b) Green/Black Serpentinite under Plain Light; (c) Pistachio Green Serpentinite under Plain Light

Tool specimens used for the experimental work were made from quartz, sandstone and chalcedony (See Figure 3). It should be noted here that "tool" specimens are those used to polish/grind/cut work piece specimens. In this case the work piece specimen also happens to be a tool itself which could cause confusion. While chalcedony does not appear in the archaeological assemblage (i.e., it has not been used for polishing/grinding) it is known that is has been used for different processes in the manufacture of other artefacts so it was thought appropriate to include it in this study. The quartz and chalcedony specimens were of fairly cylindrical form and about 15mm diameter by 30mm long, with a rounded tapered end. The quartz was colourless and had a hardness of 7 on the Mohs scale. Chalcedony differs from quartz as it is made up from small parallel bodied fibres rather than the trigonal crystals that are associated with quartz. Chalcedony is rated 6.5 to 7 on the Mohs scale [26]. The material used was black in colour and significantly less hard than the quartz. Both the quartz and chalcedony had a far more homogenous structure and smoother surface than the sandstone. The form of the specimens was probably created by tumbling in water, in a similar manner to stones in a river, which is probably what Neolithic people would have had access to.

The sandstone structure is very different, being made up of medium and coarse angular grains of quartz (0.2 to 2mm in size). Porosity tests (see [27] gave values of 15.1% to 17.0%. This relatively high value is due to the presence of inter-granular pore space. Prismatic pieces 12mm×12mm×30mm of the sandstone were cut as shown in Figure 3.

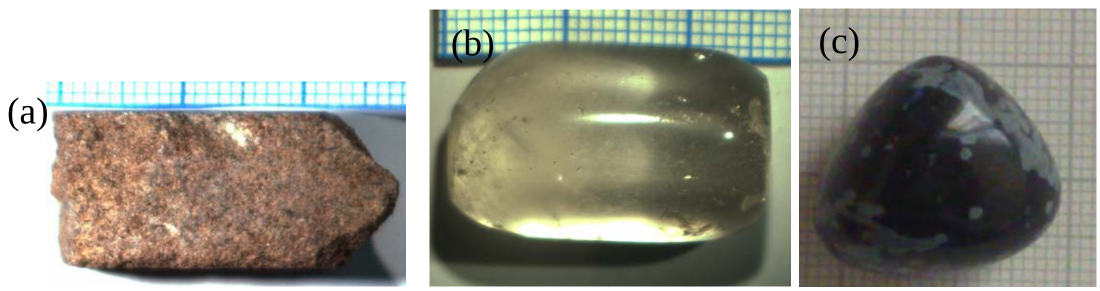

Figure 3. Tools used for Tests (a) Sandstone; (b) Quartz; (c) Chalcedony

HUMAN PERFORMANCE TESTS

Force/Speed

The purpose of this initial test was to evaluate the forces and speeds produced by humans using the different stone combinations in a reciprocating motion that may be used in a polishing process. The results were fed into tribological tests carried out to evaluate the polishing performance of various combinations of leather, animal fat and stone. All types of tool stones (quartz, sandstone and chalcedony) were used against new black/green and new pistachio green serpentinite.

The measurements were carried out using a rig designed for measuring finger friction (see [28] for more details). The rig, shown in Figure 4, consists of two load cells, one for measuring normal force and one for friction force, the data from which are downloaded to a PC during experiments. In these tests the serpentinite specimens were mounted on the rig and the tool stones were moved manually backwards and forwards across the surface in as “natural” a motion as was possible in order to replicate the kinetics employed by prehistoric people during a similar task/activity. The output from a sample test is shown in Figure 5. Tests with other stone combinations showed similar results. Figure 5 shows the normal and friction forces. Whilst the friction force is not necessarily of interest here it gives an indication of the number of cycles carried out from which the speed can be calculated. In this case 39 cycles were achieved in 16 seconds (see Figure 5) and as the wear track was 80mm long, the average speed was 192mm/s.

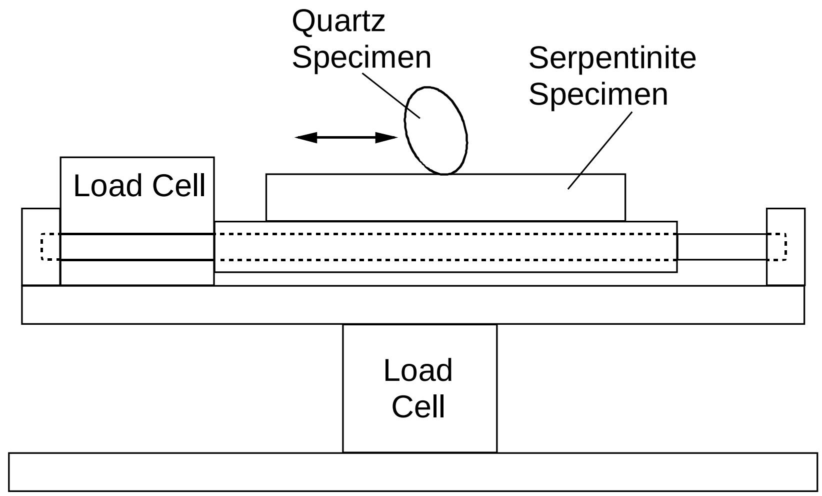

Figure 4. Force Rig used for Measuring Polishing Motion Forces and Speeds

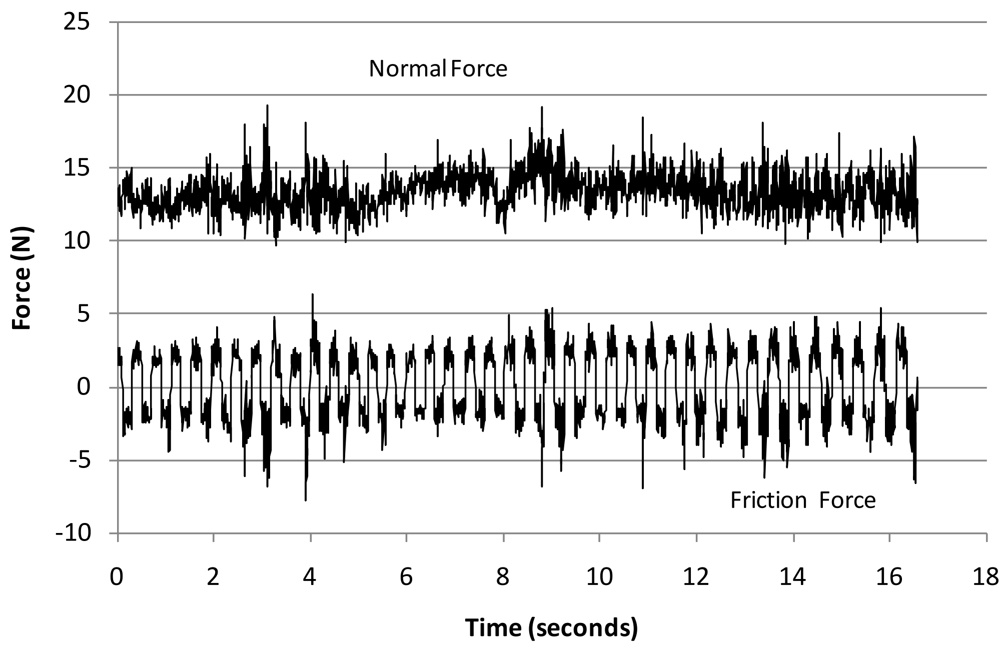

Figure 5. Force versus Time Plot for Test with Quartz against New Black/Green Serpentinite

Impact

The impact velocities during manual hammering of the stone with a quartz specimen were studied using high speed video techniques (see Figure 6). It should be noted here that the tool stone would actually have been much bigger than those used in the tests (7x6cm and average mass of is 0.3kg), which would have perhaps changed the speed of impact. Larger specimens, however, were not available.

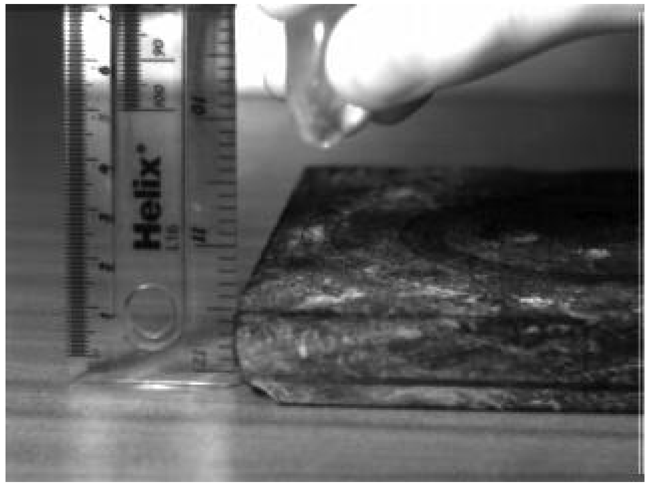

Figure 6. High Speed Video Image of Quartz Impacting New Black/Green Serpentinite

The video was analysed frame by frame to determine the impact speed. The reference points were used to determine a distance covered during one frame and the time taken was determined from the frame used in the recording. The calculated impact velocity was approximately 4m/s. If the weight of a hand is considered to be 0.37kg [29] and it is assumed that the motion is generated purely by the hand pivoting at the wrist and the mass of the forearm is not involved, then the impact energy is approximately 2.9J.

MECHANICAL STRENGTH TESTS

Uniaxial compressive strength (UCS) tests were performed on the two types of serpentinite and the dolerite. As with the previous study these values were intended to be used with porosity and wear test data to explain how the materials may have been worked to produce the archaeological tools etc. It should be noted here that the deformation and strength properties of rock cores measured in the laboratory usually do not accurately reflect large-scale in-situ properties of a rock mass. It is the strength of intact rock material, as measured in these tests, however, that would be relevant to the working of the stone to form small tools and other objects. The method used was based on that specified by ASTM [30].

Test Specimens

Cylindrical test specimens were manufactured from the dolerite and new black/green serpentinite (an example can be seen in the test apparatus in Figure 7) in line with the requirements of the ASTM standard [30]. The pistachio green serpentinite was extremely fragile and it proved impossible to make a cylinder that did not break up. This in itself indicated the low strength of the stone.

Test Method

Tests were carried out using a uniaxial compressive strength testing machine with a maximum load capacity of 2MN and a capability of applying load at a rate of 0.4 – 1.0MPa/s. The two loading faces of the machine were parallel to each other and a 40mm thick steel disc of flatness better than 0.005mm was placed at the bottom of each specimen. The load was applied axially at a rate of 1kN/s until failure occurred (see Figure 7).

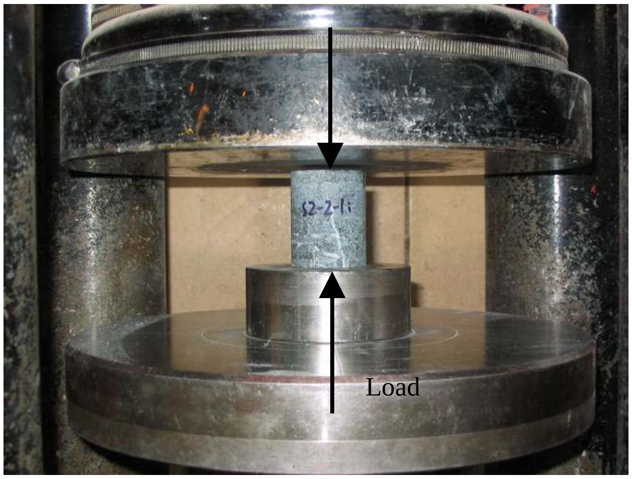

Figure 7. Uniaxial Compression Strength Test

Strength Test Results

The results from the tests are shown in Table 2 and are similar to those available from previous tests [1]. The dolerite specimen was extremely strong and did not reach its failure load. For the purposes of this work, however, it was enough to know that it was stronger than the serpentinite.

Stone Type	Failure Load (kN)	Compressive Strength (MPa)	Compressive Strength from previous study (Lewis et al., 2009)
Dolerite	>734	>405	-
Black/Green Serpentinite	195	108	205
Pistachio Green Serpentinite	-	-	33.3

Table 2. Results of the Uniaxial Compressive Strength Tests

POROSITY TESTS

Test Method

Porosity tests were carried out applying the same method used in the previous work [1]. Tests were performed on one dolerite, one new black/green serpentinite and three new pistachio green serpentinite specimens.

The measurements were performed using a vacuum water saturation method [31] in which the specimens were initially dried, and weighed (m_1, g). They were then saturated with water under vacuum. Following this the outer surfaces were then wiped dry with absorbent paper, before the specimens were reweighed (m_2 (g)). The volumes (v (mm^3)) of the specimens were determined by measurement. The porosity was then calculated using Equation 1, where the density (χ_w) of water was taken as 1 Mg/m^3.

$$\text{porosity} = \frac{(m_2 - m_1)}{\chi_w v} \times 100\% \qquad (1)$$

Porosity Test Results

Results from the porosity tests carried out are shown in Table 3 together with the results for serpentinite from the previous study. There is reasonable correlation between the old and new data. The dolerite is less porous than both serpentinite samples.

Stone Type	Mass Dry, m_1 (g)	Mass Wet, m_2 (g)	Volume, v (mm^3)	Porostity (%)	Average Porosity (%)	Porosity from previous study (Lewis et al., 2009)
Dolerite	243	244	173000	0.57	0.57	-
Black/Green Serpentinite	355	357	274000	0.69	0.73	0.60
Light Serpentinite	210	213	176000	1.70	2.13	4.30
Light Serpentinite	183	186	148000	2.03		
Light Serpentinite	318	324	260000	2.31		

Table 3. Porosity Test Results

WEAR TESTS

Introduction

Three types of test were planned. The first set on a pin-on-disc unidirectional sliding rig was designed to repeat the tests from the previous work, but with a greater range of tool and work piece materials. Reciprocating tests using a leather covered tool with various lubricants/abrasives were then carried out to study possible polishing methods. Finally some percussive impact tests were also run.

Pin-on-Disc Uni-directional Sliding

The test apparatus used for the sliding tests is shown in Figure 8. 145mm square by 20mm thick pieces of the serpentinites and dolerite were fixed with two screws onto the rotating disc. The quartz, chalcedony or sandstone tools were mounted on the loading arm. The load on the pin and speed of rotation were adjustable.

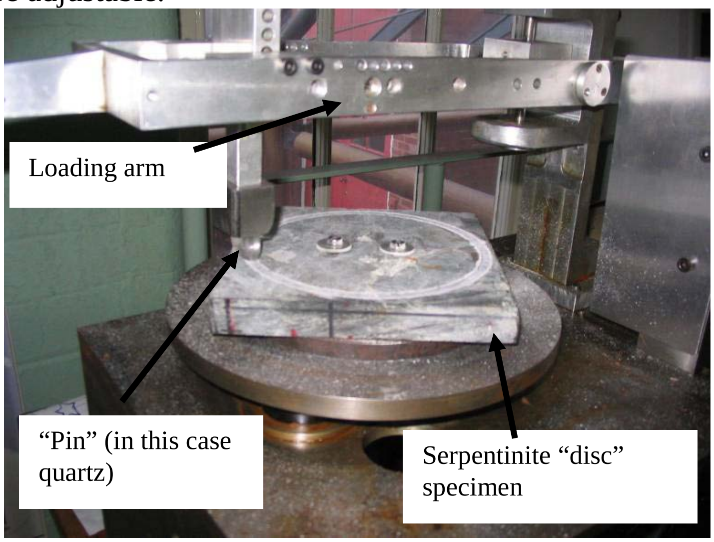

Fig. 8. Pin-on-Disc Wear Testing Machine

Due to differences in the composition and structure of the serpentinites and dolerite used in the study the initial roughness of the surfaces varied, despite the same cutting methods being used. Initial roughness values for the test areas were measured andcanbe seen in Table 4. Tests were carried out using each tool specimen (quartz, chalcedony or sandstone) with each work piece material under wet and dry conditions.

A load of 7kg was used in the tests and a contact sliding speed of 5.6 m/min. These parameters were the same as those used in the previous work [1] to allow comparison, rather than those identified in the human performance testing which were used in the polishing tests. Tests were planned to run for 40 minutes, but in one case excessive wear on the tool or work piece meant that the test was stopped after 20 minutes.

Wear losses were determined by mass loss measurements for the tool specimens and by weighing wear debris collected after the tests for the work piece specimens (mass lost from the top specimen was subtracted from the overall mass of wear debris). The data are respectively shown in Figures 9 and 10. Roughness values measured post test are shown in Table 4.

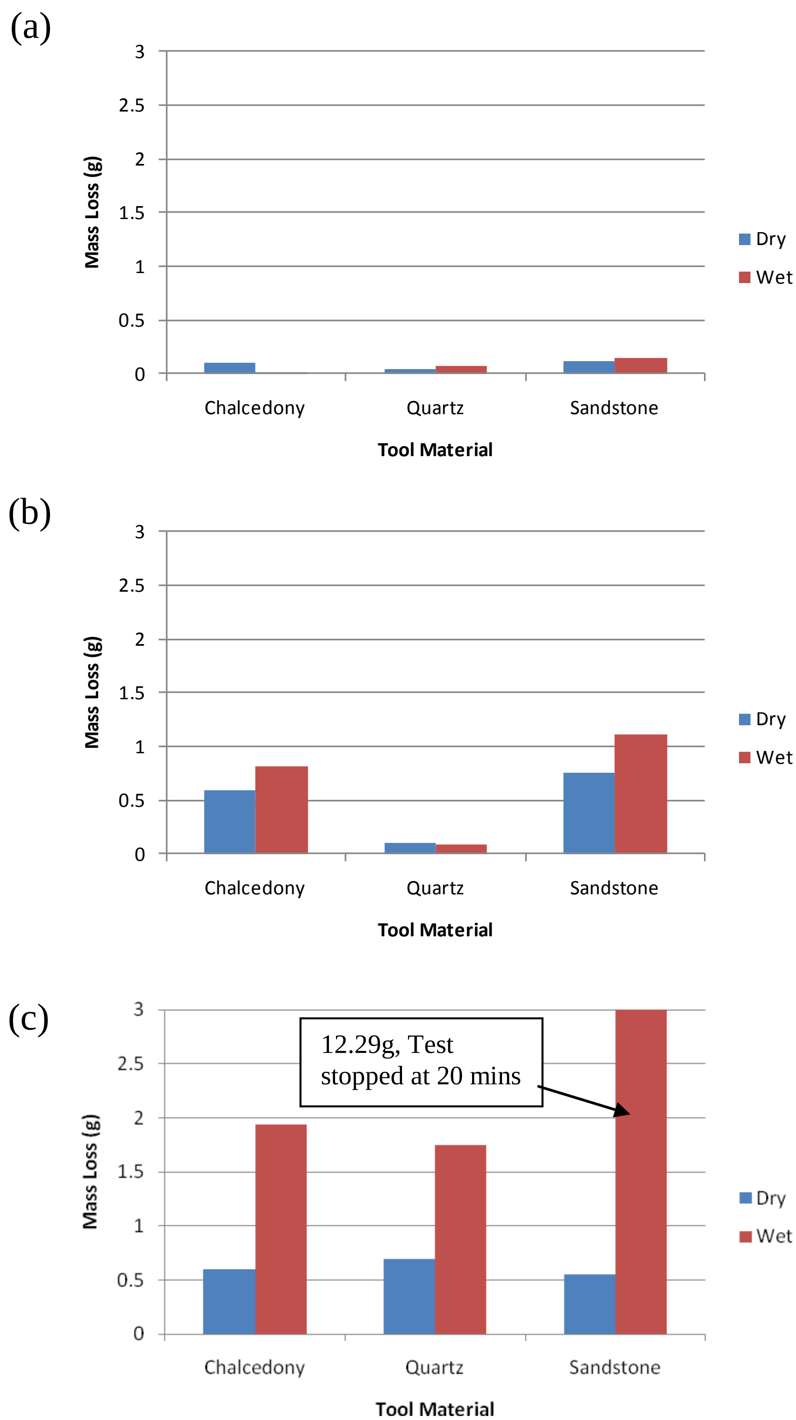

Figure 9. Wear of Work Piece Materials during Pin-on-Disc Sliding Test (a) Dolerite; (b) New Black/Green Serpentinite; (c) New Pistachio Serpentinite

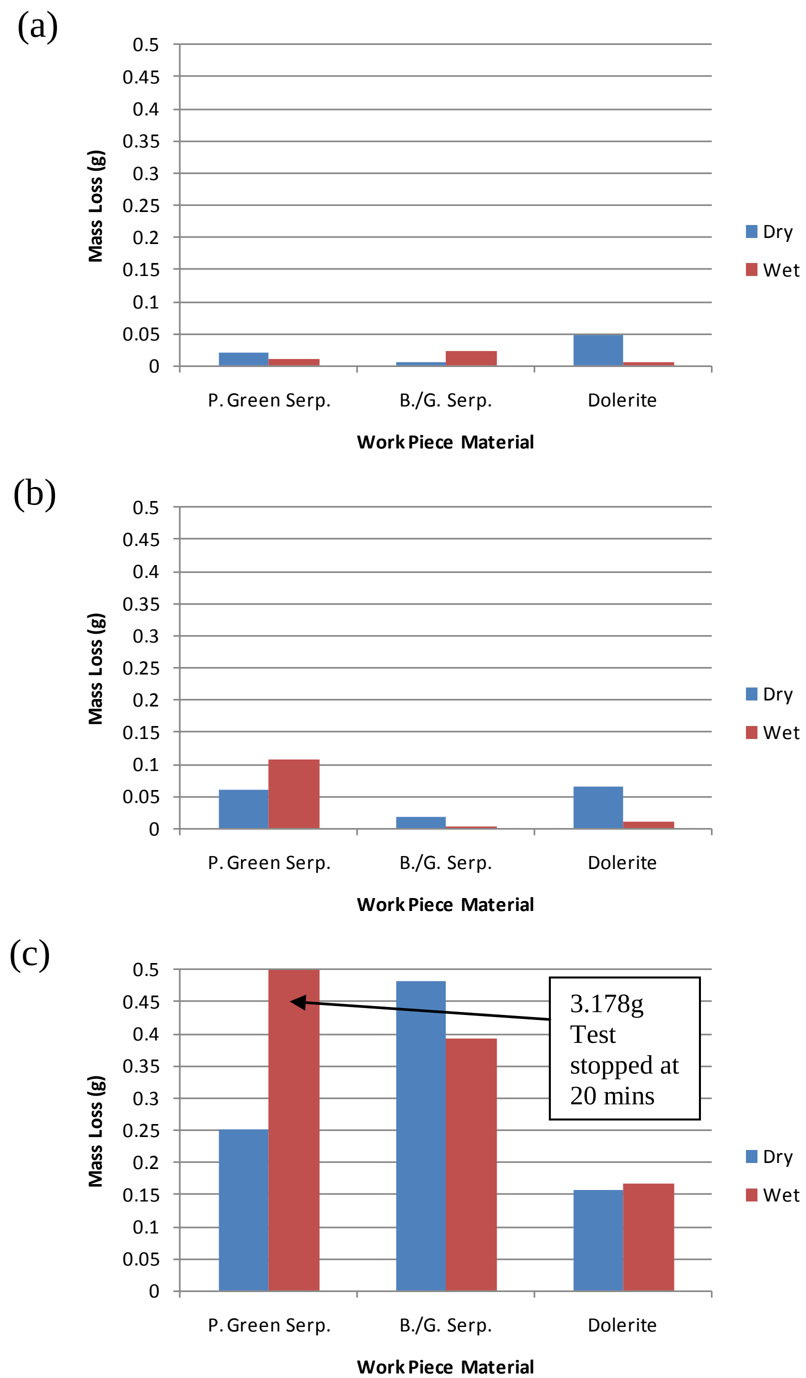

Figure 10. Wear of Tool Materials during Pin-on-Disc Sliding Test (a); Quartz (b) Chalcendony; (c) Sandstone

Work Piece Material	Tool Piece Material	Condition	Initial Ra Value (μm)	Final Ra Value (μm)
Dolerite	Chalcedony	Wet	1.73	1.93
Dolerite	Chalcedony	Dry	2.83	6.40
Dolerite	Quartz	Wet	1.73	1.39
Dolerite	Quartz	Dry	2.82	2.54
Dolerite	Sandstone	Wet	1.63	4.43
Dolerite	Sandstone	Dry	1.63	3.24
New Black/Green Serpentinite	Chalcedony	Wet	0.98	12.5
New Black/Green Serpentinite	Chalcedony	Dry	1.14	7.97
New Black/Green Serpentinite	Quartz	Wet	0.98	7.53
New Black/Green Serpentinite	Quartz	Dry	1.43	7.15
New Black/Green Serpentinite	Sandstone	Wet	1.43	17.2
New Black/Green Serpentinite	Sandstone	Dry	1.14	2.45
New Pistachio Green Serpentinite	Chalcedony	Wet	10.4	26.5
New Pistachio Green Serpentinite	Chalcedony	Dry	10.4	12.1
New Pistachio Green Serpentinite	Quartz	Wet	15.8	48.7
New Pistachio Green Serpentinite	Quartz	Dry	10.7	20.3
New Pistachio Green Serpentinite	Sandstone	Wet	15.8	54.7
New Pistachio Green Serpentinite	Sandstone	Dry	10.7	16.2

Table 4. Roughness Values before and after Testing

Reciprocating Sliding

A Plint TE77 reciprocating wear test rig was used for the polishing tests. A schematic of the test is shown in Figure 11.

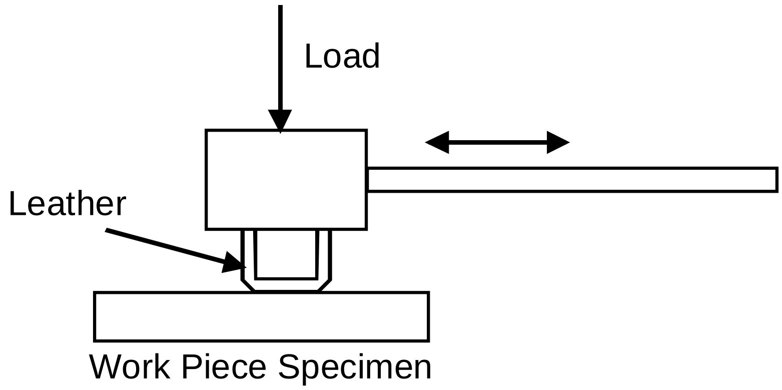

Figure 11. Schematic of Plint TE77 Test Rig used for Polishing Tests

The new black/green serpentinite sample (sliced from a core) was mounted onto the rig and securely held in place using a clamp. The desired materials were then added as appropriate, e.g. a layer of fat could be applied across the entire surface of the test specimen. The pin containing the top specimen, which in all test cases was a piece of natural leather, was then slotted into the mechanical fastening and locked into place. The mechanical arm was lowered so the two specimens were in contact. The required load was then applied. Full test conditions are shown in Table 5. The load and speed were selected on the basis of the Human Performance Tests described earlier. A frequency of 4.8Hz over a sliding distance of 40mm per cycle gave an average sliding speed of 192mm/s and each test was run for a period of 20 minutes.

Test No.	Medium	Time (mins)	Frequency (Hz)	Load (N)	Ra Before Test (μm)	Ra After Test (μm)	Ra Diff.
1	None	20	4.8	12.5	0.64	0.55	0.09 (↓)
2	Sand	20	4.8	12.5	1.18	0.75	0.43 (↓)
3	Fat (lard)	20	4.8	12.5	1.57	0.73	0.84 (↓)
4	Sand and Fat (lard)	20	4.8	12.5	0.99	0.86	0.13 (↓)
5	Water	20	4.8	12.5	1.69	0.56	1.13 (↓)
6	Water and Sand	20	4.8	12.5	0.56	3.48	2.92 (↑)

Table 5. Reciprocating Polishing Test Conditions

Table 5 shows the results of the tests, where in all cases except water and sand a reduction in Ra occurs. Images of some of the polished surfaces are shown in Figure 12. The result for the water and sand combination is not unexpected as fat would clearly help lubricate better than water. Water would act to keep sand particles in the contact area and so help create a more damaging condition resulting in the creation of abrasive scratch marks, than dry sand which would be less likely to remain under the leather. While improving the finish, tests with just leather, fat or water did not generate any scratches so they might be used after the abrasive to remove finishing marks.

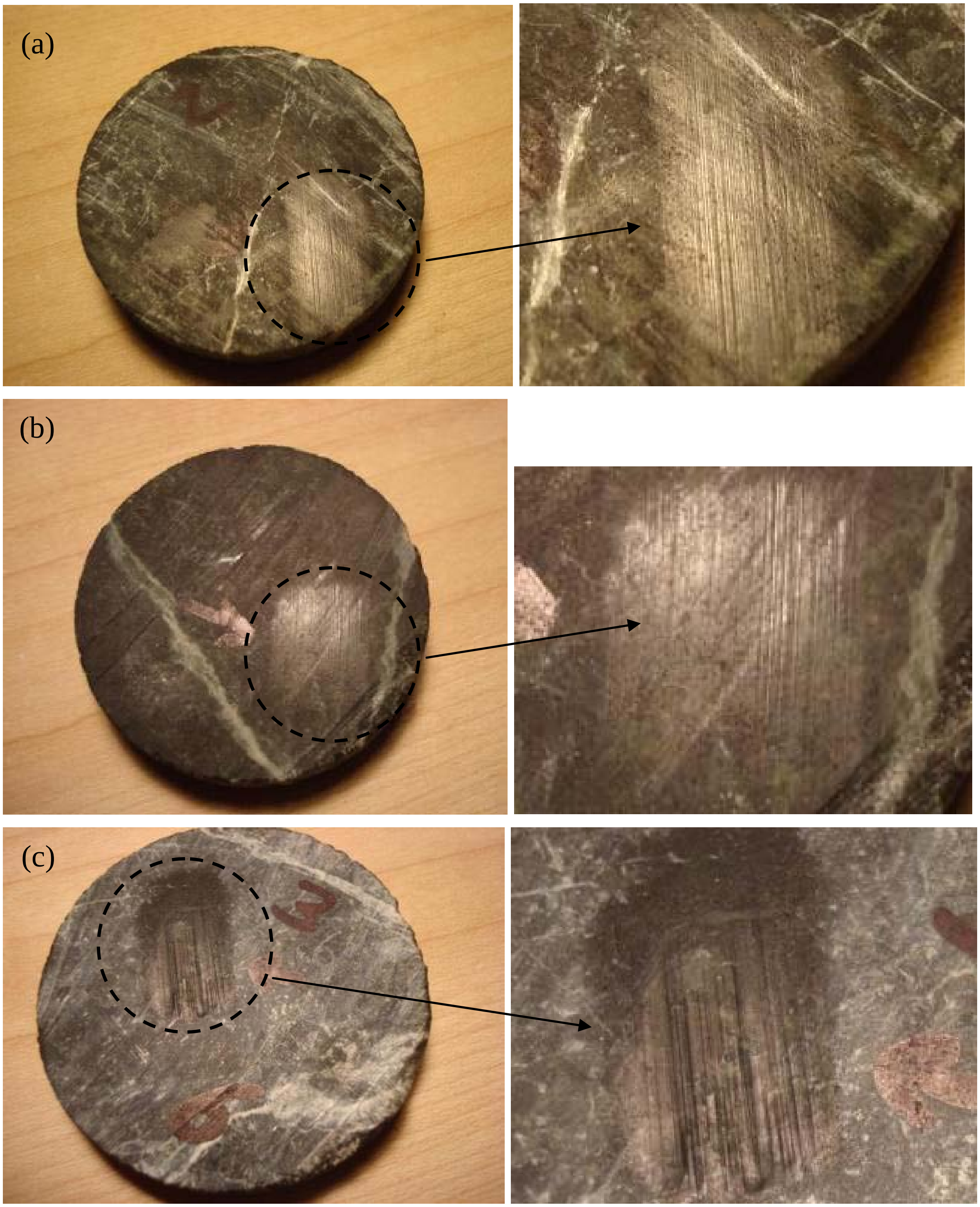

Figure 12. Reciprocating Rig Specimens (a) Sand; (b) Fat and Sand; (c) Water and Sand (disc diameter 50mm)

Impact

The test-rig used for the impact tests is shown in Figure 13 (for more information see [32]. The rig is a reciprocating hammer type percussive impact machine and consists of a striker connected to an arm. The motion of the arm controlled by a spring/cam system where the cam is rotated by a speed controlled AC electric motor. The arm is driven upwards by the cam and compresses a spring, which then controls the downward motion as the profile of the cam falls away.

The frequency of impact is adjustable by altering the speed at which the motor turns. For the purposes of this test, the cam was rotated at a speed of 10Hz. The impact velocity was 1.4 m/s at this frequency (derived from the cam lift curve). This gave an impact energy of 2J (for an approximate acting mass of 1kg), which while not being exactly the same as that measured in the human performance tests, it is as close as the rig would allow.

Tests were carried out on black/green serpentinite and pistachio green serpentinite. Specimens were again sliced from cylinders cut to the geometry required for the strength tests. This was straight forward for the black/green serpentinite, but with the pistachio green as the cylinders consistently failed. This meant that although a flat smooth surface was achieved for the black/green serpentinite, a coarse rough surface was the best that could be achieved for the pistachio green serpentinite. This meant that only qualitative results could be attained from the tests as it was impossible to generate robust quantative wear data across all specimens. The top specimen, or striker, for these tests was a 15mm diameter chrome steel ball with an equivalent specification to that of EN31 or AISI52100 with a specified hardness range of 700-900 Hv. The maximum surface roughness of the ball was 0.125μm.

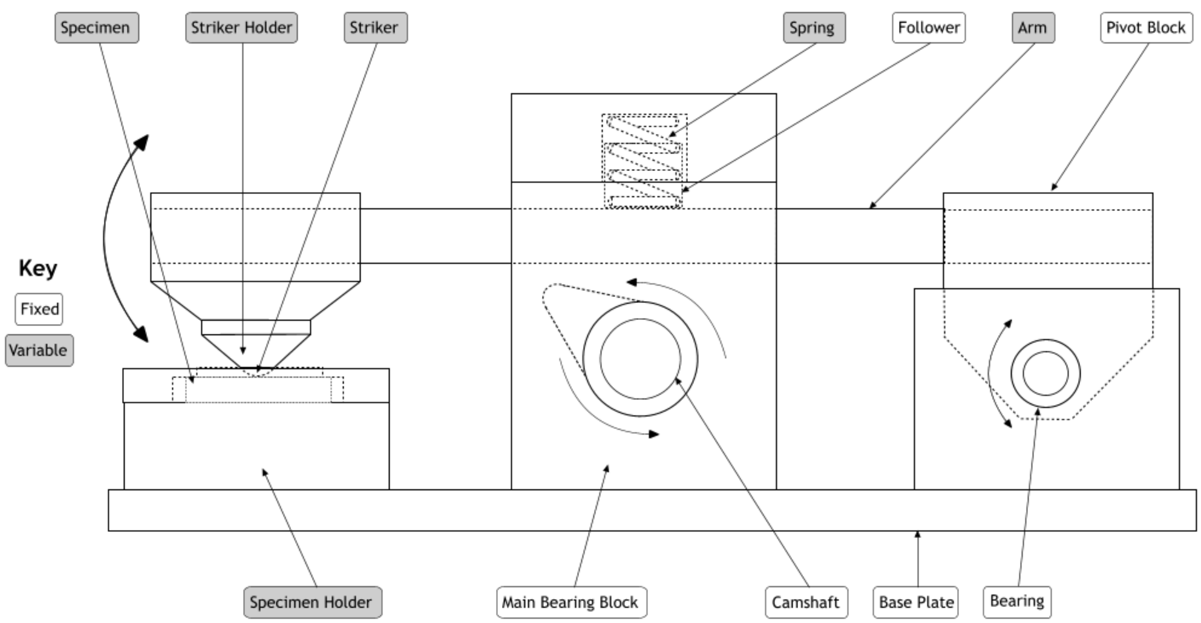

Figure 13. Impact Wear Test-Rig

With the new black/green serpentinite, the wear scars were small and shallow (see Figure 14). Small plate like fragments of stone became detached, particularly after 2400 cycles where the scar was larger, but still very shallow. The stone was very resilient to impact.

The procedure resulted in the loss of a large chunk of the pistachio green serpentinite at around 280 cycles (see Figure 15). As a result, the test was stopped as the large change in height caused the ball bearing to lose contact with the stone. The pistachio green serpentinite is not very resistant to impact.

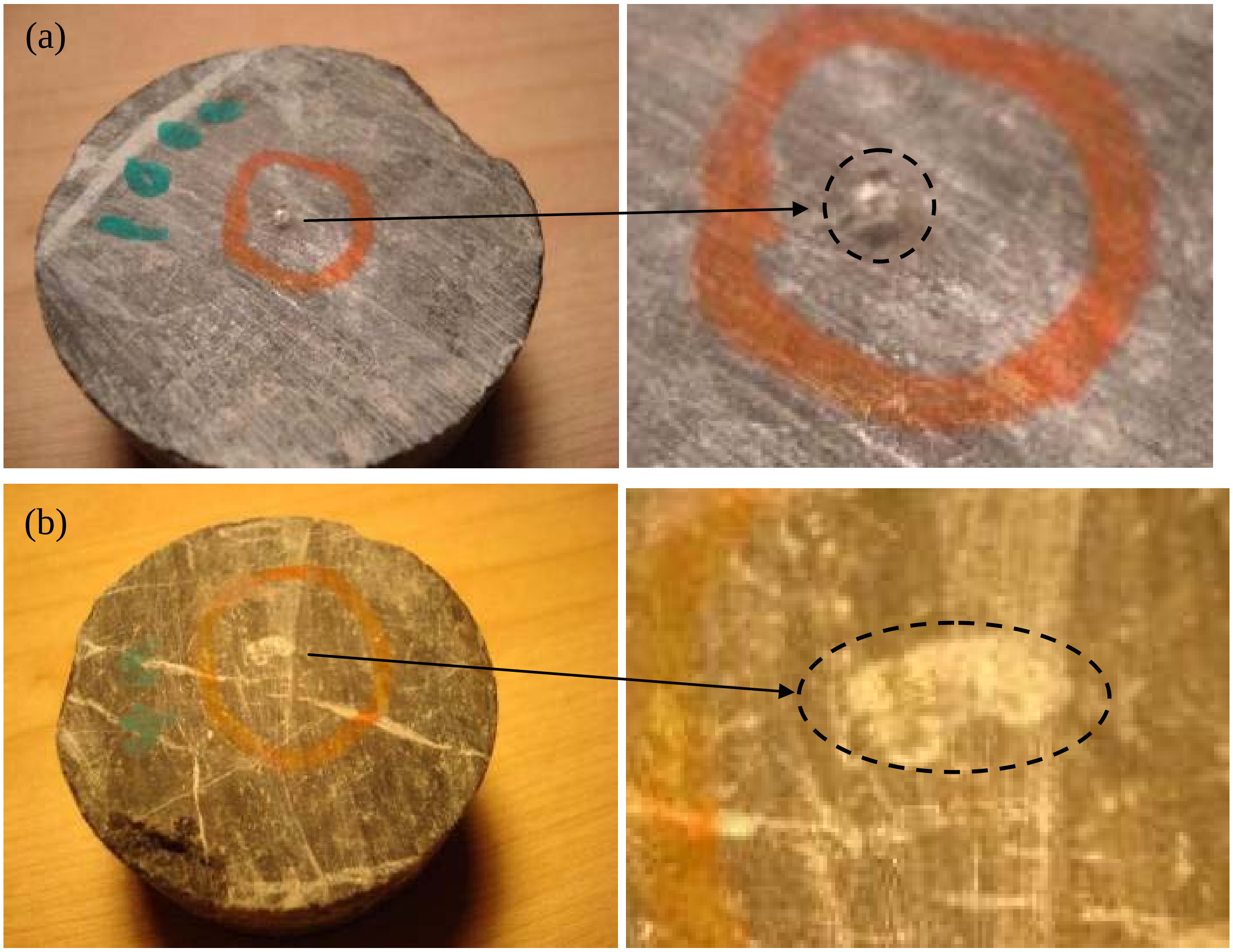

Figure 14. New Black/Green Impact Specimens (a) 1000 Cycles and (b) 2400 Cycles (disc diameter 50mm)

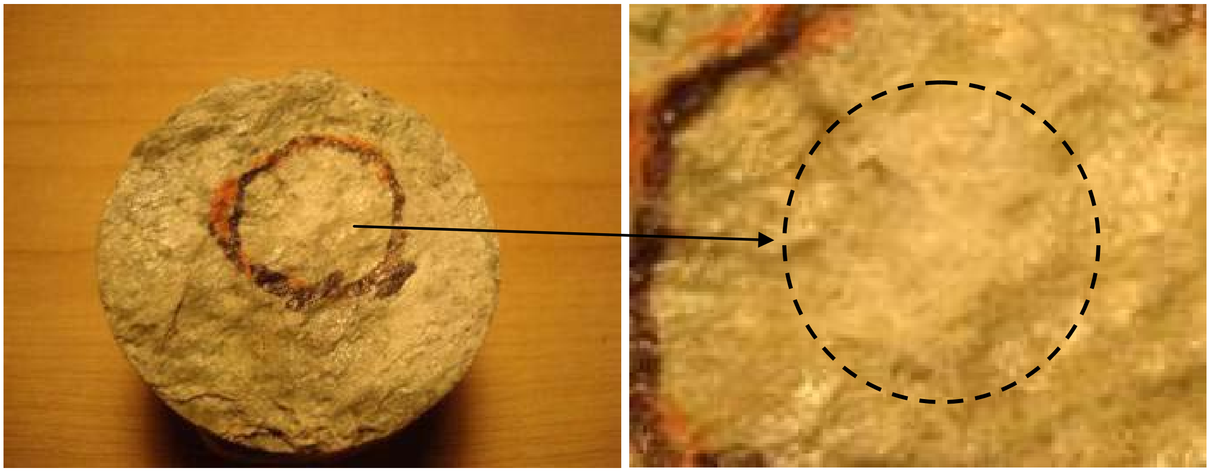

Figure 15. Pistachio Green Impact Specimen (280 cycles) (disc diameter 50mm)

DISCUSSION

Uni-directional Sliding Tests

Generally speaking, where comparable the same trends in the uni-directional sliding tests have emerged in this work that were seen in the previous testing [1]. As before, the same issues arise with the number of tests carried out. More would have been desirable to increase the statistical significance of the results, but availability of the work piece materials would not allow this. The other issue with all the tests was the initial state of the specimens. The specimens were sawn, which would have imparted a much smoother surface than Neolithic man would have had to contend with. This is probably why in the uni-directional tests, for example, the final roughness values did not seem to offer an improvement over the original values (see Table 4), in fact in most cases the roughness worsened. Qualitative analysis of the wear tracks, however, in some cases, indicated that while grooves had formed in the wear tracks as a result of abrasion, there was still a polished finish to the surface.

In terms of strength and porosity, dolerite offered the greatest strength and lowest porosity, new black/green serpentinite was in the middle for both and new pistachio green serpentinite had the highest porosity and, although a strength test could not be carried out, it was clear given the ease with which the specimens fractured and the measurements from the previous tests, that it was the weakest.

This is reflected in the mass losses from the sliding wear tests. Dolerite wore the least in all conditions and new pistachio green serpentinite wore the most in all conditions. In terms of the tool materials, sandstone, despite being the weakest material due to its inhomogeneous structure gave the highest work piece wear rates and quartz (the hardest tool piece material) the lowest. This is on first examination counter intuitive. However, the fact that the sandstone broke up and wore down increased its ability to wear the counterface material. The wear particles stayed in the contact with the surfaces, particularly in wet conditions and produced severe three-body abrasive wear. The particle supply was continually replenished during the test as the sandstone kept wearing down. For the tests where little wear debris was produced, including dolerite and new black/green serpentinite run against chalcendony and quartz, wear rates were much lower. In tests with new pistachio green serpentinite, a great deal of work piece wear debris was generated which increased both work piece and tool piece wear. The wear increased further still in wet conditions when due to increased porsity the new pistachio green serpentinite was weakened further. This was particularly evident in the test with sandstone where the sandstone also weakened due to water absorption. This effect was also apparent in tests on new black/green serpentinite.

Any material combination could be used to cut the new pistachio serpentinite and this effect would be increased in wet conditions. Suitable materials for polishing are harder to identify, although the best option would appear to be chalcendony (although it was not actually used for polishing in the archaeological assemblage) or sandstone in dry conditions, although this would only be the first stage of several. Another solution, for example using the animal fats studied in the reciprocating tests would be required to achieve a finely polished finish in this material.

The new black/green serpentinite would be best cut using sandstone or chalcedony. Quartz did not prove as effective in these tests as the previous tests [1]. The best polishing option this time was dry, rather than wet, sandstone. For this to have occurred, a more high durability sandstone with a finer, stronger grain structure would be required, i.e. that absorbs less water and does not breakdown as easily as it absorbs water. None of the options trialled presented an effective way to cut dolerite, which is not surprising given its immense strength. All options, though offered ways to polish it.

Some simple manual tests were carried out to study how effective new dark green serpentinite was at cutting through new pistachio green serpentinite. The specimens used and the resulting groove are shown in Figure 16. The groove actually compares well with that shown in Figure 1b, indicating that dark green serpentinite offers a further option for cutting of pistachio green serpentinite.

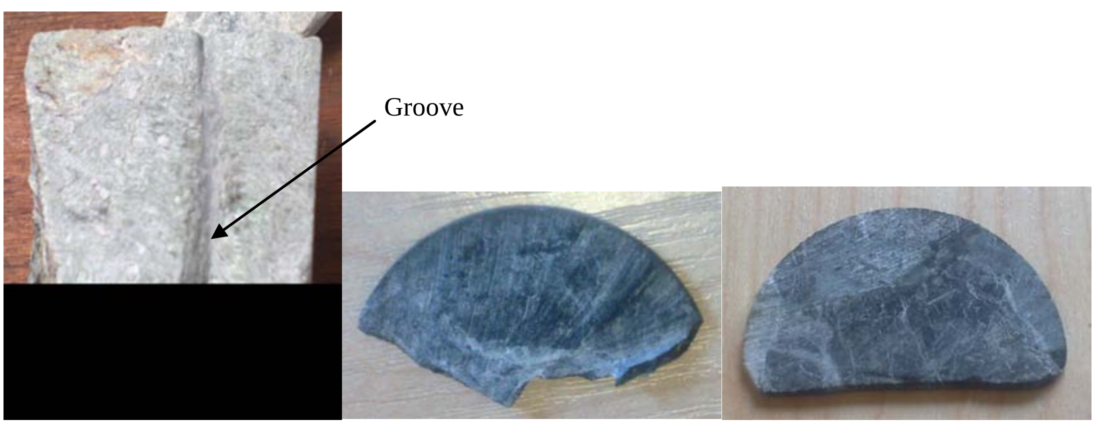

Figure 16. (a) Manual Groove Cut in New Pistachio Green Serpentinite; New Dark Green Serpentinite Specimen (b) Before Test and (c) After Test

Reciprocating Polishing Tests

The polishing tests gave interesting results. It is clear that different combinations would be useful in a staged approach to improving the finish of the work piece materials. One option would be to use sand and water initially and then move on to using fat and sand and then fat/water on their own where the latter would be to remove abrasive scratches created by the sand. There is evidence showing that the actual finishing process was carried out in stages like this. In fact it likely that some of the combinations used in the uni-directional sliding would be the initial rough polishing option, then leading on to the use of leather and fat for fine polishing.

Impact

Not enough impact tests could be carried out to establish firm conclusions. However, it was clear that the new black/green serpentinite was very resistant to impact. The impact was at 90 degrees to the layers that make up the stone, as it was for the new green pistachio serpentinite, which was far less resistant to impact. This will have been due to its weaker more porous structure and weaker minerals. Impact would be a good method for rough shaping of this type of stone, but it would tend to break along the foliations and cracks present in the rock.

CONCLUSIONS

In this paper a study to further understanding of the materials and methods used by Neolithic people in Greece has been carried out.

Tool materials have been identified that would be suitable for cutting/sawing and polishing a number of different work piece materials.

Pistachio green serpentinite, being the weakest and most porous was very easy to machine. Percussive impact enabled large pieces of stone to be removed. Sliding with all tool materials (sandstone, quartz and chalcedony) removed sufficient material to form a groove that could be further worn to potentially cut through a slab of stone. When water was added the cutting action was more effective with the hard tool piece materials (quartz and chalcedony) as the pistachio serpentinite was further weakened. With sandstone wear was even greater as the sandstone itself also broke down and an abrasive slurry formed increasing three-body abrasive wear.

The dark green serpentinite was harder and less porous and there harder to cut through. Clearly with this material Neolithic man would have had to spend many more hours creating an artefact. It was, however, easier to produce a polished finish on this type of serpentinite. The reciprocating wear tests indicated that using leather and combinations of different lubricants and sand enables the creation of various levels of surface finish.

In fact this was perhaps the most significant conclusion from this study. Archaeological evidence has indicated that a staged approach was taken in artefact manufacture, but now methods for carrying out each stage are better defined.

The dolerite being the hardest and least porous work piece material was the hardest to wear. None of the tool piece materials wore dolerite significantly. This may have reduced the likelihood of many artifacts being made from this material. It was perhaps more likely to have been used as a tool piece material.

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