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Variance in the response of silcrete to rapid heating complicates assumptions about past heat treatment methods

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Variance in the response of silcrete to rapid heating complicates assumptions about past heat treatment methods

Abstract

Heat treatment of silcretes in the Middle Stone Age of southern Africa has been taken to indicate complex behaviour among early modern humans. This inference is based on the apparent sensitivity of silcretes to rapid changes in temperature, requiring well-regulated heating and cooling rates, and controls over maximum heating temperatures. Alternative arguments have been made that silcrete can effectively be heat treated with limited control over heating rates such that heat treatment may have been a relatively simple process. These apparently contrasting points of view elide the fact that different silcretes may respond differently to heating, and that no single approach may be appropriate in all cases. To test this proposition, we undertook a series of controlled experiments in which silcrete from two sources on the south coast of Australia were prepared into blocks of specific sizes and heated rapidly to a range of maximum temperatures in a muffle furnace. In addition to potential differences in response between sources to heat, our experiments test two factors—stone volume and maximum heating temperature—that were advanced by past explanatory models to account for the probability of sample failure (fracture) during heating. The results of our experiments suggest that the tolerance of silcretes to high heating rates is highly variable between sources within regions, and that the effect of variation between sources is stronger than the other factors examined. Additional tests on limited samples from sources in South Africa support the general relevance of our findings. From these results, we infer that optimal approaches to heating in the past were probably sensitive to the silcretes being heated.

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1 **Variance in the response of silcrete to rapid heating complicates assumptions about past**
2 **heat treatment methods**

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10 **Abstract**

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12 indicate complex behaviour among early modern humans. This inference is based on the
13 apparent sensitivity of silcretes to rapid changes in temperature, requiring well-regulated
14 heating and cooling rates, and controls over maximum heating temperatures. Alternative
15 arguments have been made that silcrete can effectively be heat treated with limited control
16 over heating rates such that heat treatment may have been a relatively simple process. These
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20 sources on the south coast of Australia were prepared into blocks of specific sizes and heated
21 rapidly to a range of maximum temperatures in a muffle furnace. In addition to potential
22 differences in response between sources to heat, our experiments test two factors – stone
23 volume and maximum heating temperature – that were advanced by past explanatory models
24 to account for the probability of sample failure (fracture) during heating. The results of our
25 experiments suggest that the tolerance of silcretes to high heating rates is dramatically
26 variable between sources within regions, and that the effect of variation between sources is
27 stronger than any of the other factors examined. Additional tests on limited samples from
28 sources in South Africa support the relevance of our findings to other contexts of silcrete
29 heating. From these results, we infer that optimal approaches to heating in the past were
30 probably sensitive to the silcretes being heated.

31

32

33 **Introduction**

34 The use of heat to alter the physical properties of siliceous rocks is a behavioural trait so far
35 documented only among modern humans, and reasonably widespread in the global record.
36 The apparently species-specific nature of this practice, coupled with underlying assumptions
37 about the uniqueness of *Homo sapiens*' behavioural capabilities (Villa and Roebroeks 2014),
38 has encouraged a perception that heat treatment reveals aspects of complexity in human
39 cognition. Like many aspects of debates concerning the evolution of human behaviour,
40 however, the link between evidence and inference is not straightforward. In this particular
41 case, the link largely hinges on whether and to what extent effective heat treatment requires
42 detailed planning, high initial costs with delayed-return benefits, and/or abstract reasoning
43 (Brown et al. 2009; Wadley and Prinsloo 2014). Whether these elements are intrinsic to heat
44 treatment is contested.

45 Current debate on heat treatment research and its implications for human behavioural
46 evolution is guided by two different concepts of how the process was enacted. The earliest
47 known use of heat treatment involved thermal alteration of the sedimentary rock silcrete and
48 occurs in the southern African Middle Stone Age (Brown et al. 2009; Delagnes et al. 2016;
49 Schmidt and Mackay 2016; Schmidt et al. 2013). Building on prior research, initial
50 experiments to recreate that process worked on the assumption that successful heat treatment
51 – that is, having the stone remain relatively intact after heating – required slow heating and
52 cooling rates, and control over maximum temperatures (Brown et al. 2009). In order to
53 achieve these controls, researchers buried silcrete blocks in an insulating medium (sand)
54 before building a fire over the top. The fire was sustained for a period of hours before being
55 allowed to burn out, and the sand was allowed to cool before the silcrete was extracted.
56 Supporting research suggested that this insulated method was necessary to avoid the silcrete
57 blocks fracturing, something which occurred regularly at higher temperatures in open fires
58 (Wadley and Prinsloo 2014). This approach, which we might term 'high-cost', involves the
59 planning and execution of hierarchical actions, and warrants many of the above-mentioned
60 inferences regarding behavioural complexity.

61 An alternative 'low-cost' approach suggests that heat treatment can be carried out
62 successfully when silcrete pieces are placed directly in an open fire (Schmidt et al. 2015a;
63 2017a). The underpinning principal is that, while slow heating/cooling rates and low
64 maximum temperatures may be required for rocks such as chert and flint, the greater porosity
65 of silcrete enables it to withstand both greater heating/cooling rates and higher maximum
66 temperatures (Schmidt 2014; Schmidt et al. 2017b). Experimental and ethnographic
67 observations on the heating of other rock types may thus not be relevant to the process as it
68 applies to silcrete. In support of this proposition is evidence for carbonised green wood
69 exudates (residues) on heated silcretes from archaeological sites in southern Africa, along
70 with frequent evidence for heat fracture prior to flaking that, as noted above, is difficult to
71 reconcile with an insulated or 'sand-bath' heating technique (Delagnes et al. 2016; Schmidt et
72 al. 2015a, 2017a). It has also been noted that there is no ethnographic evidence that the sand-
73 bath approach was ever used during heating of silcrete (Schmidt 2016). If this 'low-cost'
74 approach is a more accurate characterisation of typical silcrete heat treatment in the past, then

75 the implications for behavioural complexity are probably quite limited. While the process is
76 transformative, it is not necessarily any more conceptually complex than cooking food.

77 One potential complication to past experimental work in this debate is the tendency to treat
78 silcrete as a coherent class of rock that is likely to respond consistently to heating. Yet,
79 silcrete is heterogeneous in formation, composition and character (Roberts 2003;
80 Summerfield 1981), and responses to heating have been demonstrated to be variable at
81 regional scales (Schmidt et al. 2017c; note also Byers et al. 2014 with respect to chert).
82 Developing reasonable expectations for the practice of silcrete heat treatment in the past thus
83 requires some understanding of the range of variation in tolerance for different heating rates
84 and maximum temperatures between samples from different sources. Indeed, it seems
85 plausible that both the high-cost and low-cost approaches outlined above may be viable for
86 different silcretes, given sufficient variation in response.

87 To begin to address this problem, we undertook a set of controlled experiments on silcrete
88 samples from two nearby sources located on the east coast of New South Wales (NSW),
89 Australia. Our objective with these experiments was principally to explore the extent of inter-
90 source variation on the response of silcretes to rapid heating. These controlled experiments
91 emerged from a series of actualistic (camp fire) experiments carried out with silcretes from
92 three sources around the site of Varsche Rivier 003 (VR003) in South Africa (Steele et al.
93 2016). In those early trials we observed differences in fracture rates between sources during
94 individual heating runs. We had intended to conduct subsequent formal controlled
95 experiments on samples from the same sources but lacked sufficient material for multiple
96 replications with different factors (as described below). We thus switched to the NSW
97 sources as they were easy to access – providing enough material for multiple replications –
98 and because both are known to have been used archaeologically (Hanckel 1985; Hughes et al.
99 1973). While our results focus on the NSW samples, we provide a brief discussion of the
100 results from limited controlled experiments on a small sample of South African silcretes for
101 comparative purposes.

102 **Controls on fracture during heating of silcrete**

103 A range of controls on the probability of fracture during heating of silcrete have been
104 identified by past research, including porosity, heating rate, nodule volume, maximum
105 temperature, mineralogy, and mineral phase change (Wadley and Prinsloo 2014; Schmidt et
106 al. 2017b; Schmidt 2014; Mercieca and Hiscock 2008; Kenna 2016). In this paper we do not
107 undertake any mineralogical analysis but concentrate on the effects of two factors – heat and
108 volume – on the probability and extent of silcrete fracture during heating. We focus on rapid
109 heating because the tolerance of silcrete to steep temperature gradients is, along with
110 maximum temperature tolerated, one of the key elements of the current debate.

111 In a classic and influential set of controlled experiments, Mercieca and Hiscock (2008)
112 explored how silcrete blocks of different volumes respond when exposed to different
113 maximum temperatures. In their experiments, blocks were cut into consistent shapes (cubes)
114 and placed in a preheated furnace, producing very steep temperature gradients. Their results

115 differentiated three zones of response – intact, cracking and fracture (Figure 1). In the intact
116 zone, blocks had no visually-noticeable adverse effects from heating. In the cracking zone,
117 blocks had visually-noticeable cracks but remain coherent. The fractured blocks broke apart.
118 Probability of cracking and fracturing both increased in response to maximum temperature
119 and block volume, such that smaller blocks were able to withstand higher maximum
120 temperatures prior to cracking/fracturing than larger blocks. In general, no cracking or
121 fracturing was witnessed below 600°C, and in the smallest blocks, temperatures of up to
122 700°C could be tolerated without cracking.

123 The Mercieca and Hiscock (2008) experiments established that silcretes can tolerate high
124 heating rates without fracturing, albeit more easily when volumes are small. They did not
125 speculate on the underlying mineralogical or chemical causes of this pattern; nevertheless the
126 results stand in contrast to other statements that have been made with respect to temperature
127 controls. In a set of actualistic experiments, for example, Wadley and Prinsloo (2014) noted
128 that blocks heated to $\geq 573^\circ$ - either in an open fire or on a bed of coals - invariably fractured,
129 while those heated to $\leq 521^\circ\text{C}$ – whether on a bed of coals or buried in sand beneath the fire –
130 did not. Ascribing this pattern to energy release during a phase change in quartz minerals,
131 Wadley and Prinsloo (2014: 49) concluded that: “Rapid heating or cooling through the phase
132 transformation at 573°C will cause fracture of the silcrete”. Their results suggest that, size
133 effects notwithstanding, the propensity of silcrete to shatter will increase around and beyond
134 that value.

135 A limitation common to both of these sets of experiments is that they used silcrete from
136 singular sources to generate general statements about controls on fracture. Yet as Schmidt et
137 al. (2017c) demonstrate, different silcretes may respond quite differently when heated,
138 complicating the formulation of general response curves. In order to explore this idea further
139 we set up a series of controlled experiments modelled on Mercieca and Hiscock’s (2008)
140 work, testing the effect of volume and maximum temperature on probability of fracture under
141 conditions of rapid heating. In contrast to earlier experiments, however, we used silcrete from
142 multiple sources, including one of the sources (Bannisters Point) used by Mercieca and
143 Hiscock (2008). Our interest here is not to test the validity of earlier results, but their
144 universality. More specifically we ask: To what extent do silcretes from different sources
145 exhibit similar responses to rapid heating when volume and maximum temperature are
146 controlled for?

147 We should note at the outset that our experiments only tested for the probability of visually-
148 noticeable fracture. It is plausible that unfractured rocks could sustain sufficient damage to
149 their internal structure as to be unusable for tool production, and equally that fractured blocks
150 were otherwise fine for knapping. Those consequences of heating were not explored in those
151 experiments.

152 **Material and Methods**

153 *Australian (NSW) samples*

154 Silcrete samples were collected from two outcrop sources in NSW: Bendalong Point (BDL)
155 and Bannisters Point (BNS) (Figure 2). The latter is the same source used by Mercieca and
156 Hiscock (2008). The two sources are in close proximity from each other (~10 km) and are
157 both associated with the deeply weathered Tertiary sediments in the Bendalong-Ulladulla
158 area (Hughes et al. 1973; Young and McDougall 1982). The silcrete in this area is generally
159 grey in colour and composed of poorly-sorted quartz clasts set in a fine-grained authigenic
160 quartz cement (Challender 1978 cited in Young and McDougall 1982). Multiple large nodules
161 (~40 cm in maximum dimension) were collected from the two sources; stones with dissimilar
162 colour and cortex were purposely included to maximise the variation represented in each
163 source.

164 Three nodules from each source with suitable morphology for cutting were selected for
165 sample preparation. Each nodule was cut into 60 cubes of four different volumes (15 cubes
166 per volume): 1×1×1 cm (1 cm³), 2×2×2 cm (8 cm³), 3×3×3 cm (27 cm³), and 4×4×4 cm (64
167 cm³). These four volume designs cover the size range used by Mercieca and Hiscock (2008)
168 and allow us to evaluate the effects of volume at given heating temperatures. Importantly, by
169 preparing the samples with the standard cube shape, we hold the effect of sample shape
170 constant and thus isolate the influence of volume. The cubes were cut by a brick saw with a
171 diamond blade and refined by a trim saw if necessary. Each sample was weighed to the
172 nearest 0.1 g. Based on visual inspection of the cut surfaces, all of the samples had similar
173 lithological properties, being composed mainly of matrix with some notable grains, and could
174 be classified as ‘floating fabric’ according to Summerfield (1981).

175 The silcrete samples were heated in an electrical muffle furnace preheated to three set
176 temperatures: 550°C, 600°C, and 700°C. Five samples per volume per parent nodule from
177 each source were heated at every temperature level. This factorial design allows an equal
178 spread of observations across all possible combinations of the independent variables. Such an
179 approach involves trade-offs. In the case of explosive fracture (see below) it is not always
180 possible to recover all of the fragments of the original block, and detail is necessarily lost.
181 Furthermore, adding multiple blocks involves leaving the furnace door open for a longer
182 period than when single specimens are heated, and the addition of different total volumes in
183 each heating run may also impact the heat within the furnace. While we did not attempt to
184 document the effects of these factors (furnace opening times and volume added) on starting
185 temperature, in all cases the furnace temperatures returned quickly to the selected maximum.
186 The benefit of this approach is to allow multiple replications, with less reliance on the
187 representativeness of single specimens.

188 Following Mercieca and Hiscock’s (2008) results, our samples should remain intact
189 regardless of their size after heating to either 550°C or 600°C. When heated to 700°C,
190 however, we would expect samples with greater volume to experience more heat fracture
191 than those of smaller volumes. In contrast, following Wadley and Prinsloo, our samples
192 heated to 550°C should largely remain intact, while those heated to temperatures above
193 573°C should exhibit much higher rates of heat-induced cracking or fracture. As the furnace
194 was preheated, and the samples taken from room temperature, heating rates were rapid in all
195 cases—this is a variable we do not explicitly explore here. The samples were positioned in

196 the furnace according to a predetermined arrangement with gaps in between samples so they
197 did not have contact with each other. Each heating event included samples from all size
198 groups. In this way, any variation among the heating episodes was spread across the different
199 volume categories and would not bias particular size levels. The locations of samples of
200 different sizes within the furnace were randomised to ensure that there were no confounding
201 effects from zones of variable temperature within the heated area. All samples were heated
202 for one hour before the furnace was turned off to allow the stones to cool gradually; one hour
203 is sufficient for major heat-induced mineralogical transformations in chert and flint (Schmidt
204 et al., 2015b). This gradual cooling procedure limits the occurrence of fractures caused by
205 rapid cooling. The furnace was not opened until its temperature had fallen back to ambient.
206 After heating, the samples were retrieved from the furnace and weighed. If a sample was
207 fractured (broken with largest remaining fragment $\geq 50\%$ of original mass) or exploded
208 ($< 50\%$ of original mass), the largest remaining piece was identified, based on the sample's
209 original placement location, and weighed. If samples could not be found, we took this as an
210 indication of severe heat fracture and noted the remaining sample weight as zero.

211 To quantify the extent of heat fracture, we computed the percentage of surviving mass for
212 each sample by dividing the post-heating weight by the pre-heating weight. If the post-
213 heating sample weight is zero because no remaining pieces were found, we marked the
214 percentage as zero. This measure, however, has some uncertainties. Namely, samples
215 experiencing similar levels of heat fracture could have dissimilar post-heating weight due to
216 the influence of fabric arrangements and incipient faults/fractures on fracture pathways – a
217 fracture through the centre of a sample would result in a $\sim 50\%$ surviving mass while a
218 fracture closer to the edge would result in a greater percentage of surviving mass. Thus,
219 treating the percentage of surviving mass as a continuous measure could misrepresent the
220 actual degree of heat fracture represented among the samples. To minimise the impact of this
221 uncertainty, we classified the percentages into three arbitrary intervals defined to reflect
222 varying states of heat fracture: 0–49% (“exploded”), 50–89% (“fractured”), and 90–100%
223 (“survived”).

224 We constructed a cumulative link model to evaluate the effect of temperature, sample
225 volume, and source on the heat fracture categories. A cumulative link model, or an ordinal
226 regression model, is a type of generalized linear model for handling ordinal response
227 variables where the distance among the variable categories are unknown (Agresti 2007;
228 Christensen 2015a). For this study, although the distances among the three heat fracture
229 intervals are known (as we defined them), the variable was treated at an ordinal scale
230 (survived $>$ fractured $>$ exploded) for the purpose of model building. We used a proportional
231 odds model which includes a logit link to describe the log odds of the probabilities for
232 observations falling in a lower category versus the remaining higher categories (Agresti 2007;
233 Christensen 2015a). The model produces a set of coefficients describing the effect of
234 predictor variables (temperature, volume, and source) on the response variable (heat fracture
235 extent) and two intercepts that mark the thresholds separating the three response categories.

236 Model fitting was conducted using the R statistical software (R Core Team 2017) and the
237 ‘*ordinal*’ package (Christensen 2015b). The *clm* function from ‘*ordinal*’ was used to

238 construct the proportional odds model; the *nominal_test* function from the same package was
239 used to perform a likelihood ratio test (Barr et al. 2013) for the proportional odds assumption
240 where the influence of the predictors is assumed to be consistent across different thresholds
241 of heat fracture (Christensen 2015b). The two predictor variables are transformed to z scores
242 to improve their interpretability. We consider all two-way interactions among the three
243 predictors. Based on the observations of Mercieca and Hiscock (2008), we expect an
244 interaction between volume and temperature, that is, the effect of temperature on heat
245 fracture should be conditioned by sample volume. The significance for each interaction is
246 tested by using a likelihood ratio test. We further check the stability of the overall model by
247 computing the 90% confidence intervals for the model coefficients with a 2-fold cross
248 validation over 1000 iterations. Additional R packages of *ggplot2* (Wickham 2009), *scales*
249 (Wickham 2017) and *reshape2* (Wickham 2007) were used for data presentation. An alpha
250 level of 0.05 is employed to assess the level of significance here and the tests hereafter.

251 We also tested the proposition that rates of fracture would increase significantly for samples
252 heated above 573°C by employing a linear-by-linear association test (Agresti 2007). The
253 linear-by-linear test, implemented in the R statistical software package with the *lbl_test*
254 function from the *coin* package (Hothorn et al. 2008), assesses the association between
255 ordered categorical variables.

256 *South African (VR003) samples*

257 For the controlled experiments on South African silcretes, we used samples collected from
258 three sources within 20 km of the archaeological site of VR003 located in southern
259 Namaqualand (Figure 2). All three sources appear to have been exploited in the Middle Stone
260 Age – that is, all three have Middle Stone Age artefact scatters associated with them – and
261 macroscopic characteristics suggest that artefacts from these sources were transported to
262 VR003. The sources occur in Tertiary and Quaternary sands of the Knersvlakte region and
263 include matrix-supported (Olifants River source), floating fabric (Mustard Hill source) and
264 grain-supported (Quartz Valley source) fabric types (Roberts 2003). Sorting in these silcretes
265 is moderate to poor, with subangular quartz inclusions up to 3 mm.

266 As with the NSW sample, nodules were cut into cubes using a brick saw and refined with a
267 trim saw, and weighed to 0.1 g. Due to the limited material available, we were only able to
268 prepare three cubes for each source in the 27 cm³ and 64 cm³ volumes, and nine in the 1 cm³
269 volume. We did not prepare any cubes of 8 cm³. Samples were placed in the same electrical
270 muffle furnace preheated to 550°C, 600°C, and 700°C. Given the three test temperatures and
271 the small number of cubes we could cut, this equated to one sample per source per
272 temperature at each of 27 cm³ and 64 cm³, and three samples per source per temperature at 1
273 cm³.

274 To enhance the reproducibility of our results and to improve research transparency, we
275 include the R code (in R Markdown format) and data as supplemental material. The code and
276 data are released under the CC-BY licence (see Marwick 2017).

277 **Results**

278 *Australian (NSW) samples*

279 Table 1 outlines the percentage of surviving mass for each sample after heating; Figure 3
280 summarises the proportions of the three fracture categories by temperature and volume.
281 Looking at Figure 3, there is a clear difference between the two sources in the extent of heat
282 fracture. Most of the BDL samples survived with minimal or no mass lost. There also appears
283 to be some association between volume and heat fracture if the smallest volume group (1
284 cm³) is excluded. However, even by doing so, the actual difference of heat fracture frequency
285 among the three larger volume groups is minimal. Similarly, while there seems to be an
286 association between temperature and heat fracture, the difference is again quite small.
287 Interestingly, the BDL samples that shattered completely (i.e., 0% remaining mass) are all
288 from the 1 cm³ volume group (Table 1). This outcome could suggest that heat fracture breaks
289 up entire samples more easily when volume is small, which explains why there is a lack of
290 ‘fractured’ samples in this size category. However, this pattern could also relate to sample
291 recovery error. Specifically, since these samples are small to begin with, the fractured
292 fragments can scatter more easily inside the furnace. If this is the case, the post-heating
293 sample could be difficult to identify, and thus the weight of the surviving sample would be
294 assumed to be zero.

295 In comparison to BDL, the rate of heat fracture among BNS samples is much higher. Over
296 half of the BNS samples in the 27 cm³ group are ‘fractured’ and ‘exploded’, meaning they
297 have lost more than 10% of their original weight; for the 64 cm³ group, close to 70% of the
298 samples lost more than 50% of their original mass. The association between sample volume
299 and heat fracture is also clearer among the BNS samples, where the number of ‘fractured’ and
300 ‘exploded’ samples increases considerably with volume. There is, however, no clear
301 relationship between temperature and heat fracture. Again, all of the ‘exploded’ samples in
302 the 1 cm³ group have 0% surviving mass - this could be due to the sample recovery error
303 discussed above. That said, there are also samples in the larger volume groups with 0% mass
304 remaining. These cases are more likely to represent severe heat fracture where the samples
305 were severely fragmented by heat and became unidentifiable.

306 Turning to the proportional odds model, likelihood ratio test for all two-way interactions by
307 single term deletion returned significant outcome for the interaction between volume and
308 source (Likelihood ratio test: LR stats=6.35, df=1, p=0.012). On the other hand, no notable
309 interactive effect is detected between temperature and sample volume (Likelihood ratio test:
310 LR stats=0.018, df=1, p=0.89), nor between temperature and source (Likelihood ratio test:
311 LR stats=0.13, df=1, p=0.72). A single term addition analysis also returned identical results,
312 with only the interaction between volume and source being significant (Likelihood ratio test:
313 LR stats=6.41, df=1, p=0.011). We drop the two non-significant interaction terms from the
314 model to avoid overfitting. Table 2 summarises the model. All of the coefficients fall within
315 their respective 90% confidence interval derived from cross validation. The model suggests
316 that temperature does not have a significant effect on sample heat fracture.

317 The interaction between volume and heat fracture captures the different relationship between
318 the two variables across the two sources. Looking at Figure 3, the relationship between

319 volume and heat fracture appears to be non-linear among the BDL samples, where the
320 frequency of samples experiencing greater heat fracture declines with volume when samples
321 are small (1–8 cm³) but increases when samples becomes bigger (8–64 cm³). On the other
322 hand, the same relationship among the BNS samples is linear, with the number of heat
323 fractured samples as well as the extent of fracture both rise with volume.

324 While the inter-source difference in the effect of volume is intriguing, there exists the
325 possibility that the 1 cm³ samples are not directly comparable to other size groups due to the
326 issues of recovery bias and the overrepresentation of ‘exploded’ pieces as discussed earlier.
327 For this reason, we constructed a second proportional odds model by excluding the smallest
328 size group to see how the remaining samples behave. The results indicate that, among the 8–
329 64 cm³ samples, the interaction between source and volume is not significant (Likelihood
330 ratio test: LR stats=2.33, df=1, p=0.13). This difference makes sense as the non-linear
331 relationship between volume and heat fracture among the BDL samples observed earlier was
332 driven largely by the 1 cm³ samples. After excluding the non-significant interaction term, the
333 model (Table 4) suggests that both volume and source have significant independent influence
334 over the degree of heat fracture among the samples.

335 Based on the second model that excludes the 1 cm³ samples, Figure 4 summarises the
336 modelled effects of volume and source on heat fracture. In essence, greater stone volume
337 leads to heightened probability for heat fracture to occur (and hence lowers the chance for the
338 samples to remain intact or “survived”). While this effect is present in both sources, the
339 actual probability for heat fracture is offset by inter-source variation. Namely, the degree of
340 heat fracture is overall quite low among the BDL silcrete. Even for the 64 cm³ group where
341 the effect of volume on heat fracture is the greatest, the BDL silcrete has around 70% chance
342 of remaining relatively intact (i.e., losing only up to 10% of original weight to heat fracture).
343 On the other hand, the degree of heat fracture is notably higher for BNS silcrete. As sample
344 volume increases, the probability for substantial fracture (losing up to 50–100% of original
345 weight) to occur rises sharply. Looking at the 64 cm³ group again, the BNS samples have
346 only 18% chance of staying intact but 64% chance of becoming “exploded”. In summary,
347 while the influence of stone volume on the extent of heat fracture holds for both BDL and
348 BSN silcrete, the two sources exhibit different tolerance to rapid heating. Overall, BSN
349 silcrete has a greater probability for heat-induced fracture than BDL silcrete. Interestingly,
350 the chance for BNS samples to become “fractured” is relatively stable across different
351 volumes. This could be explained by the fact that, because BNS silcrete is less resistant to
352 heat fracture, when samples experience heat fracture, particularly those in the larger size
353 groups, they are more likely to become “exploded” rather than “fractured”—i.e., if heat
354 fracture occurs, the larger stones are more likely to suffer greater fragmentation.

355 Table 3 represents the contingency table of heat fracture categories and temperatures that fall
356 above and below 573°C. The linear-by-linear association test returned a non-significant result
357 ($Z=-0.158$; $p=0.87$), indicating that the extent of heat fracture is independent of temperatures
358 being above or below 573°C.

359 Comparing our results to previous findings, our model supports the observation that stone
360 volume influences the occurrence and extent of heat-induced fracture. Importantly, in
361 addition to the effect of stone volume, the model also indicates that inter-source variation
362 plays an important role in dictating the likelihood for heat fracture to occur. Overall, the BDL
363 silcrete exhibits much greater resistance to heat-induced fracture than the BNS silcrete.
364 Furthermore, contrary to expectation, temperature does not influence silcrete heat fracture
365 among the samples tested here – at least, not once temperatures are $>550^{\circ}\text{C}$. This outcome
366 remains true even if we only include samples from BNS, which is the same silcrete source
367 examined by Mercieca and Hiscock (2008) (see Appendix). Overall, we found no support for
368 the proposition that heating beyond 573°C significantly effects the general probability of
369 fracture.

370 *South African (VR003) samples*

371 The small sample size and lack of replications at the larger volumes necessitates cautious
372 treatment of our experiments on South African material. For this reason we present
373 descriptive results only. However the results allow an examination of whether inter-source
374 variation is likely to be a common feature in the response of different silcretes to heating. As
375 such, our data on South African silcretes provides clearer implications for the debates we
376 discussed at the start of this paper. Here we focus solely on whether there appear to be
377 differences in responses to rapid heating between sources, as suggested by our initial camp
378 fire experiments, and subsequently demonstrated using NSW samples under controlled
379 experimental conditions.

380 The proportions of the three fracture categories by temperature and volume are summarised
381 in Figure 5. As with the NSW examples, samples from the different South African sources
382 appear to fracture at quite different rates overall. None of the floating fabric samples from
383 Mustard Hill fractured at any temperatures at any volume. A single 1 cm^3 cube of grain-
384 supported material from Quartz Valley exploded at 700°C , and a 27 cm^3 cube fractured at
385 550°C ; none of the 64 cm^3 cubes from this source fractured at any temperature. In contrast,
386 the matrix-supported silcretes from the Olifants River source exploded at all volumes and at
387 all temperatures. All three of the 64 cm^3 cubes exploded, while two of the 27 cm^3 cubes
388 exploded and the remaining cube fractured. Survivorship was documented among the 1 cm^3
389 cubes only, though the number of replications here was larger.

390 **Discussion and Conclusions**

391 Heat treatment of siliceous rocks prior to knapping has a reasonably long history of research,
392 albeit generally of low intensity. That intensity of research has recently increased in response
393 to the argument that the appearance of heat treatment may carry implications for the
394 evolution of human behaviour. As noted at the outset, the validity of those implications
395 largely depends on how heat treatment was conducted in the deeper past, and whether the
396 underlying process was elaborate, with high set up costs, delayed returns, and significant
397 sensitivities to variation in heating parameters, or whether the process was expedient, and
398 with relatively low sensitivities.

399 Our purpose with this experimental program was not to resolve those debates, but to explore
400 whether there may be flaws in one of its assumptions – namely that responses of silcrete to
401 heating are consistent, such that valid general statements could be made about the likely way
402 in which heat treatment was conducted in the past. Some past work suggests that this
403 assumption is problematic (Schmidt et al. 2017c), and our results here appear to confirm this.
404 In our principal set of experiments, using silcrete from two sources located not far from one
405 another, we found quite dramatic differences in response to rapid heating. One source
406 (Bannisters Point) exhibited much lower tolerance to rapid heating than the other
407 (Bendalong), to the extent that inter-source variation had a stronger effect on the probability
408 of fracture than either of the other established factors that we tested. These results are
409 supported by experiments on South African silcretes known to have been used during the
410 Middle Stone Age. With exceptions as discussed below, it thus seems to us unreasonable to
411 make claims about the way silcrete per se responds to rapid heating without first
412 understanding the causes for the difference in heat response among sources.

413 Our results support some elements of past research but not others. In our tested samples,
414 increasing the volume of the pieces increases the probability that they will fracture when
415 rapidly heated. However, given that we included samples from the same source as Mercieca
416 and Hiscock (2008), this finding does not constitute fully independent support for that
417 proposition. Perhaps more surprisingly, we found no significant effect of maximum
418 temperature on probability of fracture in our NSW samples. This is at odds with expectations
419 from both the volume-temperature interaction model, but also with the suggestion that
420 heating to or beyond 573°C increases fracture probability.

421 Necessarily our experiments have limitations. We did not explicitly explore different heating
422 rates, and data recovery was not equivalent between samples of all volumes. Our controlled
423 experiments with South African samples were quite limited. Furthermore we have not made
424 any attempt to explain the observed variation in response between our sources – whether
425 water content, porosity, or mineralogy differed between sources in ways that might account
426 for their starkly differing probability of fracture. Such research would be valuable for
427 generating prior predictions about the ways any given silcrete might respond to heating. To
428 the extent that this is possible, it would be a more sound basis for generalised statements.

429 Perhaps a more important limitation is one that is not particular to our research, but which is
430 fairly pervasive, and that is the assumed association between fracture and failure. As we
431 noted early, the fact that a given block survived heating to 700°C has few necessary
432 behavioural implications. The surviving block, though coherent, could be unworkable, and
433 the opposite could hold for blocks that fractured. It is thus important to move beyond the
434 failure concept to quantify the benefits obtained by heat treatment, such as changes such as
435 flake size and frequency of abrupt terminations (Crabtree and Butler 1964; Mandeville and
436 Flenniken, 1974). Controlled experiments conducted by Byers et al (2014) are noteworthy in
437 this respect. Comparing two different chert types available in the same secondary deposits,
438 they found not only different sensitivities to fracture during heating, but that the quantifiable
439 change in flaking properties was also markedly different between the two types (ie., one chert

440 displayed greater benefit from heating than the other). The benefit obtained by heating can
441 thus be different between types within a raw material class.

442 Given that both costs (in the form of heating controls, modulated by raw material
443 sensitivities) and benefits (in the form of changes in flaking characteristics) of heat treatment
444 can vary, the dichotomy discussed at the start of this paper may be invalid. Silcretes that
445 display high tolerance to rapid heating might most efficiently be heated quickly, while those
446 more sensitive to heating might require greater control over heating rates. But in either case
447 how much time/effort should be invested in heating will be constrained by an assessment of
448 the resulting payoff. This raises the interesting possibility that more than one heat treatment
449 strategy may have been employed, either through time in response to changing technological
450 requirements, or at a given time in response to the tolerances of different sources. Evidence
451 for cognitive complexity might thus not reside in the application of any one approach to heat
452 treatment, but in flexible behavioural responses that are sensitive to such variation.

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459

460

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- 537

538 **Table captions**

539 Table 1. Percentage of remaining mass after heating for each of the NSW silcrete samples.
540 White cells=survived; light grey cells=fractured; dark grey cells=exploded. * denotes
541 instances where corresponding samples could not be identified in the furnace after heating.

542 Table 2. Proportional odds model for the effect of temperature, volume and source on sample
543 heat fracture among the tested NSW silcrete.

544 Table 3. Sample frequency in each of the three heat fracture categories above and below 573
545 °C.

546 Table 4. Proportional odds model for the effect of temperature, volume and source on sample
547 heat fracture among the tested NSW silcrete (exclude 1cm³ samples).

548

549 **Figure captions**

550 Figure 1. The two hypothesized models of silcrete heat fracture tested in this study.

551 Figure 2. The locations of silcrete sources in Australia (top) and South Africa (bottom) where
552 the test samples used in this study were collected from.

553 Figure 3. The distribution of sample heat fracture by volume and heating temperature
554 between the two NSW sources. Blue=Survived; Green=Fractured; Red=Exploded.

555 Figure 4. The modelled effect of stone volume (exclude 1 cm³) on the probability for
556 different degrees of heat fracture between the two NSW sources.

557 Figure 5. The distribution of sample heat fracture by volume and heating temperature among
558 the three South African sources. Blue=Survived; Green=Fractured; Red=Exploded.

559

560 **Appendix: Proportional odds model for BNS samples only**

561 *Including 1 cm³ samples*

	Coefs.	Std. error	z value	p
<u>Predictor</u>				
temperature*	-0.11	0.15	-0.76	0.45
volume*	-0.93	0.16	-5.69	<.0001
<u>Threshold (intercept)</u>				
exploded fractured	-0.65	0.17	-3.82	-
fractured survived	0.17	0.16	1.06	-

Nominal test indicates the proportional odds assumption is not violated.

Likelihood ratio test against null model (intercept only): LR stat=37.12; df=2; p<.0001

Hessian condition number=4.9

*Transformed to z score

562

563 *Excluding 1 cm³ samples*

	Coefs.	Std. error	z value	p
<u>Predictor</u>				
temperature*	-0.12	0.17	-0.72	0.47
volume*	-0.96	0.19	-4.96	<.0001
<u>Threshold (intercept)</u>				
exploded fractured	-0.77	0.20	-3.76	-
fractured survived	0.31	0.19	1.64	-

Nominal test indicates the proportional odds assumption is not violated.

Likelihood ratio test against null model (intercept only): LR stat=27.77; df=2; p<.0001

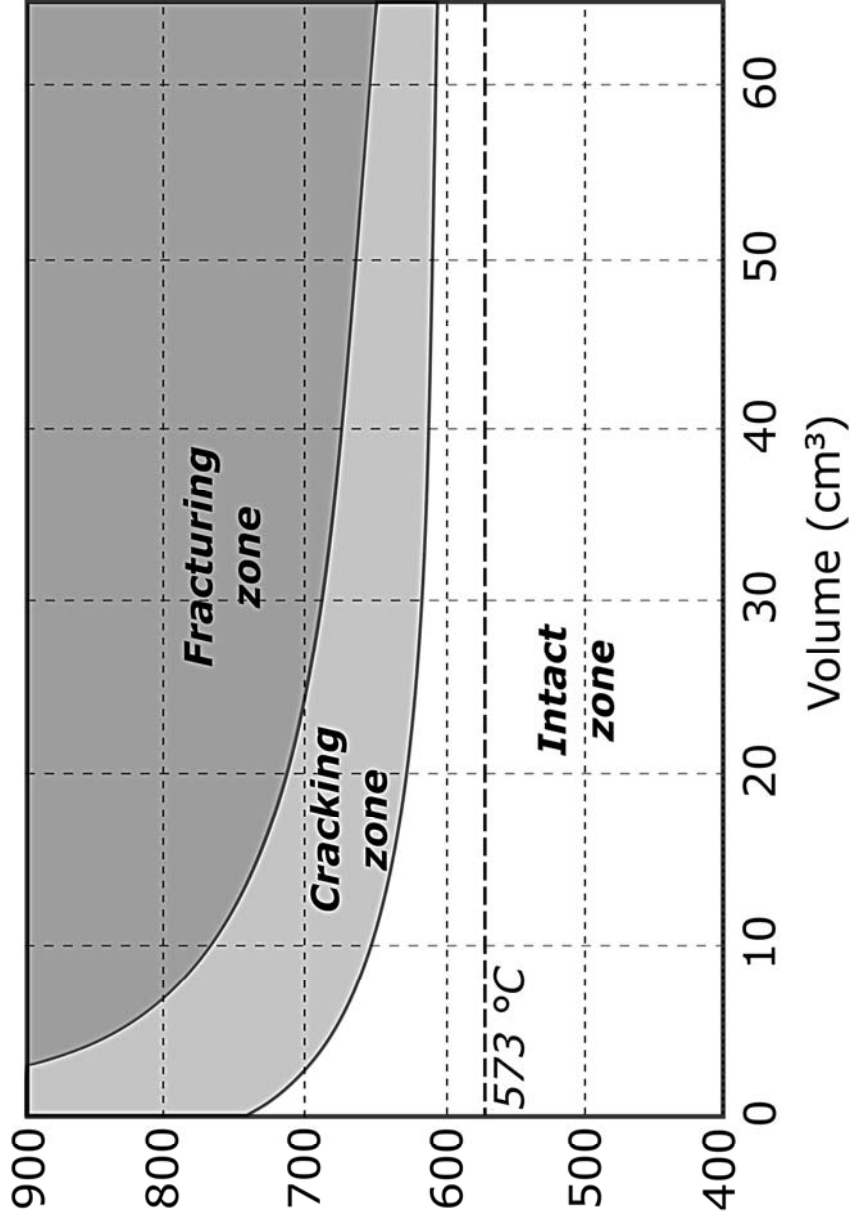
Hessian condition number=4.6

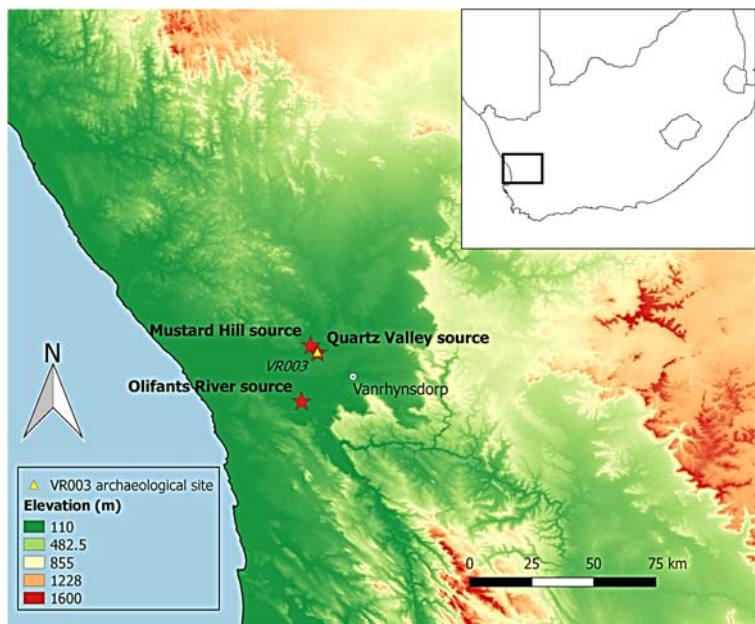
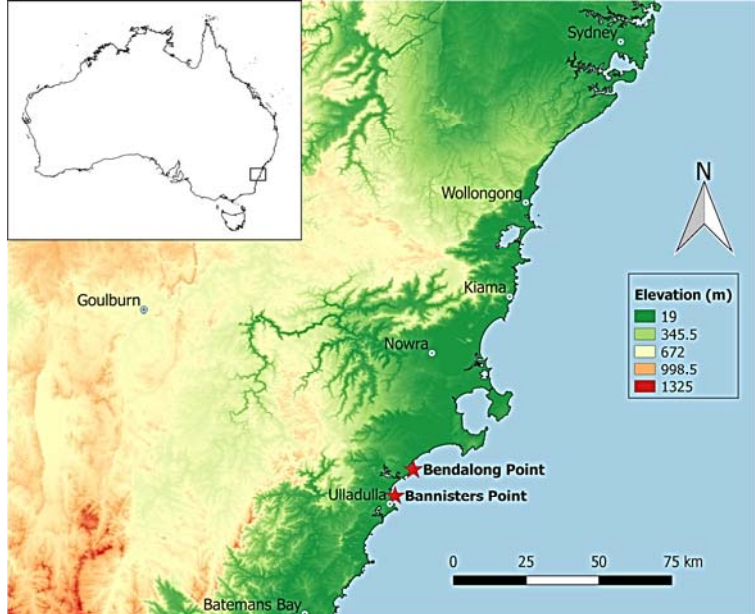
*Transformed to z score

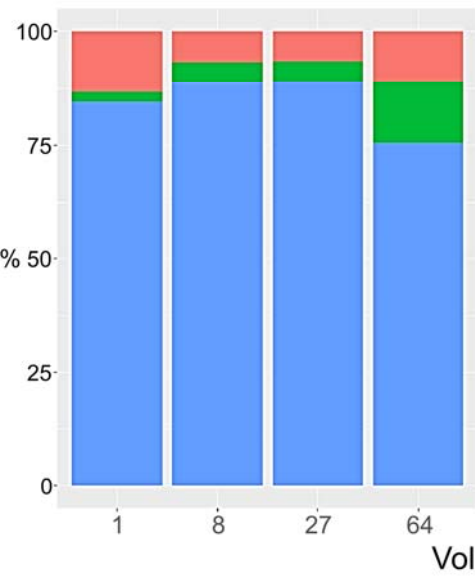
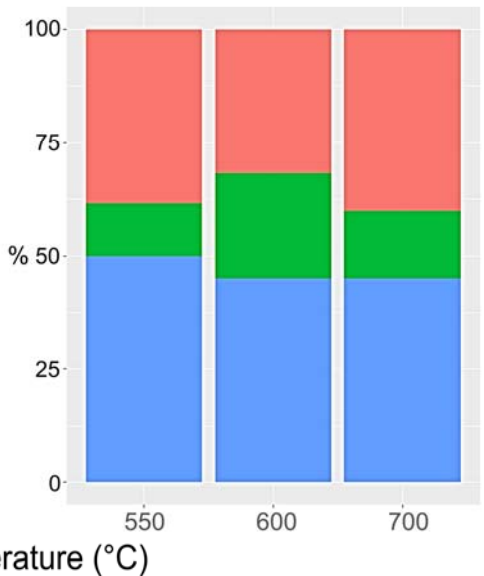
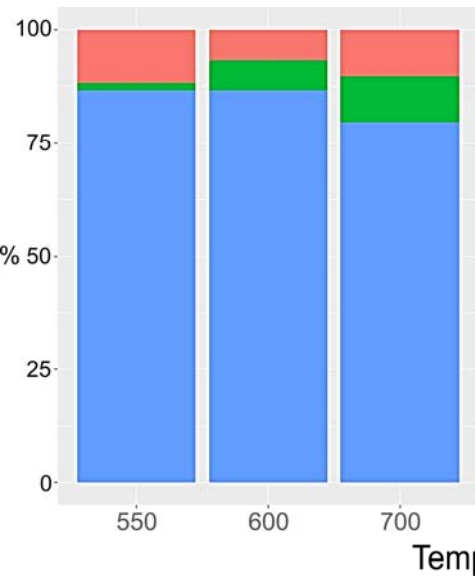
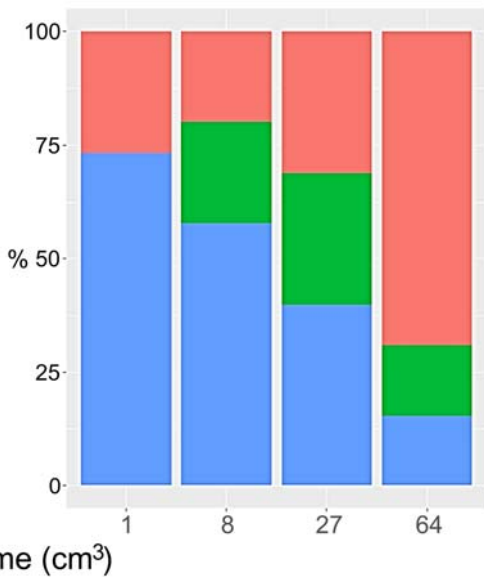
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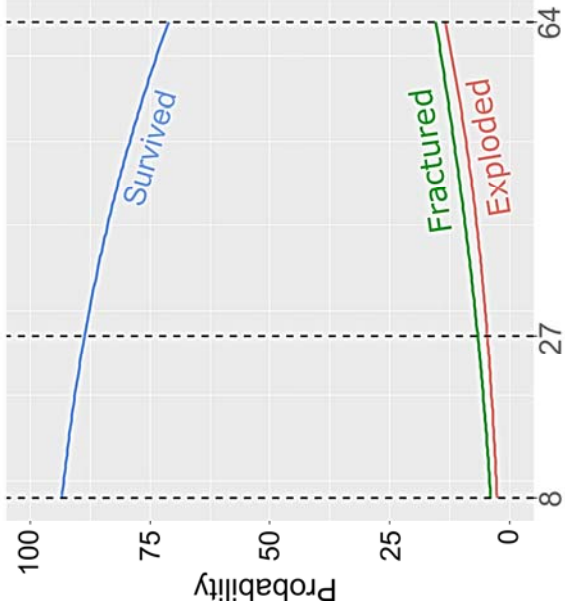
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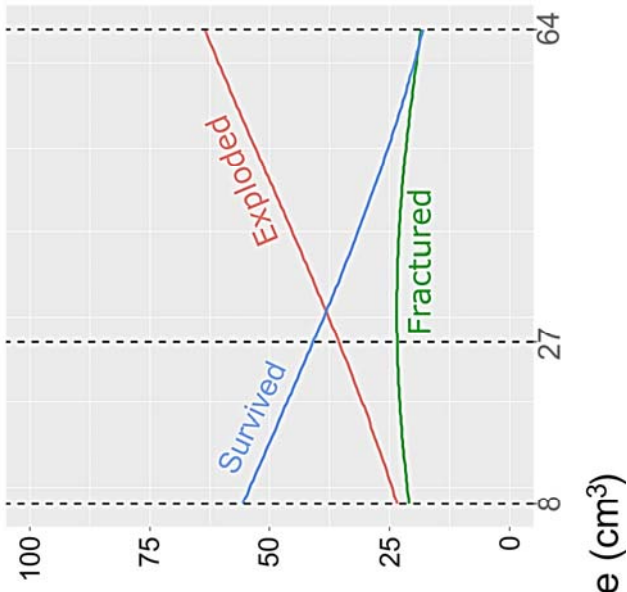


Bendalong Point (BDL)**Bannisters Point (BNS)**

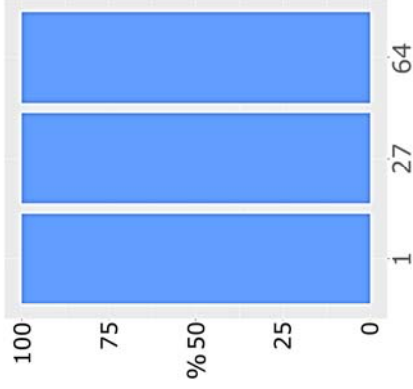
Bendalong Point (BDL)



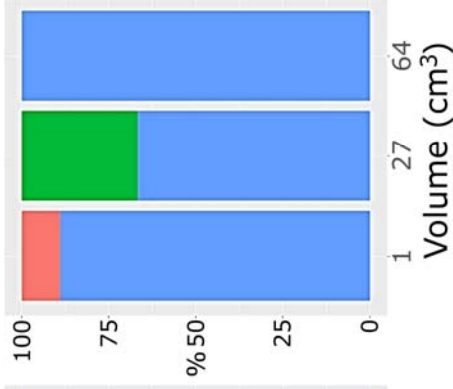
Bannisters Point (BNS)



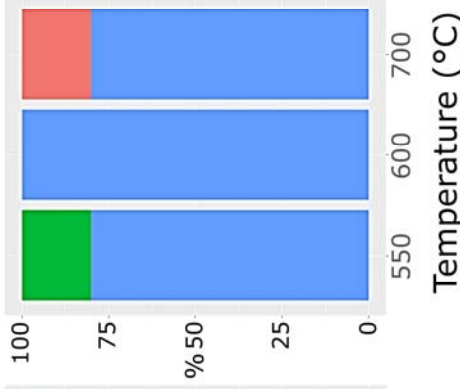
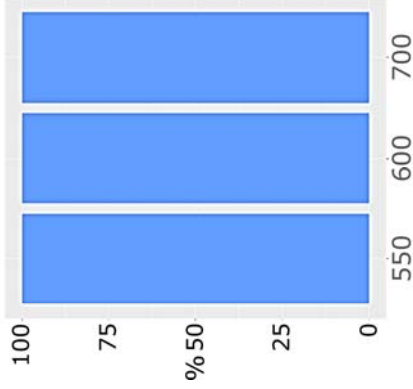
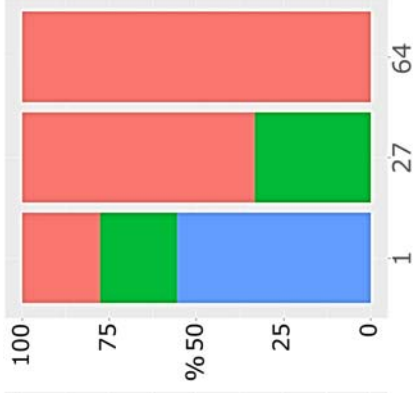
Mustard Hill



Quartz Valley



Olifants River



Source / Nodule	1 cm ³			8 cm ³			27 cm ³			64 cm ³		
	550 °C	600 °C	700 °C	550 °C	600 °C	700 °C	550 °C	600 °C	700 °C	550 °C	600 °C	700 °C
BDL Nodule 1	98	98	100	100	100	99	100	100	100	100	89	59
	98	98	98	99	100	100	100	99	100	100	100	91
	100	97	95	99	99	100	100	99	100	100	99	49
	100	0	100	99	100	99	100	99	100	100	100	99
	98	0	100	0	100	NA	99	100	99	99	100	100
BDL Nodule 2	100	100	100	100	100	100	99	58	34	99	100	68
	100	100	0	100	99	73	30	81	99	100	99	99
	100	100	98	100	100	96	94	99	99	100	96	56
	100	99	0	100	99	100	99	100	99	97	100	99
	100	98	100	0	99	88	43	99	98	100	96	99
BDL Nodule 3	98	0	37	99	99	99	99	96	99	52	31	35
	100	99	100	99	99	99	99	98	98	38	100	99
	91	100	100	100	97	99	98	99	93	47	99	99
	100	97	80	99	99	99	99	99	98	99	92	99
	100	97	100	0	99	98	100	98	99	99	87	91
BNS Nodule 1	100	100	100	100	53	49	19	74	38	47	64	0*
	98	100	95	99	100	100	100	100	39	18	36	0*
	100	98	97	100	100	99	72	51	99	14	12	0*
	100	97	100	99	33	100	99	57	100	23	85	0*
	98	100	100	0	100	89	56	100	22	40	99	38
BNS Nodule 2	96	0	100	96	99	89	85	88	60	21	87	0*
	98	0	100	0	81	81	24	99	100	99	25	0*
	0	98	95	0	62	99	59	51	86	58	96	0*
	98	100	100	91	76	60	57	99	44	26	78	94
	97	100	0	NA	0	84	99	40	97	27	92	0*
BNS Nodule 3	100	100	98	99	99	73	99	56	99	78	25	87
	0	0	100	100	24	100	28	99	16	15	47	0*
	100	99	0	99	99	100	25	9	34	99	17	100
	98	0	0	99	99	99	99	37	38	49	39	0*
	0	0	0	0	100	99	98	100	100	37	28	19

2 Table 1. Percentage of remaining mass after heating for each of the NSW silcrete samples.

3 White cells=survived; light grey cells=fractured; dark grey cells=exploded. * denotes

4 instances where corresponding samples could not be identified in the furnace after heating.

	Coefs.	Cross valid. coefs.		Std. error	z value	p
		5%	95%			
<u>Predictor</u>						
temperature*	-0.15	-0.36	0.065	0.12	-1.21	0.23
volume*	-0.27	-0.64	0.081	0.20	-1.39	0.16
source (BNS)	-1.85	-2.42	-1.43	0.26	-7.06	<0.001
volume* : source (BNS)	-0.64	-1.10	-0.19	0.25	-2.51	0.012
<u>Threshold (intercept)</u>						
exploded fractured	-2.45	-3.02	-2.09	0.23	-10.47	-
fractured survived	-1.71	-2.19	-1.40	0.21	-8.09	-

Nominal test indicates the proportional odds assumption is not violated.

Likelihood ratio test against null model (intercept only): LR stat.=98.14; df=4; p<.0001

Hessian condition number=28

*Transformed to z score

7 Table 2. Proportional odds model for the effect of temperature, volume and source on sample
8 heat fracture among the tested NSW silcrete.

9

10

11

	Survived	Fractured	Exploded
Below 573 °C (550 °C)	82 (68%)	8 (7%)	30 (25%)
Above 573 °C (500 °C + 600 °C)	153 (64%)	33 (14%)	53 (22%)

12 Table 3. Sample frequency in each of the three heat fracture categories above and below 573
13 °C.

14

	Coefs.	Cross valid. coefs.		Std. error	z value	p
		5%	95%			
<u>Predictor</u>						
temperature*	-0.081	-0.25	0.081	0.14	-0.59	0.56
volume*	-0.76	-0.96	-0.60	0.15	-5.05	< 0.001
source (BNS)	-2.42	-2.91	-2.09	0.31	-7.68	< 0.001
<u>Threshold (intercept)</u>						
exploded fractured	-3.07	-3.58	-2.54	0.31	-9.86	-
fractured survived	-2.11	-2.72	-1.82	0.27	-7.71	-

Nominal test indicates the proportional odds assumption is not violated.

Likelihood ratio test against null model (intercept only): LR stat=92.82; df=3; p<.0001

Hessian condition number=27

*Transformed to z score

- 16 Table 4. Proportional odds model for the effect of temperature, volume and source on sample
 17 heat fracture among the tested NSW silcrete (exclude 1cm³ samples).