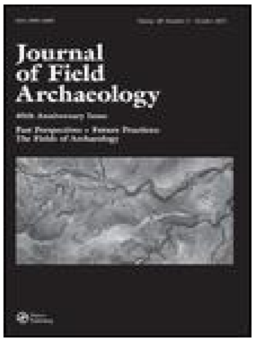

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Color Me Heated? A Comparison of Potential Methods to Quantify Color Change in Thermally-Altered Rocks

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ABSTRACT

This study investigates and compares methods to quantify color changes in quartzite rocks after repeated heating episodes. We collected quartzite samples from the southern Cape coast, South Africa, and heated them three times in experimental fires. We recorded the colors of the samples before and after heating using visual observation, Munsell color notations, Munsell color notations converted to RGB values, and digital image analysis. The methods are also tested on potentially heated and potentially unheated archaeological samples from Klasies River main site, South Africa. It was possible to distinguish between unheated and repeatedly experimentally heated quartzite using visual observation and Munsell color notation, but a large proportion of repeatedly heated samples appeared unaffected by the heat. The digitally-captured color values best discriminated color changes after heating. Color values of repeatedly heated experimental samples overlap with color values of potentially heated archaeological samples.

KEYWORDS

thermally-altered rocks; color; quartzite; experimental archaeology; Middle Stone Age; Klasies River

Introduction

Heat-affected rocks are found in abundance at archaeological sites all over the world. "Rubefied," "fire-cracked," "fire-modified," and "thermally-altered" are some of the terms used for this artifact category, regardless of the processes or behaviors that caused the heat exposure (Backhouse and Johnson 2007; Brink and Dawe 2003; Brown et al. 2009; Graesch et al. 2014; Hurst et al. 2015). Heat-affected rocks have been studied from different perspectives during the last few decades and this research has demonstrated that these artifacts can, for example, provide insight on collection and subsistence strategies, land use, cooking techniques, and site formation (Black and Thoms 2014; Homsey 2009; Jensen et al. 1999; Leach et al. 2005; Thoms 2003, 2008). Even so, these artifacts have not received sufficient attention, leading to a loss of potential information that can be gained from heated rocks (Brink and Dawe 2003; Graesch et al. 2014; Homsey 2009; Jensen et al. 1999; Petraglia 2002).

Color is one of the most important properties used to identify thermally-altered rocks in the field. Experimental studies have demonstrated how heat exposure can change the color of rocks as well as causing them to crack and break (Åkerstrøm 2014; Backhouse and Johnson 2007; Bentsen and Wurz 2017; Brink and Dawe 2003; Graesch et al. 2014; Homsey 2009; House and Smith 1975; Jensen et al. 1999; Oestmo 2013; Wilson and DeLyria 1999). Thermal alteration is often seen in reddening of the rock (Homsey 2009; House and Smith 1975; Wilson and DeLyria 1999). Other color changes, such as pieces becoming grayer or blacker, have also been documented (Backhouse and Johnson 2007; Moody 1976). In addition, it has been pointed out that some rocks do not display the expected signs of thermal alteration (Rapp et al. 1999).

Purdy (1971: 59) found that color change after heating would only occur if iron was present in a chert sample, which suggests a strong relationship between iron content and color change. Similarly, Homsey (2009) suggested a relationship between reddening after heat exposure and iron content in her study of biosparite, and Wadley and colleagues recorded reddening, caused by hematite, after heating of South African agate (Wadley et al. 2017). Iron content can, however, lead to changes to earthy colors such as black, orange, and yellow in addition to red in a rock sample (Prinsloo et al. 2018). Oxidxation of iron caused by heat exposure can lead to rubefication (reddening), but other natural processes can also cause oxidation and color changes (Dumarçay 2010). Color changes in rocks can be rooted in processes such as dispersed metal ions, a variety of defect structures created by radiation, and physical optics (see, for example, the overview by Fritsch and Rossman [1987, 1988a, 1988b]). In this paper, however, we shall focus on methods for color recording.

There is a need for systematic methods in the analysis of thermally-altered rocks (Custer 2017; Graesch et al. 2014) and a critical investigation of the particular methods used to recognize color is virtually unexplored. The few studies that investigate color change methodically include that by Oestmo (2013), who examined digital imaging technology to quantify rock color in his experimental study, in which he investigated changes in quartzitic sandstone in different burning scenarios. Following a similar method, Hurst and colleagues (2015) recorded color changes in Ogallala Formation quartzite samples, also known as Potter member quartzite. However, as there are indeed no studies that compare different analytical methods for recording color of thermally-altered rocks, we focus on this aspect of our heating experiments of Eastern Cape coastal quartzite based on finds at the Klasies River main site, South Africa (FIGURE 1).

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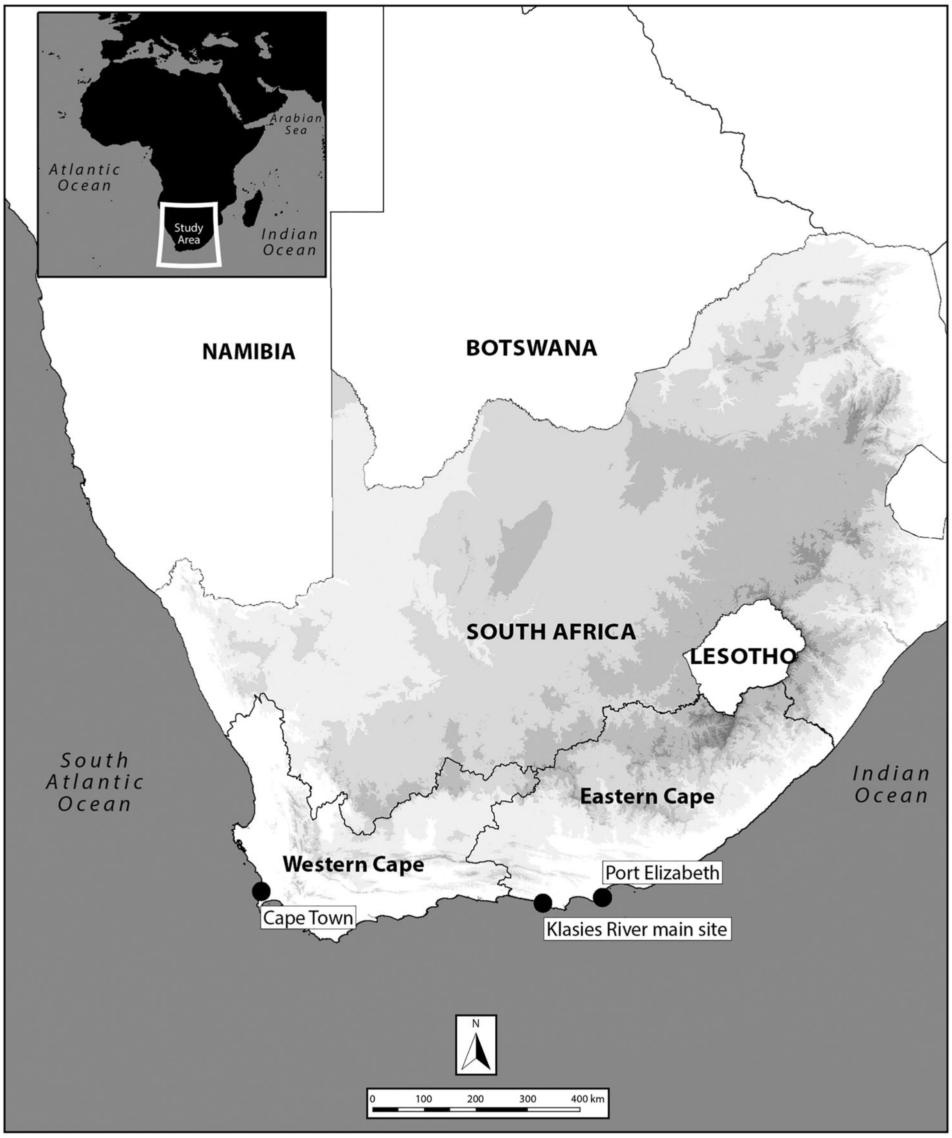

Figure 1. Location of Klasies River main site.

The origin of modern humans in South Africa, specifically in the Western and Eastern Cape, is a much-discussed issue in Quaternary archaeology (Brown et al. 2009; d'Errico et al. 2005; Grine et al. 2017; Henshilwood et al. 2001; Henshilwood et al. 2014; Marean 2010; Wurz 2012). Quartzite was the material of choice for the humans who inhabited the Cape coast during most of this period (Wurz 2014). Yet, there has been very little investigation of the properties of quartzitic raw material itself from the southern Cape coast, or how it responds to fire-related behaviors (but see work by Oestmo [2013] and Bentsen and Wurz [2017]). Attention has instead been focused on the silcrete-rich Still Bay and Howiesons Poort lithic industries (Brown et al. 2009; Wurz 2013). Understanding how quartzite responds to heating can lead to greater insight on site formation processes relating to quartzite-using populations of the Cape coast. This study is an in-depth exploration of one scenario of heat exposure, namely, repeated episodes of heating within combustion features. We compare different methods for color recording and examine, first, to what extent different methods for color recording can distinguish between unheated and experimentally heated quartzite and second, to what extent the experimental results and the color recording methods can help us understand the archaeological sample from the Klasies River main site. We aim thereby to contribute to the development of systematic methods in the study of thermally-altered rocks.

The Colors of Thermally-Altered Quartzite

Different rock types may respond differently to heat exposure (Backhouse and Johnson 2007; Brink and Dawe 2003; House and Smith 1975). Quartzite is a hard metamorphic rock usually consisting of at least 90% quartz (SiO_2) (Götze 2012). Color changes in different types of quartzite have been documented using a selection of methods. Visual observation is a very accessible method that requires virtually no training or extra equipment. Visual observation was, for example, used by Behm and Faulkner (1974) to examine experimentally-heated Hixton quartzite from Wisconsin, USA. Their study showed that rock samples displayed red, pink, deep maroon, and honey colors after heating. A weakness of the method is, however, that it relies heavily on light conditions and the color perception of the observer. It is, consequently, difficult to compare results from different observers.

Visual observation is often combined with other analytical methods, such as the use of the Munsell soil color chart. The

Munsell color system is based on human visual color perception, and uses the three dimensions of hue (color), value (lightness), and chroma (color purity) to describe colors of geological materials (Munsell 1912). The notation of a color is always a combination of the three, for example, 5R 8/1 describes a color of hue 5 red, value 8, and chroma 1. The Munsell soil color chart (e.g., 1994) contains a collection of illustrated Munsell values that can be compared to the object one wants to describe. In addition to the color notation, the Munsell color chart also gives a name for each entry (e.g., "White").

The use of the Munsell color chart requires little training and it does facilitate comparison between different sites and observations by different observers. In a study of unheated and heated quartzite from southeastern Norway, for example, visual observation was combined with the Munsell soil color chart to demonstrate that the samples became red or pink, or whitened after heating (Åkerstrøm 2014). Backhouse and Johnson (2007) also used the Munsell color chart to evaluate colors before and after experiments heating North American quartzite and found that some samples developed a red color after heating. Another example using the Munsell color chart is a recent study of color changes in heated quartzite from the southern Cape, where a more varied color range was recorded in heated samples than in the unheated quartzite (Bentsen and Wurz 2017). Individual color perception and difficulties with the surface of the material studied have been mentioned as sources of error when using Munsell color observation (Gerharz et al. 1988; Oestmo 2013). Additionally, a Munsell color value is not a numerical value that can be used "as is" in statistical tests, but needs to be converted, as discussed below. Nevertheless, the results from Bentsen and Wurz (2017) using this method provided us with a baseline for color changes that could be observed in quartzite, to be further explored in the current study.

It is important to know the temperature range that can cause color alterations to further understand the processes and behaviors leading to heat exposure and thermal alterations observed in the archaeological record. Color changes in quartzite have been reported by some researchers to appear around 250° C (Behm and Faulkner 1974; Hurst et al. 2015; Moody 1976), whereas others report that temperatures of 600° C or higher were necessary to induce color change in the majority of the quartzite rocks in their studies (Åkerstrøm 2014; Graesch et al. 2014). Color change may be related to temperatures during experimental heating, but the size of the rocks could also influence changes. Ebright (1987), for example, notes that flake-sized quartzite samples whitened in her heating experiments, whereas larger samples developed pink shades. She suggests that this difference was caused by the difference in heat penetration of the samples (Ebright 1987: 34). One of the advantages of a quantitative record of colors in heated rocks is that the relationship between colors, size, and fire temperatures can be explored statistically.

Heat exposure can lead to various thermal alterations in addition to color change. Quartzite rocks are reported to become brittle or fragile and crack or break during heat exposure (Behm and Faulkner 1974; Bentsen and Wurz 2017; Ebright 1987). Furthermore, some studies show that experimentally heated quartzite can develop few or no cracks after a single heating at relatively high temperatures (Åkerstrøm 2014; Graesch et al. 2014; Jackson 1998; Moody 1976), and Backhouse and Johnson (2007) noted that the different types of quartzite in their experiments broke or cracked differently. These examples demonstrate that breakage can depend on the type of quartzite studied and that it is important to document breaks and cracks during experimental heating in order to further understand the archaeological record. We did record breakage as reported below, but our main focus is the color of the heated rocks.

What Kinds of Processes and Behaviors Lead to Heat Exposure?

Exposure to heat can be a result of many different processes and behaviors, some of which can be characterized as unintentional. A natural bush fire could, for example, heat artifacts when sweeping over a site. However, natural fires might not generate surface temperatures that are high enough to produce changes in rocks (Bellomo 1993). Unintentional heating can also be caused by human activity. One example is through reuse of a site, when new fires are started on top of sediments containing artifacts from previous occupations. Experimental and ethnoarchaeological studies (Bentsen 2012, 2013; Mallol et al. 2007; Sievers and Wadley 2008) have shown that heat does not penetrate deep into the sediments and that the temperatures even 5–10 cm below the surface of the fire can be quite low. It is, consequently, crucial to know how local rocks react to heating and at which temperatures changes occur in order to interpret and understand the processes that caused any heat alterations.

Other processes can cause intentional heating of rocks and other objects. Here, we shall only mention a few relevant examples. Heating of some rock types can be beneficial to their knapping properties (Domanski and Webb 1992). Heating of silcretes might have been part of lithic technology as early as 164,000 years ago in South Africa and might have been regularly used by 71,000 years ago (Brown et al. 2009, 2012). The method for early heat treatment of silcrete has been debated (Schmidt et al. 2013, 2015; Wadley and Prinsloo 2014; Wadley et al. 2017). Nevertheless, rocks for knapping should not be heated beyond temperatures that causes cracks and breaks, as this would have made it virtually impossible to control the knapping process. Intensive intentional heating, though, can happen through other processes. Rocks used as hearthstones around the fire would be exposed to intense heat, possibly repeatedly, and rocks can also be used as heating elements in a fire to heat their surroundings or to roast or boil food (Graesch et al. 2014; Odgaard 2003; Speth 2015; Thoms 2008). Large quantities of thermally-altered rocks only appear in the archaeological record after 35,000–50,000 years ago, which suggests that the regular use of rocks for heating and cooking only appeared after that time (Speth 2015; Thoms 2009).

Klasies River Main Site

This study originated in the discovery of potentially heat-affected quartzite during excavations undertaken in 2015–2017 at Klasies River main site (KRM) (Bentsen and Wurz 2017; Wurz et al. 2018). The Klasies River landscape is situated in the Eastern Cape of South Africa, approximately 120 km from Port Elizabeth (FIGURE 1). KRM is the most prominent archaeological feature in the National heritage landscape that stretches ca. 2.5 km along the Tsitsikamma coast. KRM is cut into cliffs that face the Indian Ocean and form the seaward edge of a 13 km coastal platform running along the Tsitsikamma mountain range (250 masl) (Deacon and Geleijnse 1988). The lowest part of the main site is 6 m above the current sea level and, due to the steep offshore profile, would never have been far from the shoreline, despite fluctuations in sea levels through time (Deacon and Wurz 2005; Wurz et al. 2018). Table Mountain Group quartzitic sandstone with slate and shale and occurrences of Bokkeveld metashales form part of the landscape around KRM (FIGURE 2) (Butzer 1978; Marker and Holmes 2010).

More than 20 m of highly archaeologically significant deposits are preserved at KRM, which consists of Caves 1 and 2 and associated overhangs named Caves 1A and 1B (FIGURE 3). A large-scale excavation of the site was carried out by John Wymer and Ronald Singer in 1967–1968 (Singer and Wymer 1982) and a smaller excavation of the remaining sections by Hilary Deacon in 1984–1995 (Deacon and Geleijnse 1988). These excavations produced an abundance of data that increased our understanding of Middle Stone Age (MSA) site formation processes and early modern humans, including their anatomy, technology, and use of marine and terrestrial resources (Butzer 1978; Deacon 2008; Grine 2012; Grine et al. 2017; Klein 1976; Langejans et al. 2012; Milo 1998; Nel et al. 2018; Thackeray 1988; Wurz 2002, 2012, 2013). The current excavation phase started in 2015 under the direction of Sarah Wurz (Wurz et al. 2018) and continues the excavation started by Deacon of the Witness Baulk left by Singer and Wymer in Cave 1 (FIGURE 4).

The majority of the deposits at KRM accumulated during the African MSA, which in general lasted from approximately 300,000 years ago to 22,000 years ago (Wadley 2015). The extensive deposits at KRM are classified into different lithological members (FIGURE 4) and the current excavation started in the Sand and Shell Lower (SASL) sub-member, layers Hearth Hearth Hearth Base (HHH Base), Shell Midden ONE (SMONE), and the underlying Black Occupational Soils (BOS) layers (FIGURE 4) (Wurz et al. 2018). Based on available dates (Vogel 2001), the base of the SASU sub-member (FIGURE 4) was deposited ca. 100,000 years ago (see discussion by Wurz and colleagues [2018]). The material from the current excavation of BOS is being analyzed, but the general impression from faunal analyses of current and previous excavations suggests a mosaic of vegetation habitats in the vicinity of the site (Klein 1976; Nel et al. 2018; Wurz et al. 2018).

There is much evidence of fire-related behavior at KRM. Previous excavations revealed intact combustion features, sometimes superimposed and interleaved, both in the Witness Baulk excavation in sub-member Sand and Shell Upper (SASU) and in other parts of the site (Deacon and Geleijnse 1988; Henderson 1992; Singer and Wymer 1982). MSA combustion features are not generally lined by hearthstones (Bentsen 2014) and hearthstones have not been

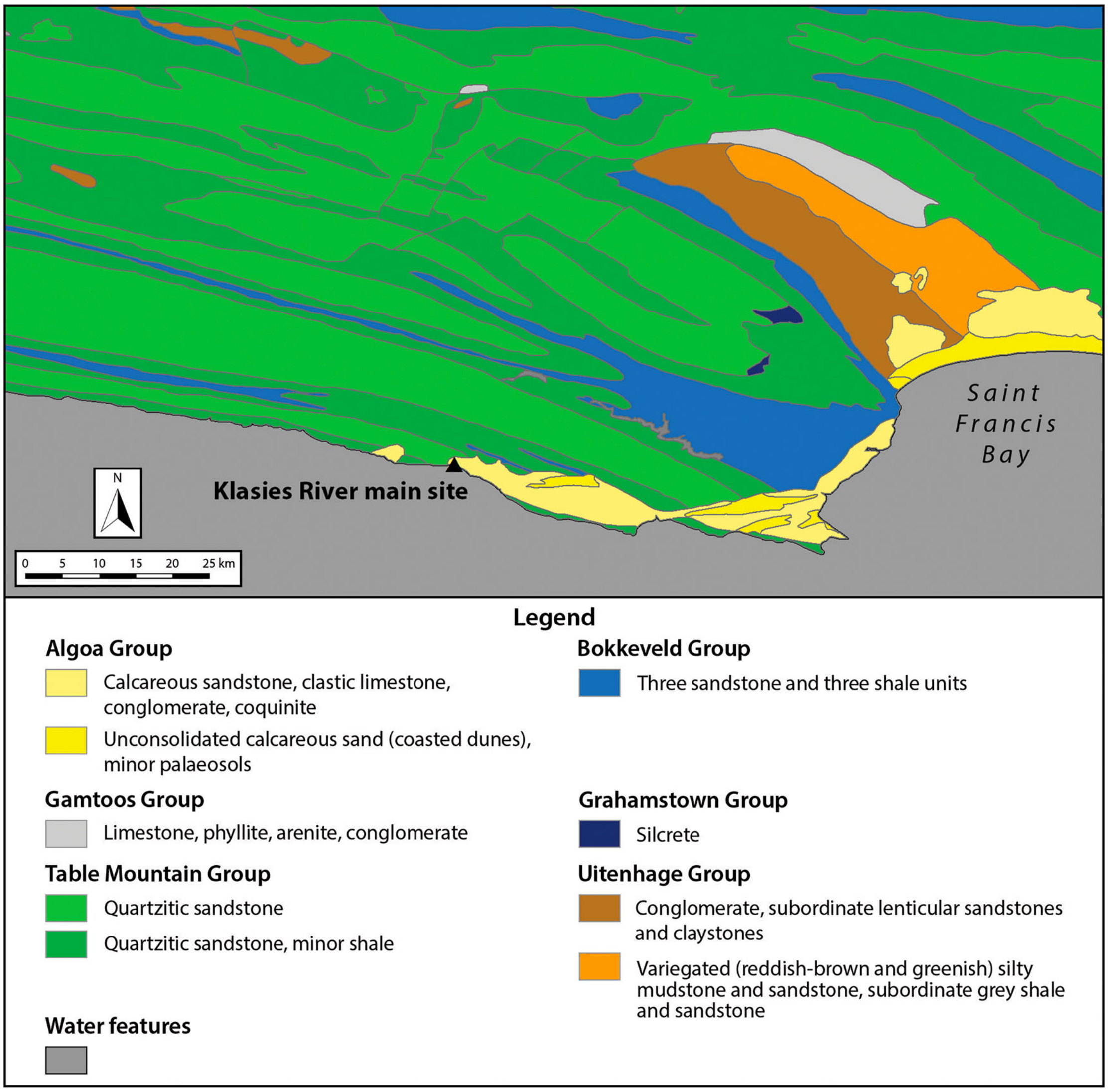

Figure 2. Geological map of the area around Klasies River main site. Geological data adapted from the South African Council of Geoscience.

Figure 3. Overview of the Klasies River main site. Caves 1, 1A, 1B, and 2 can be seen in the cliff surface. The inset (B) shows details of cobbles that can be found at the beaches by the site.

observed at KRM (Henderson 1992). Faunal, botanical, micromorphological, and spatial analyses suggest that early humans at KRM consumed a varied diet, including shellfish, plants, fish, and both marine and terrestrial mammals (Henderson 1992; Klein 1976; Langejans et al. 2012; Milo 1998; Thackeray 1988; Wurz 2012; Wurz et al. 2018). It is highly likely that some of the food resources were cooked, and there is direct evidence for the cooking of starchy tubers in some of the hearths dating to ca. 120,000 and 65,000 years ago (Larbey et al. in press).

The potentially heated quartzite from BOSONE

During excavation of the uppermost BOS layer (BOSONE) in 2015, 323 quartzite fragments had signs of heat exposure, including dull red or pink or color and fractures (FIGURE 4C–

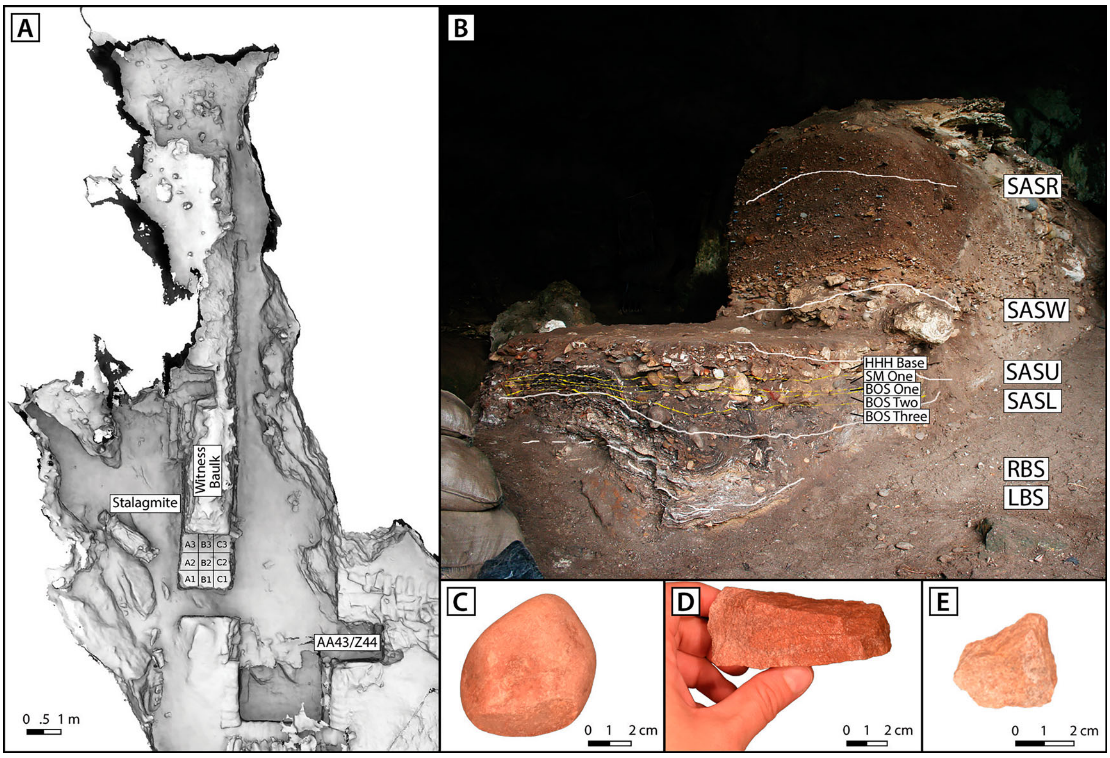

Figure 4. Klasies River main site. A) The interior of Klasies River Cave 1 showing the location of the Witness Baulk excavation. 3D scan provided by the Zamani project. Edited and text added by Liezl van Pletzen-Vos. B) The Witness Baulk in 2015. White lines indicate members and sub-members, the yellow lines indicate layers excavated since 2015. C–E) Examples of potentially heated quartzite excavated in layer BOSONE in 2015.

E). Some of these looked like they were parts of larger cobbles broken into several small spalls, but we did not find any large broken cobbles in situ, nor were we able to refit any spalls to reconstruct the original cobbles. Some of the potentially heat-affected quartzite samples were knapped, others not. The fracturing and brittleness of some of the fragments implied that they had been extensively heated, to the point that knapping would be virtually impossible. The hearths from BOSONE were not preserved, and thus the association of these stones with possible combustion features could not be determined. As mentioned above, other processes than heating can potentially cause rubefication. However, the fracturing of the quartzite and the color shades represented pointed to heat exposure as a possible explanation for these artifacts.

One of the hypotheses for the formation of these artifacts was that they had been in direct contact with fire, for example through use as hearthstones or cooking stones. We conducted initial heating experiments of locally sourced quartzite to examine the hypothesis. One result was that the colors of experimental samples heated in the fire (as if used for roasting or as hearthstones) resembled those of the archaeological samples more than the color of experimental samples heated in the fire and submerged in water while hot (as if used for boiling) did (Bentsen and Wurz 2017). The Munsell color chart was used to describe the colors of the samples in that study. We were, however, concerned that the hypothesis could not be analyzed statistically. Therefore, we present here a new study expanding on Oestmo's (2013) use of digital image processing to quantify color changes during heating. We are strictly focusing here on one heating scenario (direct contact with fire in a fireplace) and avoiding other scenarios (such as boiling) because we want to test and compare different methods to analyze the colors of heat-affected rocks. We will be commenting on the different processes and behaviors that could have led to heat exposure below. However, we reserve a thorough discussion of intentional versus unintentional heat exposure and behaviors and processes that could have affected the rocks for future studies where we can further develop the results presented here and integrate more data on other properties than color.

Methods and Material

Experimental setup and laboratory protocol

We collected quartzite for this study at a local beach by the Klasies River main site (FIGURES 1, 3). The quartzite cobbles on the beach next to the site (FIGURE 2) are formed on material that eroded when water flow cut into the underlying geology (Oestmo et al. 2014), and raw materials for tool production could have been collected at similar outcrops in the past (Deacon and Geleijnse 1988). The current cobbles are covered by white or gray cortex, whereas the inside of the cobbles can be gray, yellow, pink, or light brown, some with red streaks or small white inclusions (FIGURE 2).

We broke and reduced some of the collected cobbles to smaller nodules to replicate the archaeological situation with rocks of different sizes. Thirty samples are included here for each of the stages of the heating experiment (see below). It should be noted that the experiments included more samples and that two of the samples not included disintegrated and disappeared during repeated heating. The cooled off experimental samples were rinsed and allowed to dry for at least 24 hours. The color values of the experimental samples were recorded using the methods described below before the samples were heated. To make sure that there was enough space in the fire to heat the samples thoroughly, the samples were divided into three groups and each group was heated in a separate fire. This ensured that all samples would be in direct contact with flames and coals during the experiments.

The method for the experimental fires was based on previously tested and published fire experiments (Bentsen 2012, 2013; Bentsen and Wurz 2017; Oestmo 2013; Sievers and Wadley 2008; Wadley and Prinsloo 2014) to facilitate comparisons between our work and other studies. In short, a 10 cm thick topsoil horizon of clean sand was prepared before the fire experiments started. K-type thermocouples connected to a Huato dual channel temperature data logger, Model S220-T2, recorded the surface temperatures of the fire every 30 seconds (TABLE 1). Each fire was built using 5.9–6.2 kg of *Dichrostachys cinerea* wood, available in the Klasies area. This wood taxon is generally considered good firewood and is readily available in large quantities. The moisture content of the logs was measured with a MD-4G 4-pin digital wood moisture meter and ranged between 17–30%. The weather conditions during the first hours of the fires were recorded using an Extech Thermo-RH-Anemometer (TABLE 1). After the first fire, the samples were left to cool down for at least 12 hours before being brought to the laboratory and rinsed. Dry samples were subsequently weighed and measured. The color values for both cortex and rock surface were recorded, using the methods described below, under identical light conditions. For the method requiring digital photos, a photo station was set up in the lab and photos were taken with a Nikon D3200 camera with an 18–55 mm DX ED II lens. Ashes, charcoal, thermally-altered sand, and other remains of the first fire were removed and new clean sand was used to prepare new topsoil horizons for new fires. The samples were reheated and the steps from cool down to the recording of color values repeated. Each sample was heated and examined three times following this procedure.

Table 1. Summary of fire temperatures and weather conditions during the experiments.

Fire number	Heating sequence	Maximum fire temperature (center) (°C)	Average fire temperature (center) first 5 hours (°C)	Average outdoor temperature (°C)	Average relative air humidity (%)	Average air velocity (m/s)	Fuel weight (g)
1	1	485.7	211.6	28.65	29.59	0.27	5972
2	1	492.0	313.2	27.11	32.67	0.69	6013
3	1	556.3	357.0	24.50	29.30	0.60	6040
4	2	356.1	209.1	17.65	72.56	0.04	5989
5	2	698.0	465.3	26.45	37.94	0.51	5933
6	2	550.6	329.3	26.73	30.95	0.28	6036
7	3	524.6	325.7	31.49	25.63	0.56	6155
8	3	321.3	218.9	29.38	17.55	0.23	6034
9	3	387.2	228.4	23.66	46.34	0.60	5974
10	3	272.1	190.9	23.52	43.97	1.06	6015

Archaeological samples

The artifacts from the excavation were washed and boxed by artifact category in the field laboratory. The boxes of material were transported to the laboratory at the University of the Witwatersrand for further analyses. The boxes of potentially heated quartzite were unpacked, and the artifacts inspected under the same light conditions and compared to the experimental samples. One group of archaeological samples clearly resembled the experimentally heated samples in color and fracturing and we randomly selected 30 of these samples for this study. We will refer to this group of samples as "potentially heated archaeological samples" below. A different group of 30 archaeological samples did not display similar cracks, breaks, and colors as those observed in the experimentally-heated samples. These apparently unheated samples could have been placed in the wrong box in the field laboratory or been wrongly classified in bad light conditions at the excavation and field laboratory. However, some of these samples also displayed shades of red or pink that could be mistaken for rubefication in the field. This group of samples is referred to as "potentially unheated archaeological samples" below and is included in this study to test the strength of the color recording methods in distinguishing between different sample groups.

Summary: sample groups

In summary, this study includes six sample groups, which each consists of 30 samples: unheated experimental samples (UE), experimental samples heated once (EH1), experimental samples heated twice (EH2), experimental samples heated thrice (EH3), potentially heated archaeological samples (PHA), and potentially unheated archaeological samples (PUA) (TABLE 2). Four different methods ranging from simple qualitative observation to objective digital recording were used to document the colors of all sample groups, and these methods are described in detail below.

Color recording method I: visual observation

As visual observation is often the first analytical step in field situations, it is included here for comparison with objective quantitative methods. Light conditions and the color perception of the observer can affect the results of visual observation. Consequently, all color observations in this study were conducted under identical light conditions by the same observer, Bentsen. The observed colors of the cortex and the rock surface of each sample were noted in a database after each heating episode. Up to four colors per sample were recorded on the rock surface and, for the samples with cortex, up to four colors per sample were recorded on the cortex. On average, however, between 1.6 and 2.3 colors per sample were recorded in the different sample groups (TABLE 2). To avoid bias, the color results of other sample groups were not readily available to the observer during subsequent color recordings.

Color recording method II: Munsell color notations

Each sample in the study was examined using the Munsell Soil Color Chart (1994) by one observer, Bentsen. The observed colors of the cortex and the rock surface of each sample were noted in a database. Up to four colors per rock surface and cortex were recorded. On average between 1.6 and 2.9 colors per sample were recorded in the different sample groups (TABLE 2). To avoid bias, the color results of other sample groups were not readily available to the observer during subsequent color recordings.

Color recording method III: converted Munsell color notations

Various methods that allow statistical analyses based on Munsell color notations have been developed (Hurst 1977; Kirby et al. 1999; Kirillova et al. 2015; Shum and Lavkulich 1999; Torrent et al. 1980). It is a challenge that some of these methods only work well within limited parts of the Munsell color chart, which means that only certain colors can be used for statistical analyses (Kirillova et al. 2015). Here, we have chosen to convert Munsell notations to numerical values within the CIE color system using the statistical software R, ensuring easy replication of our methods in similar studies. R produces conversions of a major portion of the Munsell chart, although a small portion of the Munsell color notations could not be converted (TABLE 2).

The CIE color system was created by the International Commission on Illumination (CIE) in 1931, and is associated with different mathematical methods that use color spaces (coordinate systems) to describe how wavelengths are perceived as colors by the human eye (Trussell et al. 2005). One example is the RGB color mode, where color is described as a combination of a red (R), a green (G), and a blue (B) color channel. This very commonly used method for color display is device dependent; that is, the output color might look different on different devices and using different display methods (Trussell et al. 2005). We used the *munsellinterpol*

Table 2. Overview of sample groups and color observations.

Sample group	Number of samples	Total number visual color observations	Total number Munsell color observations	Total number converted Munsell color observations*	Total number digital color observations*
Unheated experimental samples (UE)	30	49	50	49	63
Experimental samples heated once (EH1)	30	47	63	61	63
Experimental samples heated twice (EH2)	30	56	74	71	63
Experimental samples heated thrice (EH3)	30	51	77	72	63
Potentially heated archaeological samples (PHA)	30	68	86	82	63
Potentially unheated archaeological samples (PUA)	30	57	54	45	63

package (Gama et al. 2018) in R to convert the recorded Munsell notations to numerical RGB values. We shall refer to this set of values as converted RGB values below and to the color channels as ConvR (converted red channel), ConvG (converted green channel), and ConvB (converted blue channel). The collection and quality of the data are affected by factors such as individual color perception (see above), which is important to keep in mind when reviewing the results below.

In his study, Oestmo (2013) normalized RGB color values and performed principal component analysis (PCA) on the data. We chose to follow this approach on the converted Munsell notations to allow for inter-experiment comparison. The standard deviation of color values in each color channel (ConvR, ConvG, and ConvB) for each group of samples was calculated. The normalized color value was calculated by dividing each color value by the standard deviation of the corresponding group of rocks. A PCA, using the FactoMineR package (Lê et al. 2008) in R, was performed on the normalized color values and scatterplots of the data produced to visualize the results. We also did statistical tests on the experimental samples of the relationship between the converted RGB values and the temperatures of the fires and the weight of the samples.

Color recording method IV: digital imaging technology

Lastly, we recorded color using digital imaging technology (Oestmo 2013). A photo station was set up in the laboratory, as described above, and all sides of each rock sample were photographed before heating and after each heating episode. Photos in RAW format were imported into Photoshop CS6, where the lasso tool was used to define areas on the rocks. The areas included the main part of the rock, but excluded any debris, markings, or other disturbances on the rocks. Photoshop offers different color modes, and we recorded color values for RGB color mode in this study so that we could compare the digital color values to the converted Munsell color values. The median color value of each color channel in the defined areas was recorded in a database. We shall refer to the digitally recorded color channels below as DigR (digitally recorded red channel), DigG (digitally recorded green channel), and DigB (digitally recorded blue channel). We randomly selected 63 digital RGB records (each consisting of the 3 color channels: DigR, DigG, and DigB) per sample group, which means that there is, on average 2.1 digital RGB records per sample in the study (TABLE 2). The digital color values were normalized, and a PCA was performed on the color data, as described above, and scatterplots of the results produced. Statistical analyses were also conducted to examine the relationships between the digital color values, the temperatures of the fires, and the weight of the samples.

Results

General experimental results

Figure 5 shows the appearance of selected experimental samples during the experiment. Fracturing and cracks developing in the samples were recorded in this study as “cracked samples” and complete breaks into two or more chunks were recorded separately as “broken samples.” Cracks, breaks, and discoloring developed in some of the samples after the first heating episode, and more developed during the second and third heating episodes (TABLE 3). 30% of the samples had broken into two or more parts after the third heating episode and 43% of the experimental samples had developed cracks after three heating episodes (TABLE 3).

Results, color recording method I: visual observation

Visual observation indicated that 40% of the experimental samples changed color during the first heating episode, 47% during the second heating episode, and 67% during the third heating episode (TABLE 3). Color changes were not found in 10 samples (33%) after three heating episodes (TABLE 3). Looking at the colors recorded in the experimental samples (FIGURE 6), we see that gray was the most common color visually observed in unheated samples. Gray was still well represented in the experimental samples heated once, twice, and thrice, but the frequency of the colors pink and red increased after heating the samples.

Figure 6 shows that the color gray was more commonly observed in the PUA samples than in the PHA samples. The frequency of the colors pink and red was higher in the PUA samples than in the UE samples, but lower than in the PHA samples. There was a greater frequency of the colors

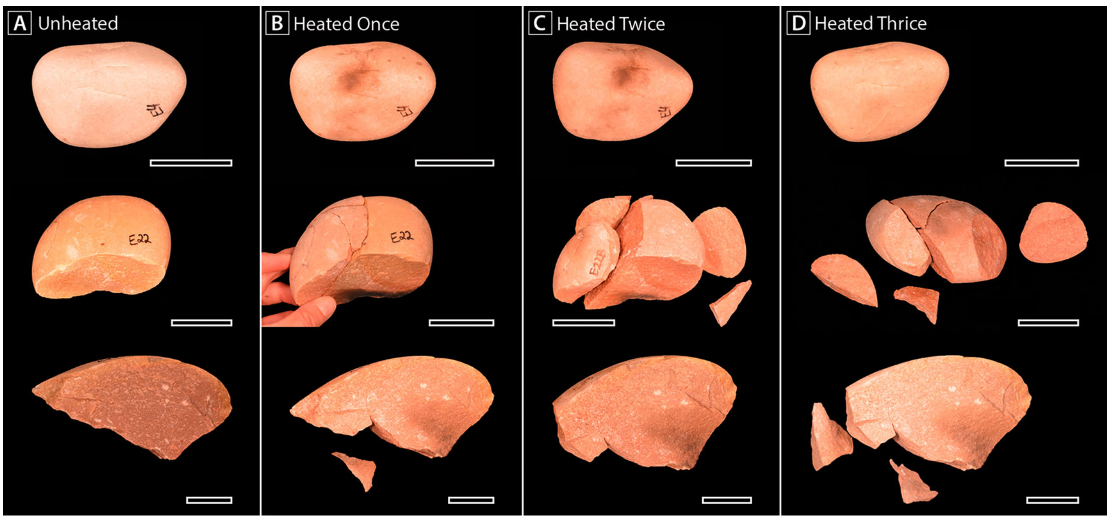

Figure 5. Examples of experimentally heated quartzite. Each row contains one sample in different heating stages. A) the unheated samples, B) samples experimentally heated once, C) samples experimentally heated twice, and D) samples experimentally heated thrice. White rectangles are 5 cm long.

Table 3. General results from the experimental heating of quartzite.

Times heated	Number of samples	Cracked samples	Broken samples	Discolored samples
0	30	0	0	0
1	30	6 (20%)	6 (20%)	12 (40%)
2	30	12 (40%)	9 (30%)	14 (47%)
3	30	13 (43%)	9 (30%)	20 (67%)

yellow and brown in the UE and the PUA samples compared to the other sample groups (FIGURE 6). The color black was visually observed only in the PHA samples.

Results, color recording method II: Munsell color notations

Figure 7 contains a summary of the Munsell colors recorded in this study, grouped by color name. This means, for example, that the color names "Weak red," "Light red," "Pale red," and "Red" are grouped together in category "Red". An overview of all Munsell color notations recorded is included in Supplemental Material 1. In general, the colors white and gray were most frequent in the UE samples and red, gray, and white were most frequent in experimentally heated samples. The color pink was only recorded among the experimentally heated samples and its frequency decreased in the samples heated thrice. The highest frequency of the color red was recorded in the PHA samples. The PUA samples had a somewhat higher frequency of the color red than the UE samples did, but lower than the heated experimental samples did.

Results, color recording method III: converted Munsell color notations

As seen in Table 2, a small number of Munsell color notations could not be converted to numerical values using R and are not included in the statistical analysis. The colors that could not be converted were mainly in the Gley range, i.e., different shades of gray. The converted color data was normalized by dividing the value for each color channel by the standard deviation of the value in each rock group, as described above, and PCAs were performed on the data.

The first PCA of the converted Munsell color notations included only the experimental samples, in order to examine if one could distinguish between unheated samples and samples that were repeatedly heated. The analysis is plotted in Figure 8a, showing that the EH1 samples form a cluster. There is some overlap with the other experimental sample groups and the other samples do not form similar clusters according to heating status. The analysis shows that 92% of the variance is explained by Principal Component 1 and 6.5% of the variance is explained by Principal Component 2. All three color channels (ConvR, ConvG, and ConvB) contribute similarly to Principal Component 1 (31.6%, 34.9%, and 33.5%, respectively), which means that the variation in the data set is best described as a combination of the colors red, green, and blue. The color channel ConvR contributes 64.8% to Principal Component 2, whereas ConvG contributes 5.3% and ConvB 29.9%.

The second PCA of the converted Munsell color notations examined if one could distinguish statistically between the potentially heated and the potentially unheated archaeological samples. The analysis is plotted in Figure 8b, showing that the samples do not cluster in two distinct groups according to potential heating status. The analysis shows that 95.9% of the variance is explained by Principal Component 1 and that 3.5% of the variance is explained by Principal Component 2. The variation in this data set is best described as a combination of the colors red, green and blue, as the three color channels ConvR, ConvG, and ConvB contribute evenly to Principal Component 1 (32.6%, 34.3%, and 33.2%, respectively). The color channel ConvR contributes 58.9% to Principal component 2, whereas ConvG contributes 1.7% and ConvB contributes 39.2%.

Lastly, a third PCA of the converted Munsell color notations was performed. This PCA combined the experimental and archaeological samples to examine if the color values of any of the experimental sample groups overlapped with any of the archaeological sample groups. The analysis is plotted in Figure 8c, showing that there is some overlap between the PHA and PUA samples and the EH1. The analysis shows that 92.5% of the variance is explained by Principal

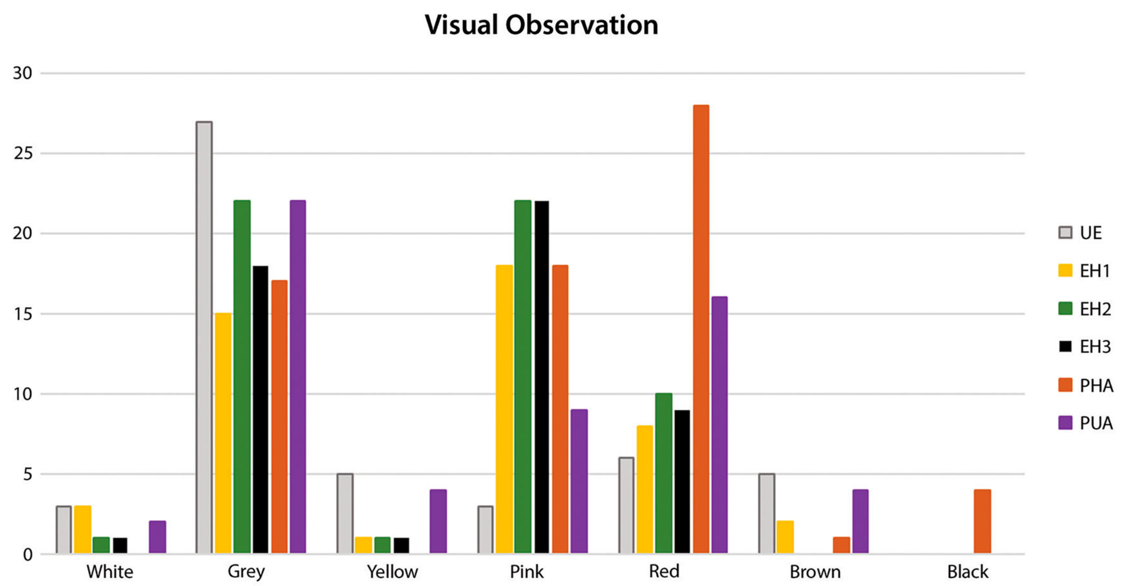

Figure 6. Results from the visual observation of colors. Abbreviations in the legend: UE = Unheated experimental samples, EH1 = Samples experimentally heated once, EH2 = Samples experimentally heated twice, EH3 = Samples experimentally heated thrice, PHA = Potentially heated archaeological samples and PUA = Potentially unheated archaeological samples.

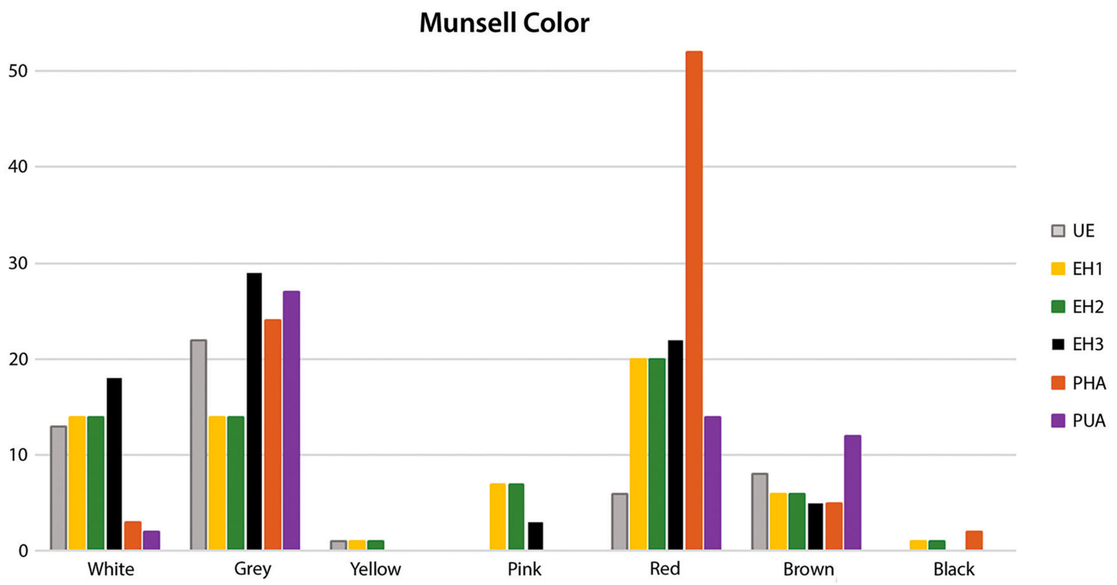

Figure 7. Results from the recording of Munsell color notations. Abbreviations in the legend: UE = Unheated experimental samples, EH1 = Samples experimentally heated once, EH2 = Samples experimentally heated twice, EH3 = Samples experimentally heated thrice, PHA = Potentially heated archaeological samples, and PUA = Potentially unheated archaeological samples.

Component 1 and 6.5% of the variance is explained by Principal Component 2. All the three color channels (ConvR, ConvG, and ConvB) contribute similarly to Principal Component 1 (31.9%, 35.3%, and 32.7%, respectively), which means that the variation in the data set is best described as a combination of the colors red, green, and blue. The color channel ConvR contributes 56.7% to Principal Component 2, whereas ConvG contributes 0.8% and ConvB 42.5%.

As the data was not normally distributed, we ran a Spearman's rank-order correlation to determine the relationship between the color values of the heated experimental samples (ConvR and principal components) and the weight of the samples. There were only very weak relationships between the variables (r_s = -0.01–0.09) and the relationships were not statistically significant ($p > 0.05$). We also tested the relationship between color values and the average and maximum temperatures during the experimental heating of samples. There were only weak to very weak relationships (r_s = 0.01–0.27) between color on the one hand and fire temperatures on the other hand although the relationships between the principal components and the fire temperatures were statistically significant ($p < 0.05$).

Results, color recording method IV: digital imaging technology

Digital image analysis was performed on the samples following Oestmo (2013), as described above. The digitally recorded color data was normalized by dividing the value for each color channel by the standard deviation of the value in each rock group, as described above, and principal component analyses were performed.

The first PCA of the digitally recorded color values included only the experimental samples to examine if one could distinguish between unheated samples and samples that were repeatedly heated. The analysis is plotted in Figure 9a, showing that the samples from the EH2 and EH3 samples form distinct clusters. Figure 9a also shows that the UE samples and the EH1 samples together form one group that is distinct from EH2 and EH3. The analysis shows that 84.6% of the variance is explained by Principal Component 1 and 14.9% of the variance is explained by Principal Component 2. The red color channel (DigR) contributes less (26.6%) to Principal Component 1 than the green (DigG, 37.6%) and blue (DigB, 35.7%) color channels. This means that the variation in the data is best described as a combination of the colors red, green, and blue, but that green and blue are somewhat more important than red. Red is the most important color channel for Principal Component 2 and contributes 72.5% to it, while DigG contributes 8.3% and DigB 19.1%.

The second PCA of the digital color values examined if one could distinguish statistically between the potentially heated and the potentially unheated archaeological samples. The analysis is plotted in Figure 9b, showing that the two sample groups form different clusters with some overlap. The analysis shows that 91.6% of the variance is explained by Principal Component 1 and that 7.3% of the variance is explained by Principal Component 2. The variation in this data set is best described as a combination of the colors red, green and blue, as the three color channels DigR, DigG, and DigB contributes evenly to Principal Component 1 (32.2%, 35.6%, and 32.2%, respectively). Principal Component 2 is dominated by the colors red and blue, contributing 49.7% and 50.3%, respectively.

Lastly, a third PCA of the digital color values was performed. This PCA combined the experimental and archaeological samples to examine if the color values of any of the experimental sample groups overlapped with any of the archaeological sample groups. The analysis is plotted in Figure 9c, showing that the archaeological samples do not overlap with the experimentally heated samples. The analysis shows that 75.3% of the variance is explained by Principal Component 1 and 23.1 by Principal component 2. DigG contributes most (43%) to Principal Component 1, followed by DigB (31.3%) and DigR (25.7%), implying that the variation in the data is best described as a combination of colors where green contributes most, blue second most, and red least to the final shade. DigR (red) contributes most (59.4) to Principal Component 2, followed by DigB (blue, 40.2%).

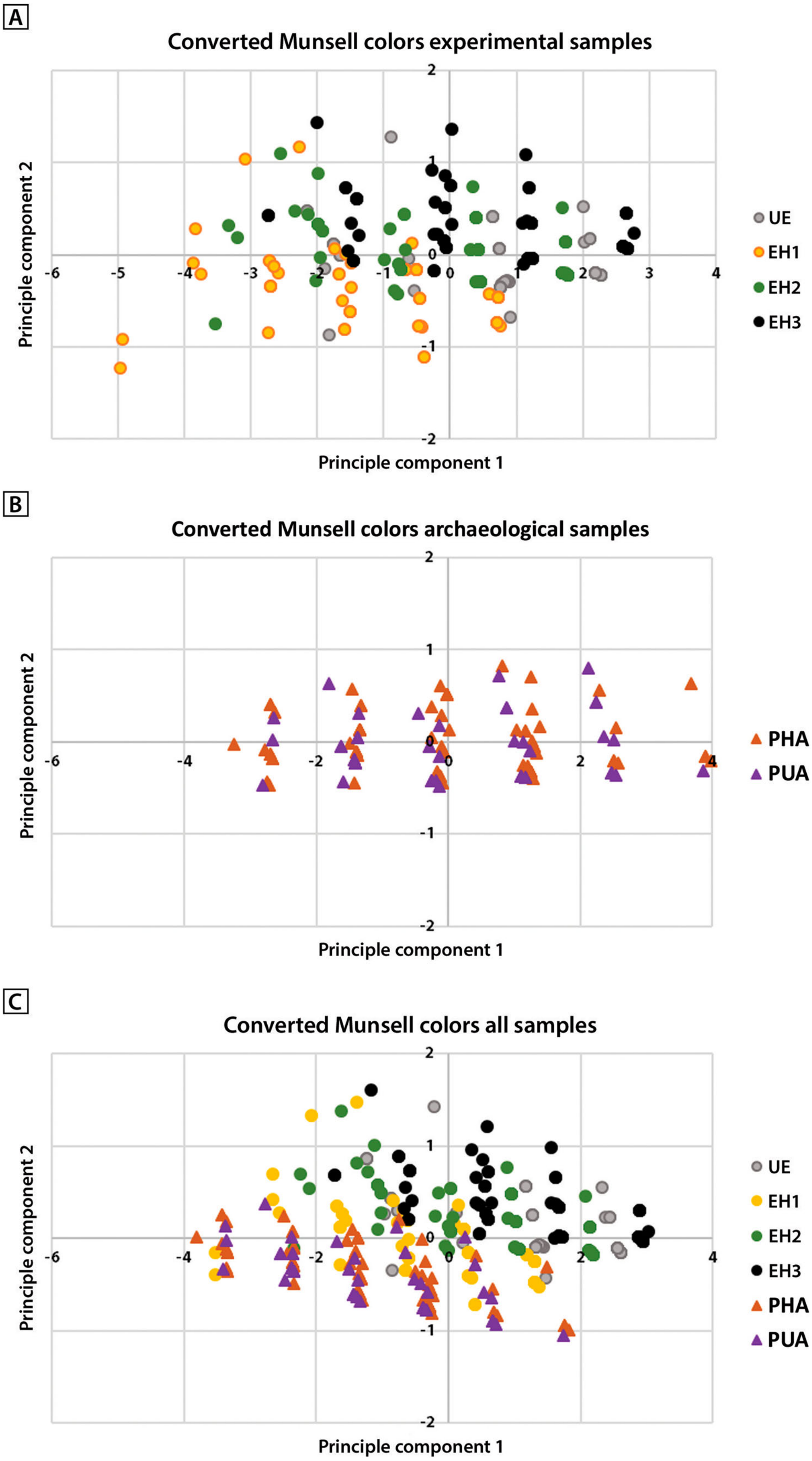

Figure 8. Scatterplot of the principal component analyses of the converted Munsell color notations. A) Experimental samples only, B) Archaeological samples only, C) All samples. Abbreviations in the legends: UE = Unheated experimental samples, EH1 = Samples experimentally heated once, EH2 = Samples experimentally heated twice, EH3 = Samples experimentally heated thrice, PHA = Potentially heated archaeological samples, and PUA = Potentially unheated archaeological samples.

As the data was not normally distributed, we ran a Spearman's rank-order correlation to determine the relationship between the color values of the heated experimental samples (DigR and principal components) and the weight of the samples. There was a very weak but statistically significant relationship between Principal Component 2 and the weight of the samples ($r_s = 0.17$, $p = 0.0185$). There were weak to moderate relationships between the other principal components and DigR on the one hand and the weight of the samples on the other, but none of these were statistically

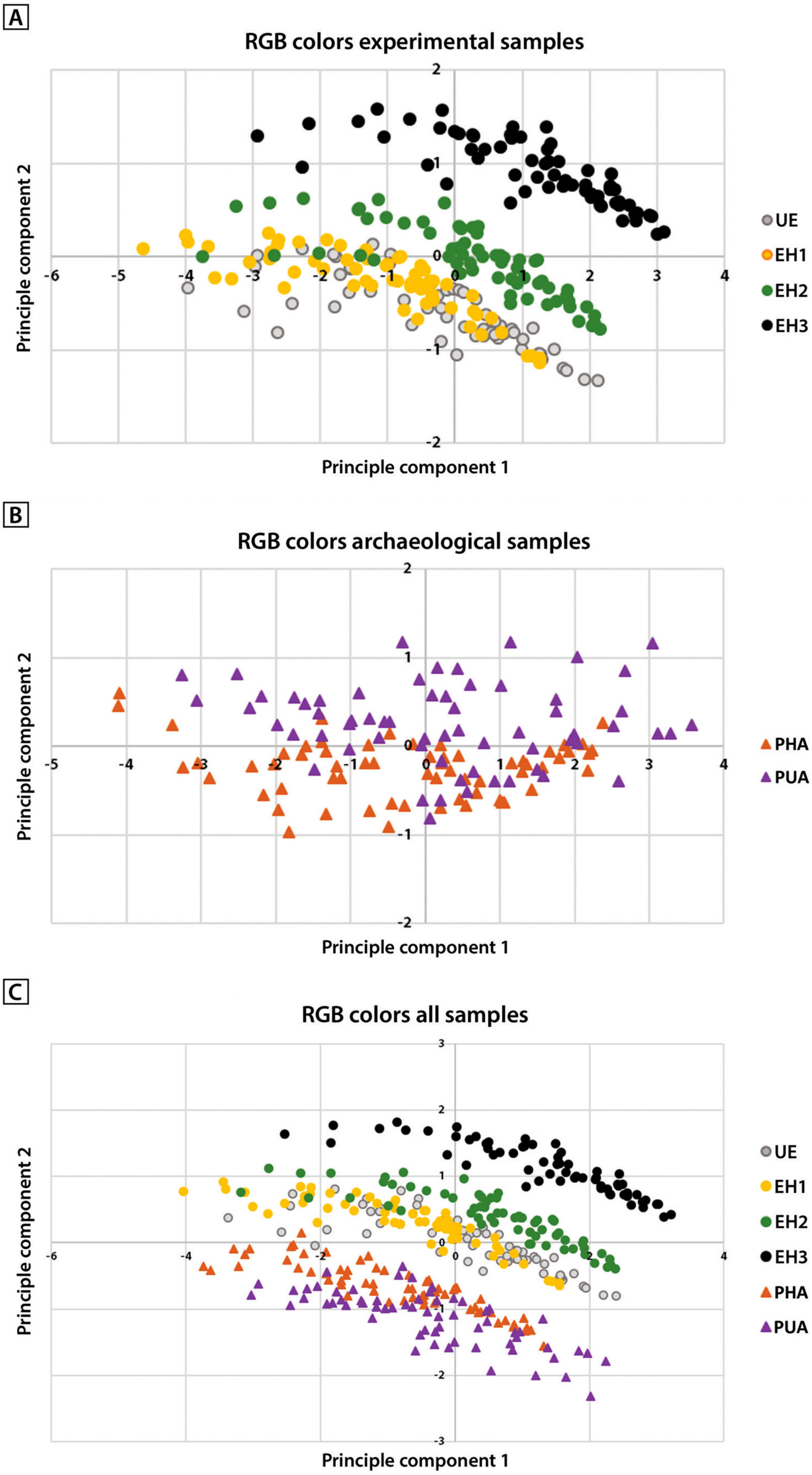

Figure 9. Scatterplot of the principal component analyses of the digital color values. A) Experimental samples only, B) Archaeological samples only, C) All samples. Abbreviations in the legends: UE = Unheated experimental samples, EH1 = Samples experimentally heated once, EH2 = Samples experimentally heated twice, EH3 = Samples experimentally heated thrice, PHA = Potentially heated archaeological samples, and PUA = Potentially unheated archaeological samples.

significant. We also tested the relationship between color values and the temperatures during the experimental heating of samples. There were weak and statistically significant relationships between Principal Component 1 and the average temperature ($r_s = 0.22$, $p = 0.0021$) and Principal Component 1 and the maximum temperature ($rs = 0.24$, $p = 0.0007$). There were weak and not statistically significant relationships between other variables.

Discussion

Cracking and breaking

Noting the presence of cracking and breakage in experimentally-heated samples is essential when using visual observation to distinguish between unheated and heated rocks. We saw, for example, in Table 3, that 33% of the samples did not appear to have changed color after three heating episodes. However, if the presence of cracks and breaks is incorporated in the visual observation of color, the proportion of rocks unaffected by the heat decreases noticeably to 23%. The importance of combining color with cracking was also noted by Oestmo (2013), who found that the inclusion of cracking data led to more realistic models of burning scenarios because cracking was influenced by temperature and, consequently, provided an extra measurement of the effects of heating. Nevertheless, only 43% of our samples developed cracks and 30% broke after three heating episodes in an open campfire (TABLE 3) with maximum surface temperatures ranging from 272.1–698.0° C (TABLE 1). These proportions of cracked and broken samples and the temperature ranges represented suggest that extensive repeated heating is needed to crack and break quartzite from the Klasies River area.

In addition to breakage and fracturing, two samples disintegrated during the heating experiments, showing that brittleness and severe weakness do develop when Eastern Cape quartzite is exposed to repeated heating episodes. Fracturing, breakage, and other weaknesses might affect why and how people heated rocks and, indeed, if heating was required at all for certain activities. We saw, for example, in Table 3, that 20% of the experimentally heated samples fractured after the first heating episode, which would have affected their knapping properties negatively. It thus appears that heating reduces the proportion of quartzite cobbles that could be used for knapping and from this it follows that the cost of tool production would be higher if heating was involved. Some of the potentially heated archaeological samples included in this study were knapped, but heat exposure could have happened after the knapping event. It is, however, important to keep in mind that the experiments reported here only focus on direct exposure to fire through heating in open campfires, and not on controlled heating in sand (Brown et al. 2009) or other gentle heating methods. Nevertheless, the experimental data on breaking and cracking from this study do suggest that the chaîne opératoire of quartzite tool production at Klasies River main site did not include heating. This hypothesis must be addressed through knapping experiments and other methods that are beyond the scope of this paper.

One might expect that cracking and breaking after heat exposure are affected by the size of the heated samples. If we examine the samples experimentally heated in this study, 57% (17 of 30 samples) weighed 300 g or less before the first heating episode and approximately 43% (13 of 30 samples) weighed 301 g or more before the first heating episode (SUPPLEMENTAL MATERIAL 1). There is a difference in cracking and breaking between these two sample groups: 15 samples weighing < 300 g (nearly 90%) did not display any cracking or breaking after three heating episodes, whereas only two samples weighing > 301 g (ca. 12%) displayed no cracking or breaking after three heating episodes. It is possible that larger samples would not heat thoroughly and that the different temperature in the core and the surface of the rock could lead to the development of cracks and breaks (see, for example literature review by Hurst and colleagues [2015]). However, this result must be tested using a larger sample size and more evenly sized quartzite samples.

Color recording methods

It was possible to distinguish between experimentally heated and unheated samples as well as potentially heated and potentially unheated archaeological samples using all the color recording methods described in this study. The methods also made it possible to compare the experimental and the archaeological samples. However, not all of the methods in our study proved equally effective, as discussed below.

Visual observation of the experimentally heated samples indicated that the frequency of red and pink increased after heating (FIGURE 6). The color differences made it possible to distinguish between unheated and heated experimental samples, although it was difficult to distinguish between samples experimentally heated once and samples that had been heated two or three times based on visual observation alone. Figure 6 also shows that the visual observation made it possible to distinguish between the PHA and PUA samples. The frequency of pink and red was much higher in the PHA than the PUA, even though the PUA included samples classified based on their pink or red color hue (see the description of the sample selection in the section Archaeological Samples).

If we compare the experimental and the archaeological samples using visual observation, it is evident that the frequency of the color gray is high in the UE, EH2, and PUA samples. It has also been shown that the frequency of pink and red is higher in the PUA samples than in the UE samples. Red is indeed more frequent in the PUA samples than in any of the experimentally heated sample groups (EH1, EH2, and EH3 [FIGURE 6]). Color was an important criterion for selecting the archaeological samples, but the frequency of red and pink do increase in the experimental samples after heating. It is possible that the frequency of red would have increased more if we had heated the experimental samples more than three times, thus increasing the similarities between the archaeological and the experimental samples. However, it is also possible that other burning scenarios might have produced experimental samples that were more similar to the archaeological samples with regard to color.

We mentioned in the introduction that reddening is one of the expected outcomes of heating rocks, but that other color changes have also been recorded (Backhouse and Johnson 2007; Behm and Faulkner 1974; Homsey 2009; House and Smith 1975; Wilson and DeLyria 1999). Our study additionally recorded other color changes than reddening, such as whitening (FIGURES 6–7), through both visual observation and Munsell color notations. The quartzite sourced at Klasies River is, consequently, similar to other types of quartzite in that it turns red and pink when heated and that other color changes than reddening can occur.

Munsell color observation (FIGURE 7) indicated that the frequency of red and gray increased after heating, while the color pink was less frequent than in the visual color observations. If we compare the visual observation (FIGURE 6) and the Munsell color notations (FIGURE 7), we also see that the color red is less frequent in the PUA samples than in the experimentally heated samples and more similar to the UE samples. The difference in perceived colors demonstrates the importance of objective and standardized methods to describe the observed color pattern. The visual observation provided a subjective opinion of the color of a sample, while the Munsell color analysis provided a framework for color description which facilitates intra-site and intra-experiment comparison. Nevertheless, we see that the PHA samples still has a much higher frequency of red than any of the other sample groups. While the Munsell color notations could help compare these results to other studies and future experiments, we still would not be able to explore and potentially explain these differences through statistical methods.

The converted and digital color values proved to be more discriminatory in that they provide numerical values for objective and statistical analysis, although there were some limitations with the method. For example, certain Munsell color values could not be converted to numerical values (Table 2, Supplemental Material 1) and these values could also not be included in the statistical analysis. In Table 2, it is shown that 83% or more of the Munsell color notations for each sample category could be converted, so the limitations in conversion only affected a very small part of the sample. Nevertheless, it is important to be aware of this limitation, especially if the sample data contains many Munsell color notations that are gray.

Figure 8 indicates that there is little distinct clustering of the variables by heating status after conduction PCA on the converted Munsell colors. Figure 8a shows that the EH1 samples form a cluster but also that there is some overlap with the other experimental sample groups, and that the unheated samples cluster with the samples experimentally heated twice and thrice. The impression from this first PCA of the converted Munsell color notations is that this method is inadequate for distinguishing between unheated and repeatedly heated samples. The PCA of the archaeological samples (Figure 8b) strengthens this impression, as no distinct clustering of samples could be found in the scatterplot.

The last PCA of the converted Munsell color notations (Figure 8c) produced a scatterplot where both groups of the archaeological samples cluster with the EH1 samples. The UE samples and the experimental samples heated two and three times do not form separate groups, and neither do the PHA and PUA samples. This pattern suggests that overlap and clustering of the sample groups might be grounded in limitations with the color recording method rather than an indication that the archaeological samples were heated once. We cannot, for example, disregard the possibility that these patterns could be a result of the collection methods. The Munsell color values were captured by one observer using the Munsell soil color chart. The system provides predefined colors, but it can be difficult to find an exact match for a particular shade and an observer might be prone to, subconsciously, choose similar colors over and over again. This would affect the result also after converting the Munsell color notations to numerical values. In conclusion, conversion of Munsell color notations to numerical values do not provide a suitable method for distinguishing between unheated and repeatedly heated samples or for comparing experimentally heated samples to potentially heated archaeological samples.

The PCAs undertaken both on the converted RGB values and on the digitally recorded RGB values show that most of the variance in color is represented by the first principal components. Furthermore, the results show that the first principal components in general describe a combination of colors. In Figures 6 and 7, it is shown that red and pink increased incrementally with increased heating episodes in the visual observation and Munsell color analysis of the samples. Based on these perceptions, one might expect red to explain most of the variance in the dataset and, consequently, be the most important contributor to the first principal component. These assumptions are, however, based on subjective perception of color changes: the human eye interprets many of the heated rocks as redder than unheated rocks. The RGB color mode describes color as a combination of three color channels and changes in the intensity of one channel (e.g., red) will lead to changes in the contributions of the other channels (e.g., blue and green) to the final color result, which is why red does not dominate in either color mode.

The data from the digital image analysis (Figure 9) were responsive to the PCA and suitably discriminant for a PCA to answer parts of the research questions in this study. UE samples and EH1 samples form one cluster in the scatterplot and EH2 and EH3 samples form distinct clusters (Figure 9a). This is similar to the results by Oestmo (2013), although he demonstrated the potential of the method when analyzing rocks heated in different burning scenarios.

Although the second PCA of digital color values shows that the method is also suitable for distinguishing between PHA and PUA samples (Figure 9b), the PCA of all the sample groups (Figure 9c) shows that the archaeological and experimentally heated samples do not overlap. This result is different from that of Oestmo (2013), who produced overlapping clusters of archaeological and experimentally heated samples. One possible explanation is that the difference is based on the burning scenario chosen for our study. Oestmo (2013) tested four different burning scenarios but produced overlapping digital color values in a simulated campfire, whereas we only tested one burning scenario (open campfire) to focus on the color recording methods. The archaeological samples from KRM could have been exposed to heat in other scenarios than those tested here, affecting their color values, which could be further tested in future experiments.

However, another possible explanation of the lack of overlap of color values in archaeological and experimentally heated samples in our study is that the results are affected by the sample size of the study. This possible explanation was explored in a case study in which we conducted a PCA on an increased sample size of 38 for the PHA and experimental samples. Unfortunately, we did not have more than 30 PUA samples (see group description under Archaeological samples above). Figure 10a contains the results for sample groups UE, EH1, PHA, and PUA and shows that there is overlap between the two former sample groups and the PUA samples. The test results from sample groups EH2, EH3, PHA, and PUA are shown in Figure 10b, which demonstrates overlap between the repeatedly heated experimental samples and the potentially heated archaeological samples. Lastly, Figure 10c combines the results from all sample groups and shows that the UE samples and EH1 samples form a cluster in one area of the chart while the EH2 samples and EH3 samples form separate clusters in a different area of the chart.

The overlap between sample groups EH2, EH3, and PHA in Figure 10 implies that the potentially heated samples from KRM could have been repeatedly exposed to the flames of an open campfire. This is important as studies of heated rocks in MSA contexts of South Africa have focused on tool

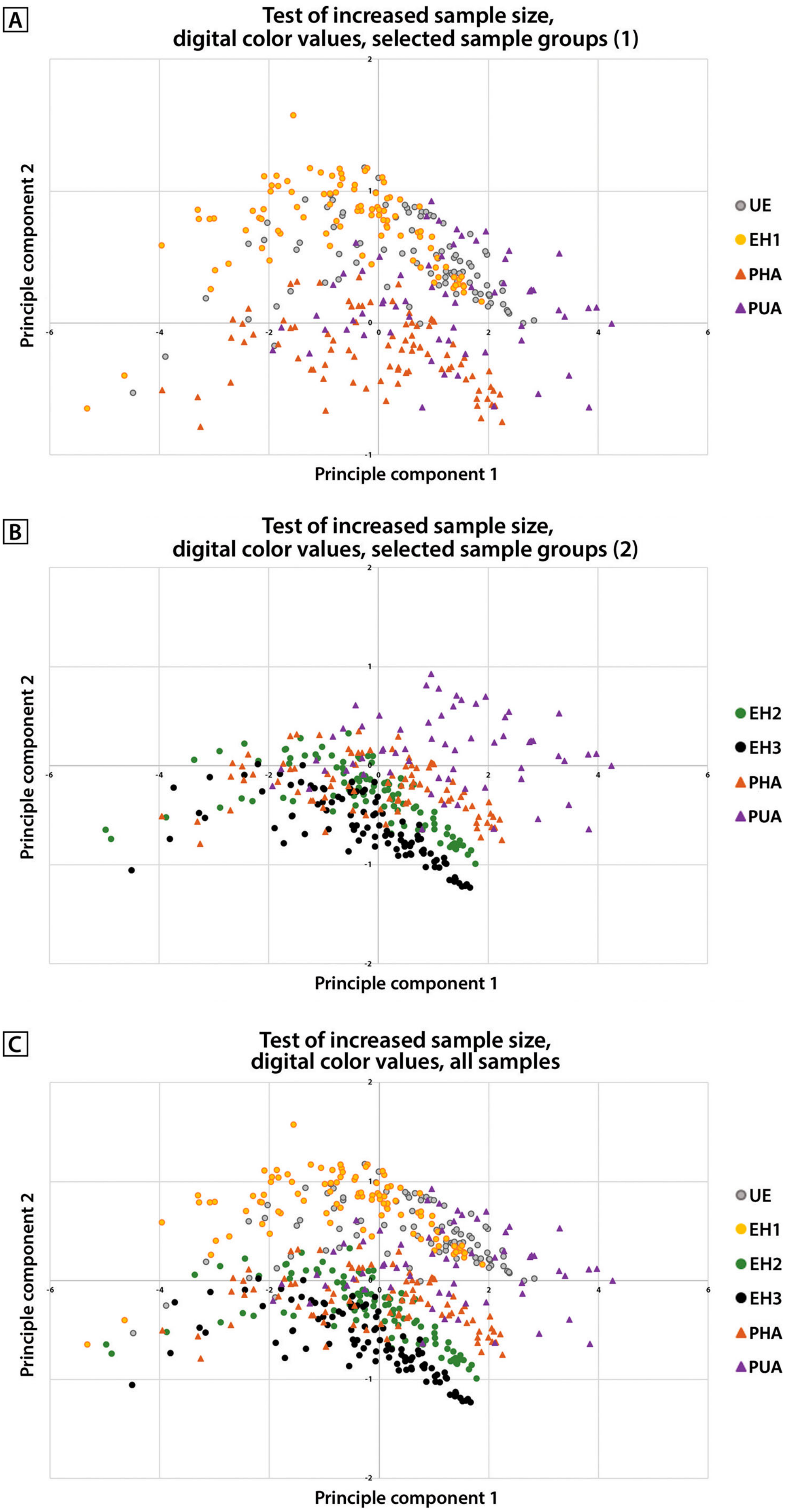

Figure 10. Principal component analysis of digital color values (case study with increased sample size). A) Sample groups UE, EH1, PHA, and PUA, B) Sample groups EH2, EH3, PHA, and PUA, C) All samples. Abbreviations in the legends: UE = Unheated experimental samples, EH1 = Samples experimentally heated once, EH2 = Samples experimentally heated twice, EH3 = Samples experimentally heated thrice, PHA = Potentially heated archaeological samples, and PUA = Potentially unheated archaeological samples.

production (Brown et al. 2009, 2012; Schmidt et al. 2013), but the experimentally heated samples included in this study developed cracks and fractures that would not be beneficial for tool production. Other potential activities leading to heat exposure are unintentional heating (Oestmo 2013) or the use of hearth stones or cooking stones, but the latter has not been documented in the MSA (Bentsen 2014). The behavioral implications of heated rocks and the question of unintentional heating or heat exposure in other scenarios than tool production should be examined in detail in future studies.

It appears that digital color analysis is sensitive to sample size. Nevertheless, the overall result from this study is that digital image analysis provides a strong method for discriminating between unheated quartzite and quartzite that was repeatedly heated in experiments and that digital image analysis proved more reliable than the other color recording methods tested.

The relationships between colors and other variables

We also examined the statistical relationship between color values on the one hand and sample weight and fire temperatures on the other hand for the converted RGB values and the digitally recorded RGB values (see sections on results above). This provided important insights. Regarding the weight of the samples, the hypothesis derived from Ebright (1987) was that smaller samples would develop different colors than larger samples. We found that there was a weak relationship for the converted color values between the sample weight and the color of experimentally heated samples, but the relationship was not statistically significant. There was a statistically significant but very weak relationship between Principal Component 2 and the weight of the samples when we tested the digital color values. These results suggest that the size of the experimental samples was not the most important variable for the color development after repeated heating experiments. We also tested the relationship between temperatures and color values. There were very weak to weak and statistically significant relationships between the principal components from the analysis of the converted Munsell colors and the fire temperatures. There were also weak and statistically significant relationships between the first principal component from the digital color analysis and the temperatures of the fire. Even though it may seem intuitive that the temperatures of a fire influence the color of the heated rocks, our results indicate that it has a limited effect on color change. The scatterplot of digital color values (FIGURE 9) show clearly that the values of repeatedly heated quartzite form separate clusters to the unheated rocks, so the temperatures do not affect the colors enough to distort this clustering.

Archaeological Implications

This study recorded new and important information on the quartzite found at Klasies River in the southern Cape. A major proportion of the sampled quartzite displayed color changes after heat exposure and nearly half the samples developed cracking and/or breaking after three heating episodes. The color changes included, but was not limited to, reddening of samples. These results establish a basic understanding of thermal alteration of quartzite in the Cape region, and future studies might expand the sample size and contribute to a more detailed understanding of the variables affecting the appearance of heated quartzite. Our study also shows that indications, such as color change and cracking, of heat exposure can aid the identification of heat-exposed quartzite in archaeological excavations. The identified raw material properties can inform research on site formation processes and technological behavior of past populations.

The findings from this study have methodological implications for studies of heated rocks from other geographical areas and archaeological periods. Color changes could be observed in samples after the first heating episode (TABLE 3), which means that some color changes in quartzite from Klasies River can happen at average fire temperatures between 211–357° C (TABLE 1). Other studies have documented color changes in quartzite to happen between 250° C (Behm and Faulkner 1974; Moody 1976) and 600° C (Åkerstrøm 2014; Graesch et al. 2014), and therefore our results put quartzite from the southern Cape region in the lower part of this range. It might be interesting in future studies to examine the differences and similarities in heat response of quartzite from different areas and to what extent there is a relationship between the heating response and elemental properties of local rocks.

A further significant methodological implication of this study is the demonstrated differences between the methods for color recording. It was possible to distinguish between unheated and heated quartzite using visual observation, but the results were limited if one only registered the color of the samples. Even when cracks in and breaks of the rocks were included, it was not possible to recognize repeated heating in some of the rocks. A similar result was achieved using the Munsell color chart to describe the color of rocks. These results were achieved under good light conditions in a laboratory. It is plausible that in archaeological field situations, when the light conditions might not be as favorable, a large proportion of thermally-altered rocks may remain undetected. Underreporting of this artifact category might have implications for our understanding of behavior at a site and should be considered during field work and subsequent analyses.

This study also examined the strength of using digital image analysis to examine color changes in rocks. This relatively cheap and accessible method was superior in identifying the distinction between unheated and repeatedly heated quartzite samples based on color. Although converting Munsell color notations to RGB values is also a relatively cheap and accessible method, it did not allow us to distinguish between unheated and experimentally heated samples based on rock color to the same extent, and the converted color values were not suitable for the principal component analysis and research questions discussed here. There might be other statistical analyses or research questions where converted Munsell color notations would be fitting, which could be examined in other studies. The results of this study suggest, nevertheless, that converted Munsell color notations should be used with caution in archaeological studies.

The color analyses used here could help us understand the archaeological sample from the Klasies River main site. The color values of archaeological samples initially did not overlap with color values of experimentally heated samples. However, the color values of repeatedly heated experimental samples and potentially heated archaeological samples did overlap when sample size was increased for the digital color values, as did the color values for unheated experimental samples, samples experimentally heated once, and potentially unheated archaeological samples. A limitation with this study is that it only tests one burning scenario, but we did reach a similar result to Oestmo (2013) in that the color values of samples experimentally heated in an open campfire overlap with color values of potentially heated archaeological samples. Factors such as sample size and choice of digital color mode could be examined in future experiments. Nevertheless, the results imply that potentially heated rocks could provide insights on MSA behavior and site formation.

Lastly, this study demonstrated the importance of standardizing the analytical methods for archaeological methods on thermally-altered rocks. Inter-site comparison is important for a broader understanding of this artifact category but is difficult when different studies use different methods to describe and analyze heated rocks. We welcome more studies on the methodological aspects of heated rocks so that future studies can be based on methods developed and customized for different rock types and heating scenarios.

Geolocation information

The Klasies River main site is situated at 34°6'29.17" S 24° 23'24.50" E.

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Disclosure Statement

No potential conflict of interest was reported by the author(s).

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