



Recognising burnt vein quartz artefacts in archaeological assemblages

Killian Driscoll^{a,*}, Julian Menuge^b

^a School of Archaeology, University College Dublin, Belfield, Dublin 4, Ireland

^b School of Geological Sciences, University College Dublin, Belfield, Dublin 4, Ireland

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ABSTRACT

The primary aims of this study were to determine how vein quartz behaves in an open wood fire and to suggest how burnt quartz may reliably be distinguished from unburnt quartz. Experimental burning was conducted on 10–50 mm pieces of knapped quartz collected from outcrops and beach cobbles near a later Mesolithic and Neolithic quartz scatter at Belderrig, north County Mayo, Ireland. Burning resulted in considerable fragmentation, with the majority of post-burning fragments <10 mm in size. Compared to experiments with flint, few quartz pieces were expelled from the hearth during burning, probably due to lower water content. Burning reduced the lustre and transparency of quartz and oxidized any iron-bearing rock impurities to a red-brown or pink colour, but these changes could only be diagnostic of burning where unburnt quartz of the same type is available for comparison. Burning did not affect the texture of the quartz, though quartz grain boundaries became more visible in some samples. Under the microscope, all >5 µm fluid inclusions in quartz lost their fluid contents, often with the development of fluid escape structures, and this is likely to be a reliable discriminant between burnt and unburnt vein quartz generally, even in the absence of unburnt material for comparison. Burning also creates microfractures, but this feature does not provide a diagnostic test of burning as there is considerable overlap between burnt and unburnt samples in microfracture density.

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1. Introduction

Archaeologists have long recognized burnt flint in the archaeological record (Purdy, 1975) and its identification is a routine part of lithic analysis. Signatures of burning include discolouration, pot lidding, and surface cracking, and analysts make distinctions between the degree to which flint has been burnt (Sergant et al., 2006). The identification of burnt lithics can aid in interpreting archaeological sites and assemblages, such as indicating evidence of hominin use of fire in the Lower Pleistocene (Goren-Inbar et al., 2004), identifying ritual practices (Bradley, 2005), and recognising 'invisible' hearths, where charcoal and other burnt organic materials have been lost through weathering or erosion (Sergant et al., 2006). Vein quartz was used in many parts of the world for stone tools but this material has proved difficult for archaeologists to analyse, with diverse approaches utilised to try and provide some analytical purchase on the material (Dickson, 1977; Barber, 1981; Knutsson, 1988; Bisson, 1990; Saville and Ballin, 2000;

Cornelissen, 2003). Evidence for burnt quartz artefacts, however, has "rarely [been] recognized, reported, described or discussed" (Ballin, 2008).

In order to understand the use of quartz in Irish prehistoric lithic repertoires, a programme of research, based on experimentally knapping quartz, was undertaken at the UCD School of Archaeology, Ireland (Driscoll, 2009, 2010). The experiments used quartz from a number of different sources and knapped the material using a variety of stone working techniques, producing an experimental assemblage of over 10,000 ≥10 mm artefacts. This experimental assemblage was analysed to formulate a framework for analysing archaeological quartz assemblages (Driscoll, 2011). A secondary experiment involved investigating the effects of burning on quartz artefacts and involved knapping a smaller assemblage using quartz from the same four sources. This experiment did not study the effects of heat treating quartz, which has been investigated by Flenniken (1981) and Leveillee and Souza (1981). The present paper presents the results of experimental wood fire burning of vein quartz and of the macroscopic and microscopic differences between burnt and unburnt quartz. The primary objectives were to determine how vein quartz behaves in a fire and to suggest how burnt quartz may reliably be distinguished from unburnt quartz. Following from the results of Sergant et al. (2006), this burning experiment focussed on placing vein quartz artefacts directly into

* Corresponding author. 3 Sli Burca, Knocknacarra, Galway, Ireland. Tel.: +353 91 515312.

E-mail addresses: killiandriscoll@gmail.com (K. Driscoll), j.f.menuge@ucd.ie (J. Menuge).

a fire. Three effects were investigated during burning: visible signs of burning, the fragmentation rate of the quartz and the spatial distribution of artefacts.

The four vein quartz sources used for the experiments (named 'beach', 'metadolerite', 'psammite' and 'Rose Cottage') were collected from three outcrops – two in association with metadolerite and one in association with psammite – and a cobble from the shoreline, all within 1 km of an excavated Later Mesolithic and Neolithic quartz scatter at Belderrig, north County Mayo, Ireland. This research-led excavation, directed by Graeme Warren (2009), acted as the primary archaeological case study for the present project. Samples of the quartz from the four sources were analysed macroscopically and in thin section. Thin sections showed that the crystal size was 1–5 mm, making all of them coarse-grained raw materials, and variable in character in terms of crystal orientation and fracture development, but with all of them being of massive habit. The samples contained multiple macro- and micro-fractures, some of which led to the subsequent development of veinlets of quartz within them.

2. Experimental burning method

A block of quartz from each of the four sources was knapped, with ten artefacts from each source used for each of the seven size grades (Table 1). This gave a total assemblage of 280 artefacts, totalling 1.7 kg, which were burnt, with an approximately equal amount of remaining artefacts from the knapping kept as references of unburnt material. The instruments for measurements, weights, and sieving were as follows: a 200 mm Vernier callipers rounded to one decimal, a ± 0.01 g scale rounded to two decimals, and two calibrated sieves – a 5 mm perforated metal plate sieve and a 1 mm woven wire sieve.

The fuel source used was pine (*Pinus*); the dead wood was collected from a forest floor and consisted of small twigs and branches up to 5 cm in diameter. Pine was a predominant species in the north Mayo forest during the date range of the Belderrig quartz scatter (Mitchell and Ryan, 2001; O'Connell and Molloy, 2001). A series of plywood sheets, covering 36 m², were placed surrounding the hearth in order to determine the extent of artefact dispersal from the fire. In order to prevent fire damage to the sheets, a layer of peat was placed surrounding the hearth, laying over the edges of the plywood.

The fire was set and fuelled for 1 h; the quartz assemblage was then placed in the centre of the hearth, in a manner to allow all of the assemblage an equal chance of burning. After a further 2 h the fire had cooled enough to begin removing the assemblage from the hearth and begin sieving, using 5 mm and 1 mm sieves. The peat surrounding the hearth was also sieved and the hearth was trowelled back until unburnt soil was exposed. The quartz samples will have reached their maximum temperature at the beginning of the time spent in the fire. This temperature was not measured but can be estimated from the type of fuel used to be at least 500 °C (Urbas and Parker, 1993). The temperature of burning wood can be

estimated from the black-body radiation colour that it glows (Planck, 1901), likely ranging from 580 °C (deep red) to 730 °C (bright red). Quartz in contact with glowing wood is therefore likely to have reached over 600 °C.

3. Results

3.1. The burning experiment

Once placed in the fire, the immediate visible sign of burning was the apparent bleaching of the assemblage. Most of the artefacts turned a pure snow white, losing their generally slightly metallic grey hue. Another immediate effect was the development of a salmon pink and burnt orange hue in places on many of the artefacts, but almost none of the quartz exhibited any blackening.

Only 0.85% ($n = 13$) of the artefacts were expelled from the hearth, defined here as any area of burning, and the final hearth was approximately 1.4 m². The expelling of small fragments started within minutes of placing the assemblage in the fire and continued sporadically for at least 90 min. None of the artefacts were expelled in the prevailing breeze's direction. The furthest expelled artefact noted was 2.8 m from the hearth's centre. This may imply that some pieces could have been expelled further than the area monitored. Most of the expelled artefacts, however, fell within 1 m radius of the hearth centre. Most movement of the artefacts was limited to within the hearth itself. Within the hearth, the final area covered by the quartz was double the initial area. Fig. 1 shows the fire once cooled, 3 h after the assemblage had been deposited into the hearth.

The initial 280 artefacts resulted in a post-burning assemblage of 1534 ≥ 1 mm artefacts. When removing the quartz from the fire, the quartz had increased in brittleness and a number of the larger artefacts snapped and/or crumbled; on returning to the artefacts two days later, they had become less brittle and did not crumble as easily as when initially taken out of the hearth. Fig. 2 highlights the changed proportions for the size ranges of the artefacts, which began in equal proportions with no <10 mm artefacts.

Fig. 3 graphs the change in weight for the size grades. The largest artefacts ($\geq 40 < 50$ mm), were reduced from 40 artefacts to 31, and the $\geq 35 < 40$ mm artefacts had a similar reduction in quantity. While the pre-burnt assemblage contained no $\geq 5 < 10$ mm artefacts, the post-burnt assemblage consisted of 12.8% of that size range; <15 mm artefacts initially accounted for 14.3% of the assemblage, and after burning they accounted for 80.5% of the assemblage, with <5 mm artefacts accounting for the majority of that proportion. Therefore, the burnt assemblage contains a significant quantity of <10 mm artefacts. Because the experimental knapping assemblage

Table 1
Pre-burning weight in grams for ten artefacts per size grade.

Size grades	Beach	Rose Cottage	Metadolerite	Psammite	Total
$\geq 10 < 15$ mm	4.48	3.35	3.02	6.20	17.05
$\geq 15 < 20$ mm	6.97	12.37	15.85	8.25	43.44
$\geq 20 < 25$ mm	21.90	25.18	23.73	20.60	91.41
$\geq 25 < 30$ mm	40.23	43.15	78.56	37.33	199.27
$\geq 30 < 35$ mm	77.11	48.48	51.16	89.31	266.06
$\geq 35 < 40$ mm	83.43	103.68	104.08	72.18	363.37
$\geq 40 < 50$ mm	164.60	195.23	205.33	158.14	723.30
Total	398.72	431.44	481.73	392.01	1703.90



Fig. 1. Quartz in hearth 3 h after deposition in fire.

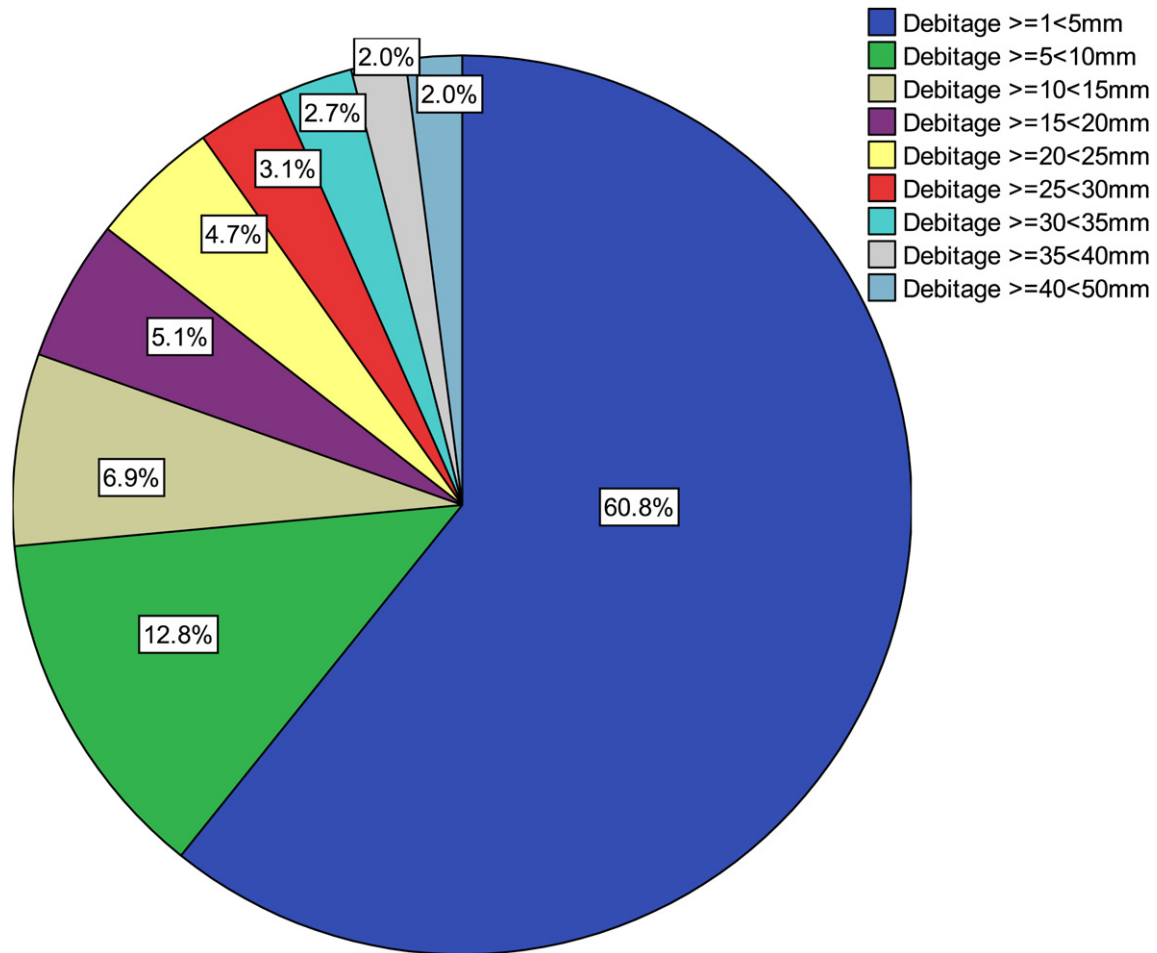


Fig. 2. Post-burning size grades. The pre-burn assemblage had the same number of artefacts in each size grade but with none < 10 mm.

(see Driscoll, 2010) did not count the < 5 mm debitage, consequently comparisons are made on the proportions of ≥ 5 mm debitage – for the ≥ 5 mm debitage, 25% of the experimental assemblage was < 10 mm while 33% of the post-burnt assemblage was < 10 mm, highlighting that burning will substantially increase the quantity of small fragments in a given assemblage.

Overall, 93% of the $\geq 5 < 10$ mm artefacts exhibited signs of burning. The $\geq 1 < 5$ mm fragments proved difficult to identify as burnt so this category was not quantified. Similarly, the $\geq 5 < 10$ mm group had the lowest rate of visible burning. This is not necessarily because these fragments were not 'burnt', but rather because these smaller fragments are more difficult to identify as burnt. The Rose Cottage quartz was the most difficult to identify as burnt; while it is possible that some of the artefacts may in fact have remained unburnt and coincidentally have been only the Rose Cottage quartz, this does not seem likely. For the burnt ≥ 25 mm artefacts, it was reasonably easy to categorise their source materials (Fig. 4). For the < 25 mm artefacts, however, it was harder to categorise them by source material due to the general similarities of the sources, so their source was labelled as "?".

3.2. Macroscopic comparison of burnt and unburnt quartz

Once the artefacts were removed from the fire it was clear that the four sources had reacted differently, albeit subtly, depending on the mineral inclusions present within the matrix of the vein quartz. Table 2 gives the pre- and post-burn characteristics for the four sources. All the materials had a slightly metallic grey primary

hue and all but the Rose Cottage turned white; the Rose Cottage only turned partially white. The secondary hue of the materials was not apparent on all the pre-burnt artefacts, and when present it was usually confined to small patches, apart from the beach when it was more extensive (Fig. 5). For the metadolerite and beach quartzes, the pale yellow secondary hue was formed by iron oxides, while the psammite's grey hue was formed by an intermixing of the parent psammite rock into the vein quartz matrix as well as iron oxides. The metadolerite's secondary hue was burnt orange, and the psammite's and beach's were salmon pink/burnt orange.

In terms of the texture, or granularity, of the materials, the unburnt materials were described as either sugar, sugar/smooth, or smooth. Sugar texture (psammite samples) describes quartz crystal grains that appear like granulated sugar that has been moistened and subsequently dried, allowing some of the grains to meld. Smooth texture (metadolerite samples) is where the crystal grains are not readily apparent, even though microscopic examination (Section 3.3) shows that the individual crystals are nevertheless large (1–5 mm). Sugar/smooth (beach and Rose Cottage samples) is intermediate between the two textures. Sample textures did not visibly change on burning. However, changes in the materials' hue accentuated some of the grain patterning by creating a greater degree of contrast in the material. This didn't apply to the metadolerite, which retained its smooth appearance, or to Rose Cottage which had less of a colour change and no secondary hue.

The unburnt materials' opacity was divided into translucent and semi-opaque. The metadolerite's opacity changed from semi-

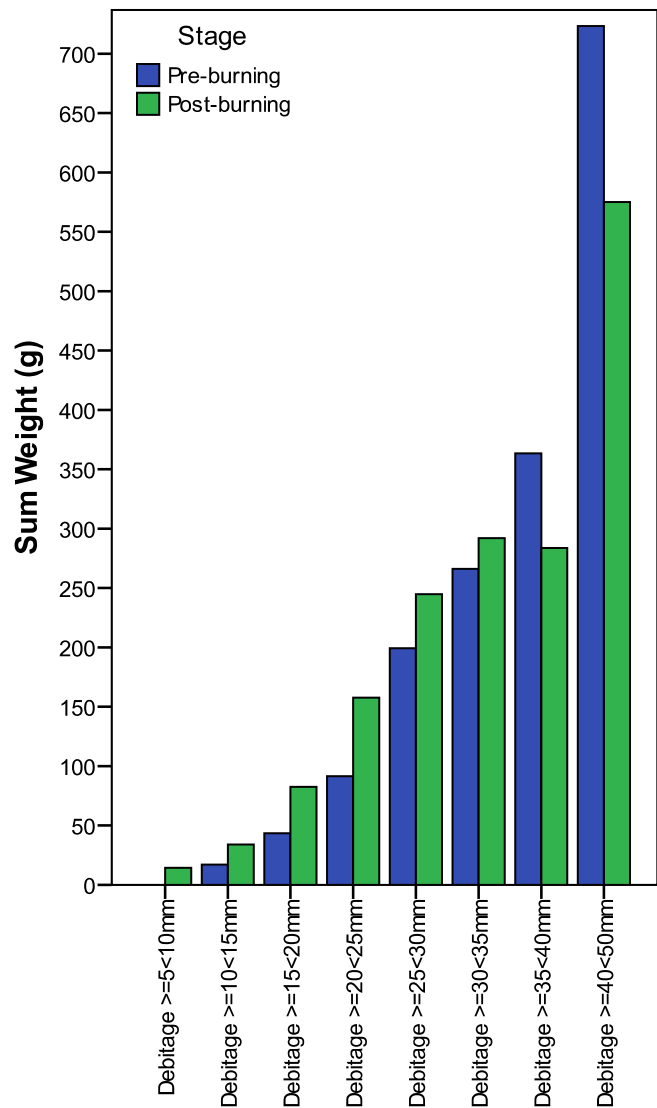


Fig. 3. Pre- and post-burning weight of artefacts.

opaque to opaque, and the change was the most uniform of all the materials; the metadolerite was also the least granular of the materials. The beach began and ended as semi-opaque, but the level of opacity increased slightly. Both the psammite and Rose Cottage changed from translucent to semi-opaque with the latter's opacity increasing to a lesser extent. Fig. 6 shows backlit pre- and post-burnt beach and metadolerite artefacts of similar thickness to highlight the change in opacity.

All of the quartzes had an initial vitreous lustre; the psammite has a lesser vitreous lustre in places because of contamination of

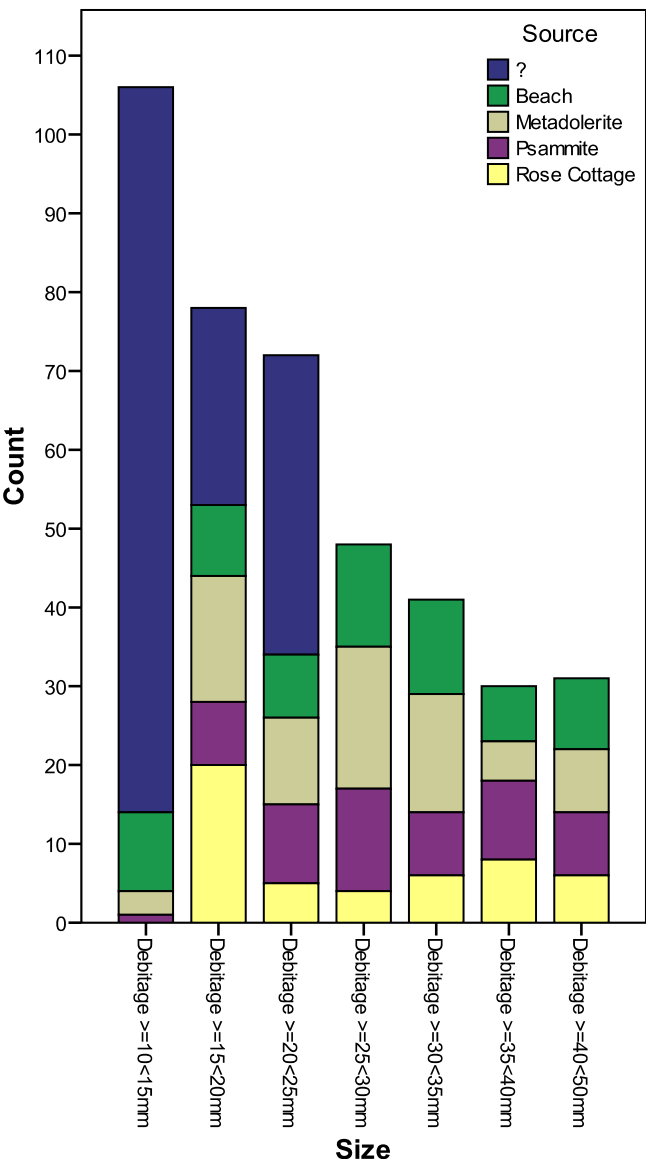


Fig. 4. Post-burning quartz count by source and size grade. Pre-burn assemblage had 40 artefacts per size grade.

the vein quartz by particles of psammite rock. After burning, the artefacts were generally dulled giving a less vitreous lustre, especially the metadolerite which became uniformly white and duller.

3.3. Microscopic comparison of burnt and unburnt quartz

Six samples of vein quartz were selected for microscopic examination. These comprised three unburnt samples, one each from the

Table 2
Pre- and post-burn macroscopic characteristics of quartz.

Material source	Stage	Primary Hue	Secondary Hue	Grain	Opacity
Metadolerite	Pre-burn	Metallic grey	Pale yellow	Smooth	Semi-opaque
Metadolerite	Post-burn	White	Burnt orange	Smooth	Opaque
Rose Cottage	Pre-burn	Metallic grey	—	Sugar/smooth	Translucent
Rose Cottage	Post-burn	White/metallic grey	—	Sugar/smooth	Semi-opaque
Psammite	Pre-burn	Metallic grey	Grey	Sugar	Translucent
Psammite	Post-burn	White	Salmon Pink/Burnt orange	Sugar	Semi-opaque
Beach	Pre-burn	Metallic grey	Pale yellow	Sugar/smooth	Semi-opaque
Beach	Post-burn	White	Salmon Pink/Burnt orange	Sugar/smooth	Semi-opaque

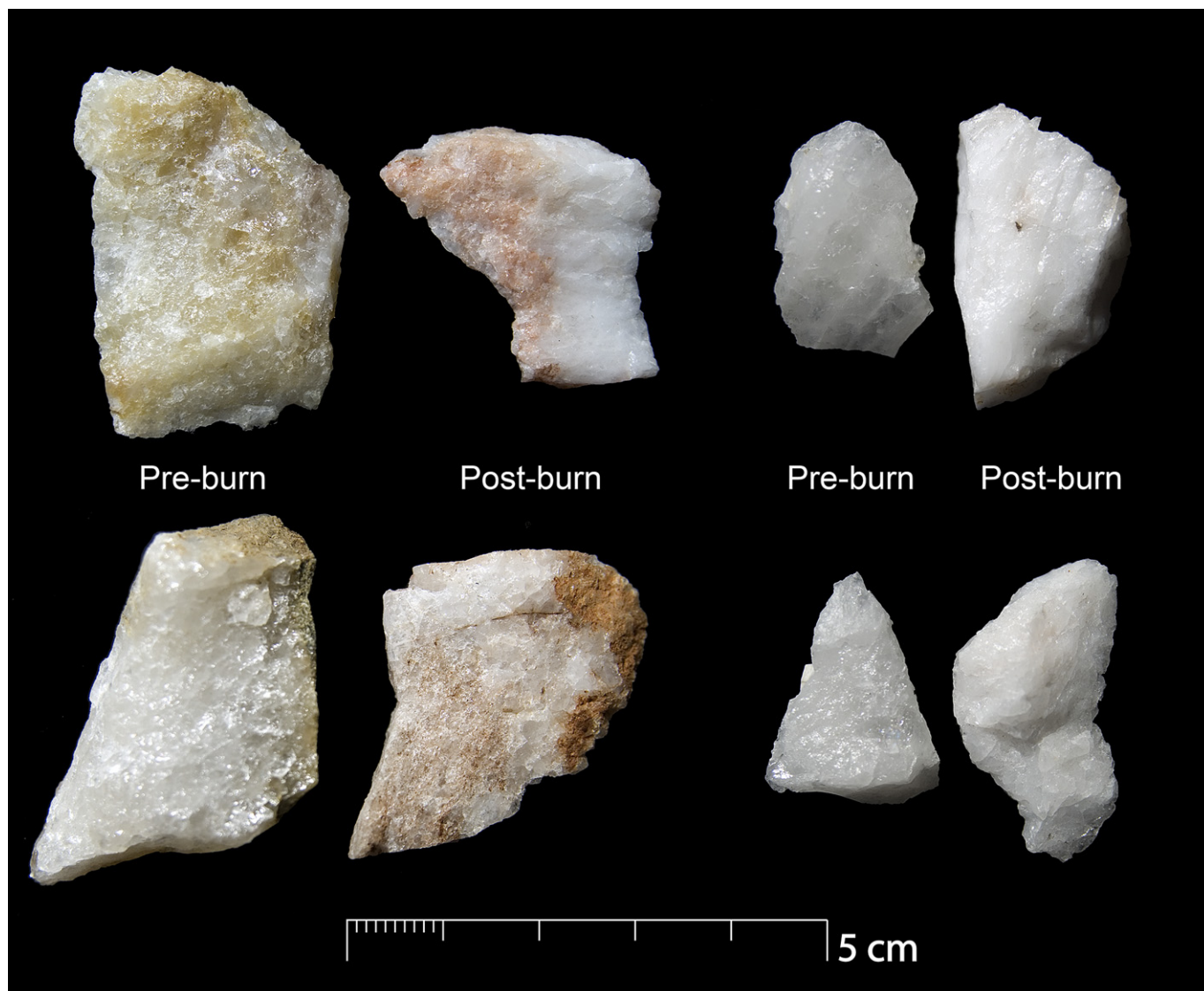


Fig. 5. Colour change due to burning. Top left: beach. Top right: metadolerite. Bottom left: psammite. Bottom right: Rose Cottage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Rose Cottage, psammite and metadolerite localities, and three burnt samples from the same localities (Table 3). The beach samples were excluded from the microscopic examination as the beach cobbles are derived from either the metadolerite or psammite localities.

Standard petrological thin sections 0.03 mm thick with cover slips were made of each sample. Thin sections were examined using a transmitted light petrological microscope, both in plane polarized light and between crossed polars, at total magnifications of 20–500.

All samples consisted of >99% quartz. Other minerals present have not been identified but in all cases are present only as isolated grains <0.05 mm diameter. The edges of the veins, containing occasional fragments of the surrounding rocks, have not been studied. Some of the more significant textural features observed in thin section are summarised in Table 4. The three types of difference observed between burnt and unburnt samples are described in Sections 3.3.1–3.3.3.

3.3.1. Fluid inclusions

The most consistent difference concerns fluid inclusions (Roedder, 1984). These range from tens of μm in size down to the limit of resolution of the microscope (about $1\ \mu\text{m}$). Fluid inclusions

form geologically when quartz crystals grow from hydrothermal fluid and represent small samples of that fluid. On cooling they usually separate into a liquid and a bubble of vapour, as is seen in all three samples studied. In the unburnt samples, many fluid inclusions are intact and can be recognized by the presence of a darker, rounded vapour bubble within an otherwise liquid inclusion (Fig. 7a and b). It is likely that fluid inclusions in all vein quartz include a proportion of gas as well as liquid at room temperature (Fron del, 1962), sometimes accompanied by tiny crystals. In the burnt samples, all fluid inclusions above about $5\ \mu\text{m}$ diameter have decrepitated, that is they have lost their original contents and are now gas filled. In some cases, decrepitated fluid inclusions are surrounded by fluid escape structures (Fig. 7c and d) resulting from escape along new microfractures followed by partial re trapping of inclusion fluids in new secondary inclusions. Very similar fluid escape structures have been created experimentally by decrepitation of inclusions in synthetic quartz (P  cher, 1981).

3.3.2. Fractures

Two of the three burnt samples show an increase in microscopic fracture density (Fig. 8). In burnt samples, microfractures have

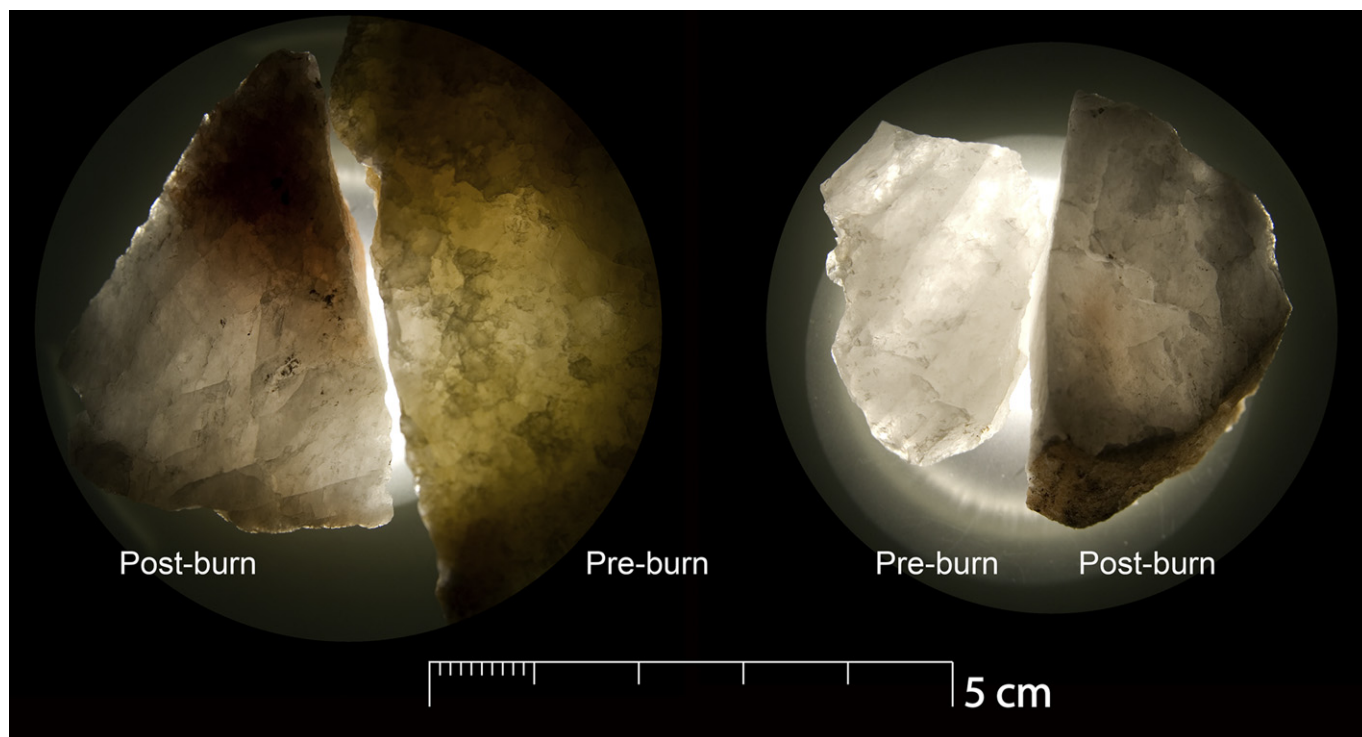


Fig. 6. Backlit artefacts, highlighting opacity change on similarly thick artefacts. Left: beach. Right: metadolerite.

developed in one or more orientations within a given crystal and they differ in abundance and in orientation from one crystal to another. They tend to have a characteristic length of 50–100 μm and appear not to be interconnected. Macroscopic fractures in burnt samples have developed along quartz grain boundaries and/or within crystals. They have a spacing and length of millimetres to centimetres.

3.3.3. Features visible between crossed polars

Between crossed polars, all three unburnt samples exhibit sub-grain boundaries and undulose extinction; on a much smaller scale, a repeating lamellar undulose extinction pattern is exhibited by some crystals in all three samples (Fig. 9). These features indicate discontinuities (sub-grain boundaries) and continuous spatial variation (undulose extinction) in the atomic structure of the crystal. They all probably reflect geological stress to which the crystals have been subjected since they formed.

Comparison of the burnt with the corresponding unburnt samples reveals that undulose extinction and most sub-grain boundaries are little affected, if at all, by heating. However the lamellar structures are absent in the burnt samples. The reason for the loss of the lamellar structures is unknown but might reflect the release of strain in the crystals during heating.

4. Implications for properties of heated quartz

4.1. Knapping behaviour

Burnt samples display macroscopic fractures, with a spacing of millimetres to centimetres, running entirely through the whole or much of the sample. They will therefore break readily along macrofractures when the quartz is knapped, especially immediately after burning when they appear to be more friable. Microfractures, whilst a common result of burning, are unlikely to affect the relative resistance to knapping in different directions because whilst fractures develop in preferred orientations in each crystal, their orientations differ from crystal to crystal. The overall strength reduction may be modest because microfractures are not interconnected. However sample 6 may be an exception because it includes crystals large enough to be individually knapped. Individual burnt crystals from sample 6 may break more easily during knapping than in its unburnt equivalent (sample 5) along the preferred microfracture directions. The other observed physical changes, fluid inclusion decrepitation and the loss of lamellar undulose extinction, are unlikely to affect knapping behaviour. It should be stressed however that no experiments have been done in the present study to determine changes in knapping behaviour resulting from burning.

4.2. Reduced transparency

The reduced transparency of burnt quartz in hand specimen may be due to two factors: decrepitation of fluid inclusions and/or formation of microfractures. After decrepitation, fluid inclusions contain residual vapour from the inclusion, or air, but no liquid. The loss of liquid increases the refraction of light passing between quartz crystal and the inclusion. Consequently decrepitated inclusions tend to block more light than those which are mainly liquid filled. The difference in light transmission can be

Table 3
Samples used in microscopic study.

Number	Material Source	Treatment	Weight (g)
1	Rose Cottage	Unburnt	80
2	Rose Cottage	Burnt	20
3	Psammite	Unburnt	30
4	Psammite	Burnt	30
5	Metadolerite	Unburnt	80
6	Metadolerite	Burnt	40

Table 4

Features observed by thin section examination.

Number & treatment	Grain size (mm)	Fluid inclusions	Fractures	Sub-grain textures
1 Unburnt	2–10	Two phase (liquid + vapour bubble) and empty	No macroscopic fractures; few microfractures	Sub-grain boundaries; undulose, and sometimes lamellar, extinction
2 Burnt	2–10	Empty only	Few macroscopic fractures; abundant microfractures in most crystals, with orientations varying between crystals	Sub-grain boundaries; undulose extinction
3 Unburnt	1–8	Two phase (liquid + vapour bubble) and empty	No macroscopic fractures; abundant microfractures in many crystals	Sub-grain boundaries; undulose, and sometimes lamellar, extinction
4 Burnt	1–8	Empty only, with fluid escape structures	Few macroscopic fractures; abundant microfractures in most crystals, with orientations varying between crystals	Sub-grain boundaries; undulose extinction
5 Unburnt	4–>30	Two phase (liquid + vapour bubble) and empty	No macroscopic fractures; few microfractures	Sub-grain boundaries; undulose, and common lamellar, extinction
6 Burnt	4–>30	Empty only, with fluid escape structures	No macroscopic fractures; abundant microfractures in most crystals, with identical orientations across sub-grain boundaries	Sub-grain boundaries; undulose extinction

appreciated by comparing intact inclusions (Fig. 7a and b) with decrepitated inclusions (Fig. 7c and d). Microfractures can reduce the transmission of light in a similar way, by refraction of light when it crosses a fracture. Whilst light can also travel along fractures so that they appear bright in thin section (Fig. 8b), the

overall effect of many microfractures in many orientations in a hand sample should be to reduce light transmission. Whether microfracturing or fluid inclusion decrepitation is the main cause of increasing opacity visible to the naked eye (Fig. 6) remains uncertain.

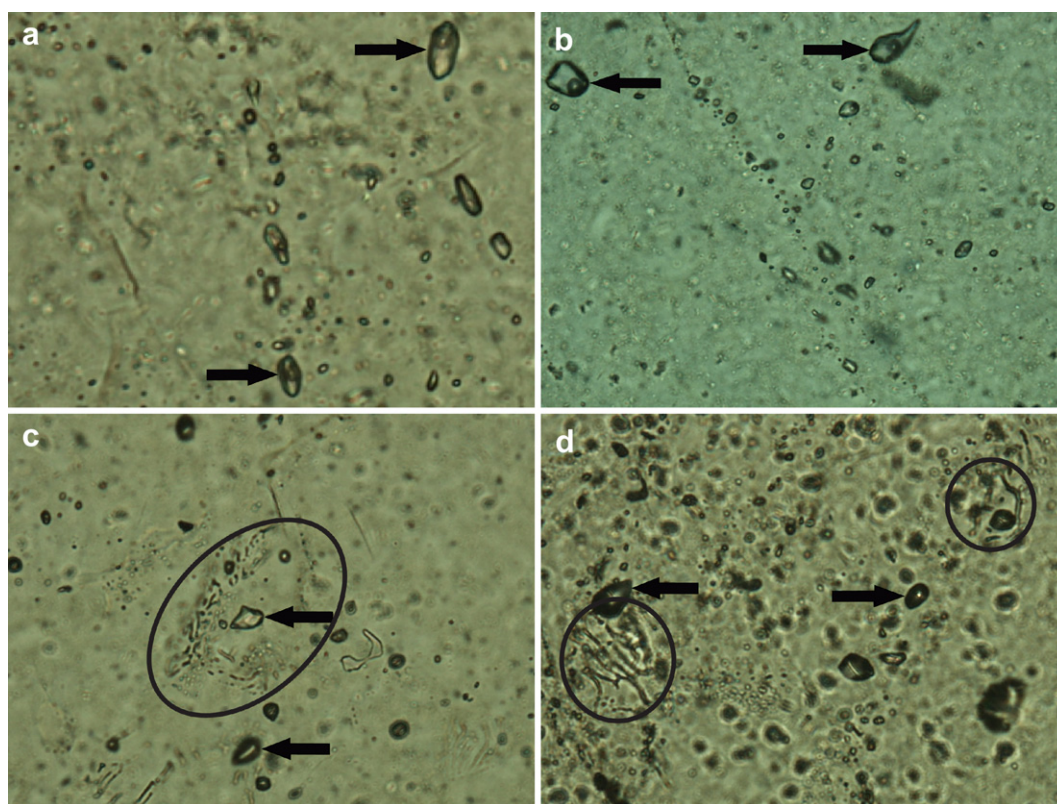


Fig. 7. Appearance of fluid inclusions before (a, b) and after (c, d) exposure to fire. All photographs taken in plane polarized light. Horizontal field of view 145 μm (b, c, d), or 100 μm (a). (a). Sample 3 (unburnt); many fluid inclusions contain liquid plus vapour bubble (examples arrowed) (b). Sample 5 (unburnt); many fluid inclusions contain liquid plus vapour bubble (examples arrowed) (c). Sample 4 (burnt); all fluid inclusions empty of liquid (examples arrowed), one surrounded by fluid escape structures (enclosed) (d). Sample 6 (burnt); all fluid inclusions empty of liquid (examples arrowed), some with adjacent fluid escape structures (enclosed).

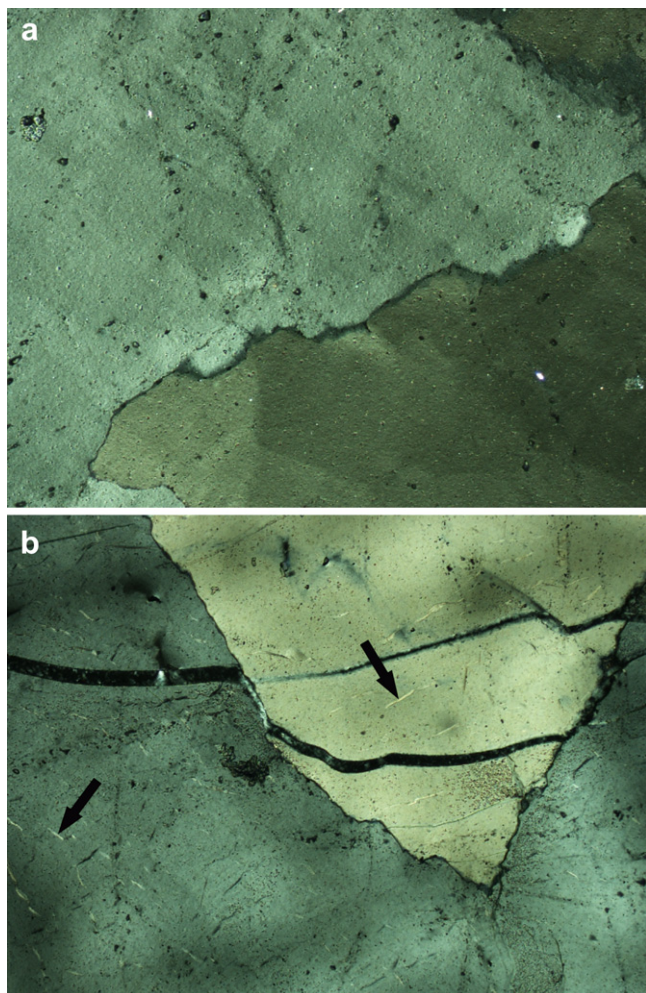


Fig. 8. Fractures in unburnt and burnt quartz samples. Both are photographed between crossed polars and have a horizontal field of view of 1220 μm (a). Sample 1 (unburnt), with no macroscopic fractures and almost no visible microfractures, in each of two crystals distinguished by different interference colours. (b). Sample 2 (burnt), showing macroscopic fractures running through and around crystals. Microscopic fractures (pale, short lines, examples arrowed) occur in both crystals, with different fracture orientations in each.

5. Recognition of burnt quartz

5.1. Macroscopic features

The results demonstrate a varied response to burning of vein quartz from several closely spaced localities. Ballin (2008) noted pitted or 'peeled-off' surfaces on possibly burnt post-Mesolithic vein quartz and was able to reproduce this effect by experimental burning. This feature was not observed in the present study, but the other changes reported by Ballin (2008) were observed, namely dulling of lustre, increased opacity, increased visibility of granular texture and formation of reddish or pinkish areas. Ballin (2008) noted a yellow-brown surface colouration of probable burnt vein quartz from post-Mesolithic Scottish sites but was unable to reproduce it in burning experiments. The present study also fails to produce this type of colouration and, as pointed out by Ballin (2008), it remains unclear whether this effect relates to burning.

Overall, there is no clear distinction between the appearance of burnt and unburnt vein quartz in the present study. Examples of unburnt vein quartz may readily be found in nature that show any or all of the features noted in burnt quartz, namely increased

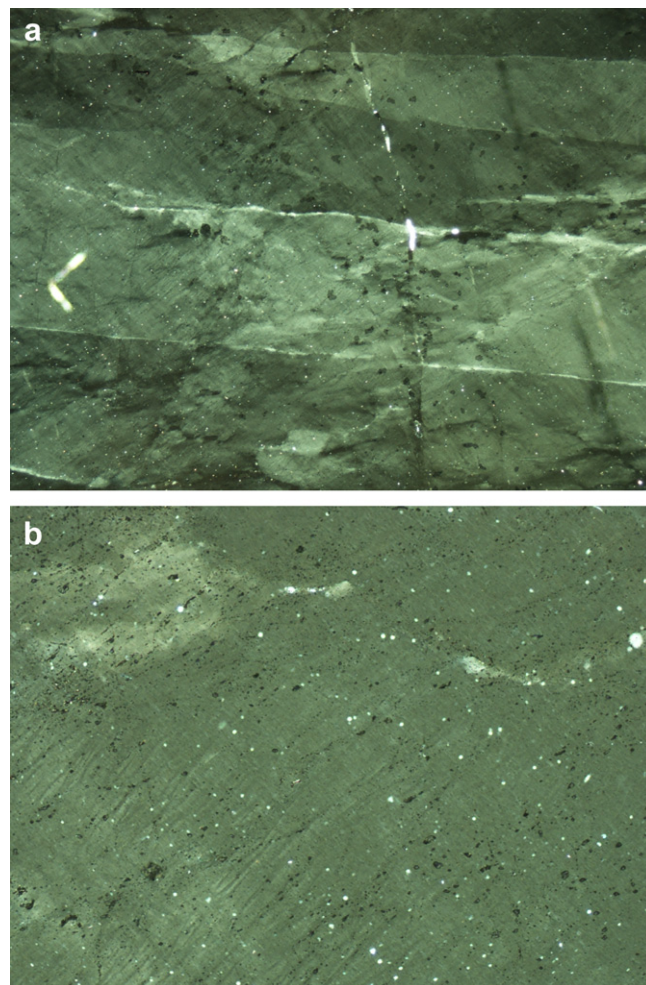


Fig. 9. Types of within-grain variation in extinction of unheated quartz, sample 5, crossed polars. (a). Sub-grain boundaries run from left to right and divide the crystal into sub-grains about a millimetre wide with slightly different crystallographic orientations. Horizontal field of view is 6150 μm (b). Detail within one sub-grain of Fig. 9(a) showing patchy undulose extinction at top left and fine repeated lamellar undulose extinction most clearly at bottom left. Horizontal field of view is 1220 μm .

macroscopic fracture density, reduced transparency, reduced lustre, colouration of attached rock or the quartz itself due to oxidized iron. These properties are consequently only reliable indicators of burning where the geological source of vein quartz can be identified with confidence for comparison with potentially burnt samples. The large natural variation at the Belderrig site would caution against this approach, especially in areas of similarly complex geology.

5.2. Microscopic features

Analysis of microfracture density and orientation seems unlikely to be useful because some unburnt samples contain similar microfracture density and orientation to burnt samples. Quartz sub-grain boundaries and undulose extinction are evidently unaffected on the timescale of the experimental burning employed. The very fine scale lamellar structures seen between crossed polars do seem to be reduced or lost as a result of burning, but as they are probably uncommon features of vein quartz they are of little practical use.

The feature most diagnostic of burnt quartz is the decrepitation of all fluid inclusions where the contents can confidently be visually

resolved, i.e. those $>5\ \mu\text{m}$ in the present study. All vein quartz may be expected to contain fluid inclusions; they form as an inevitable consequence of the growth of crystals from hydrothermal fluid because crystal growth is not perfect and some fluid is always trapped. Decrepitation may occur in vein quartz for several reasons. If the temperature of quartz is raised to the point where pressure generated by the fluid exceeds the strength of quartz, decrepitation occurs. This will normally require a temperature not much greater than that at which the fluid was originally trapped (Scott, 1948), perhaps less if the quartz vein crystallized under pressure at a depth of a few kilometres. Experimental decrepitation of fluid inclusions in vein quartz has demonstrated that most inclusion water is lost below $500\ ^\circ\text{C}$ and nearly all below $600\ ^\circ\text{C}$ (Barker and Robinson, 1984). Experiments on synthetic fluid inclusions of pure water similarly showed decrepitation mainly taking place below $600\ ^\circ\text{C}$ (Bodnar et al., 1989). These experiments were conducted using comparatively slow heating rates of $1\text{--}10\ ^\circ\text{C}$ per minute; rapid heating or rapid cooling might also bring about decrepitation by the fracturing quartz as it rapidly expands or contracts.

In some geologically complex areas, natural decrepitation may occur where a quartz vein is geologically reheated, but for a variety of reasons such situations are unlikely to create quartz vein material suitable for tool manufacture. Consequently all, or nearly all, fluid inclusions in unburnt vein quartz will be intact (a small proportion will have ruptured where the quartz is fractured). On the other hand, because the vast majority of quartz veins crystallize from hydrothermal fluid at less than $500\ ^\circ\text{C}$, burning in a wood fire should result in decrepitation of all, or nearly all, fluid inclusions. This is an irreversible process in an archaeological context, so that this evidence of burning will be preserved indefinitely.

6. Conclusions

Three aspects of burnt quartz were investigated by experiment in order to develop a framework for identifying and analysing burnt quartz in the archaeological record: visible characteristics, fragmentation rate, and spatial distribution. The effect of burning on the fragmentation of the quartz artefacts was dramatic, with a greater than fivefold increase in the assemblage's quantity. The $80\ \geq 35\ \text{mm}$ artefacts were reduced to 61, while the $15 < 25\ \text{mm}$ size grades almost doubled in quantity. The most dramatic difference was the smaller artefacts: the $1 < 10\ \text{mm}$ range began with no artefacts and ended with 1128. This has major implications for any analysis of a burnt quartz assemblage, or assemblages that contain burnt quartz. Problematically, it was noted that these smaller fragments are the most difficult to identify as being burnt. However, assemblages with high proportions of $<10\ \text{mm}$ fragments may suggest evidence of burning, other depositional and post-depositional factors notwithstanding.

The spatial analysis of the hearth has shown that, while the quartz fractures dramatically, it is expelled less explosively from the hearth than flint (see Sergeant et al., 2006). Very few artefacts were expelled outside of the hearth, with most movement occurring over centimetres, resulting in a reasonably contained final hearth spread. The lack of explosive movement compared to the flint may relate to the lesser proportion of fluid in vein quartz compared with flint, resulting in less pressure during heating. Comparison between the fragmentation rates of quartz and flint is not possible as Sergeant et al. (2006) do not provide a breakdown of the pre- and post-burn size grades.

Whilst a variety of features visible to the naked eye (increased opacity, dulled lustre, oxidation of iron and increased fracture density) are all common consequences of burning vein quartz in a wood fire, none can be regarded as diagnostic. A key consideration is what an unburnt sample of the raw material looks like.

While a given artefact may appear as dull, opaque, with numerous fractures, the source of that material should be examined to determine whether the dullness and opacity is related to its source or to burning; multiple fractures are not a useful characteristic for identification as these are common anyhow. The impurities, such as iron, in the quartz changed their hue the most, so these can be a useful indicator of burning.

Decrepitation of fluid inclusions, seen in all the experimentally burnt samples, is an irreversible process expected to be characteristic of virtually all burnt vein quartz. Although a polarising microscope was used in the present work to detect them, fluid inclusions, intact or decrepitated including escape structures, would be readily observable in a microscope using unpolarised light. Thin sections are routinely used in geological research and the facilities to make them are widely available. Where other evidence is suggestive of burning and where vein quartz artefacts can be sacrificed to make thin sections, decrepitated fluid inclusions should provide strong evidence for or against burning. It must be stressed that whilst vein quartz should be recognisable this way, other forms of quartz may not. Quartzite is less likely to contain sufficient fluid inclusions to make the technique viable. Pegmatitic quartz may respond in a similar way to vein quartz, as it crystallizes from water-bearing magma, albeit at higher temperatures. Granites, to which most pegmatites are related, have been shown to lose most of their fluid inclusion water below $600\ ^\circ\text{C}$ (Barker and Robinson, 1984).

This experiment has shown that burnt quartz will not be as easily recognisable as burnt flint in archaeological assemblages with a consequent loss of information regarding, for example, site activities such as disposal of material culture in hearths, or identifying 'invisible' hearths. Without the use of a destructive technique – thin sectioning – to reveal decrepitated fluid inclusions, it can be difficult to state definitively whether quartz is burnt or not, because the changes that quartz undergoes through burning can be mistaken for characteristics of unburnt quartz. While this experiment has shown that quartz will not be expelled from a hearth as dramatically as flint, burnt quartz has a very high fragmentation rate which must be taken into account when analysing assemblages.

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