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1 **Environmental influences on human innovation and behavioural diversity in southern**  
2 **Africa 92-80 000 years ago**

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54

55

56 **Abstract**

57 Africa's Middle Stone Age preserves sporadic evidence for novel behaviours among early  
58 modern humans, prompting a range of questions about the influence of social and  
59 environmental factors on patterns of human behavioural evolution. Here we document a  
60 suite of novel adaptations dating approximately 92-80 000 years before present at the  
61 archaeological site Varsche Rivier 003 (VR003), located in southern Africa's arid Succulent  
62 Karoo Biome. Distinctive innovations include the production of ostrich eggshell artefacts,  
63 long-distance transportation of marine molluscs, and systematic use of heat shatter in stone  
64 tool production, none of which occur in coeval assemblages at sites in more humid, well-  
65 studied regions immediately to the south. The appearance of these novelties at VR003  
66 corresponds with a period of reduced regional wind strength and enhanced summer rainfall,  
67 and all of them disappear with increasing winter rainfall dominance after 80 000 years before  
68 present, following which a pattern of technological similarity emerges at sites throughout the  
69 broader region. The results indicate complex and environmentally-contingent processes of  
70 innovation and cultural transmission in southern Africa during the Middle Stone Age.

71 **Introduction**

72 Archaeological evidence from the African Middle Stone Age (MSA, 400-40 ka) defines our  
73 understanding of human behavioural evolution in the critical window between the emergence  
74 of our species and our subsequent global spread. Yet evidence for cultural innovation—the  
75 appearance of novel items such as distinctive stone tools, engravings, ornaments, and  
76 implements made from organic materials—occurs unevenly through the MSA in both space  
77 and time. In southern Africa, evidence for innovation appears to concentrate in two  
78 successive cultural units referred to as the Still Bay and Howiesons Poort, dating  
79 approximately 77-59 ka (1, 2). In the preceding periods of the MSA ('pre-Still Bay'),  
80 instances of cultural innovation tend to be temporally and geographically isolated (3). In the  
81 subsequent MSA ('post-Howiesons Poort'), several innovations appear to be lost, including a  
82 tradition of producing engraved ostrich eggshell (OES) water flasks that previously extended  
83 across 600 km of diverse habitats from the southern Cape coast to the deserts of southern  
84 Namibia (4, 5).

85

86 Explaining the complicated and apparently non-directional pattern of MSA cultural change is  
87 key to understanding controls on human behavioural evolution. Prominent explanations have  
88 included fluctuations in effective population size (6), the advent of territorial defense  
89 associated with exploitation of dense and predictable resources (7), and climatically driven  
90 phasing of cultural connectedness across the subcontinent (8). A significant biogeographic  
91 skew in the available archaeological dataset, however, makes these explanations difficult to  
92 test. Southern Africa is an ecologically diverse region with complex climate dynamics, yet  
93 evidence for MSA cultural innovation derives disproportionately from the relatively humid  
94 southern Cape coastal fringe (Figure 1). The archaeology of the arid regions of the west  
95 coast and interior remains notably understudied (9, 10). This skew may act to exaggerate  
96 both the appearance of cultural homogeneity and the periodicity of innovation by excluding  
97 ecosystems that required different behavioural adaptations to enable occupation at different  
98 times. It also complicates our understanding of cultural transmission dynamics—of when and  
99 under what conditions behaviours were transferred across biogeographic boundaries—and  
100 thus of the interplay between population connectivity and the development and persistence  
101 of innovations.

102

103 Here we present new data from excavations at the site of Varsche Rivier 003 (VR003),  
104 located 44 km from the Atlantic coast in the Knersvlakte bioregion, southern Namaqualand  
105 (Figure 1). Falling within the modern Succulent Karoo Biome, the Knersvlakte currently  
106 receives  $\sim 175 \pm 30$  mm of rainfall per year (11, 12), almost all during the austral winter, and is  
107 characterised by a limited groundcover of xeric-adapted succulent shrubs and endemic

108 'stone plants' (13). While the MSA archaeology of the Succulent Karoo is largely unstudied,  
109 VR003 lies close to the modern limits of the Fynbos Biome. Characterised by evergreen  
110 shrubs and reeds, and closely related to winter rainfall regimes (14), the Fynbos Biome's  
111 current distribution encompasses many of southern Africa's most prominent MSA sites (15).  
112 Edaphic controls mean the Succulent Karoo / Fynbos Biome boundary is unlikely to have  
113 shifted substantially through the late Pleistocene (13, 16), though intensified winter rainfall  
114 may have supported periodic northward range expansion of some fynbos taxa (17).

115

116 Still Bay and Howiesons Poort assemblages occur in the upper strata at VR003 (18). Initial  
117 luminescence ages suggested that these occurrences were anomalously young; we redate  
118 the Howiesons Poort here to between 71.6-55.7 ka (SI Geochronology, Table S6),  
119 consistent with the majority of ages elsewhere, and supporting cultural linkages between  
120 VR003 and sites in the Fynbos during Marine Isotope Stage (MIS) 4. The character and  
121 cultural transmission dynamics of the MSA prior to the Still Bay in this region are, however,  
122 comparatively unknown. We thus focus on results from the deepest excavated layers at  
123 VR003, and their relationship to coeval MSA deposits elsewhere, to explore 1) evidence for  
124 innovative behaviours in this typically arid region, 2) the strength of cultural connectedness  
125 with sites to the south, and 3) relationships between innovation, cultural connectedness and  
126 environmental change.

127

## 128 **Results**

129 Site formation and chronology: VR003 is a north-facing rock shelter site in Neoproterozoic  
130 limestone of the Widouw Formation and located in the gorge wall of the Varsche River  
131 (Figure 1). Five excavation seasons since 2009 have focussed mainly on the upper slope  
132 deposits in front of the rock shelter (Main Area) and the accessible areas of the shelter itself  
133 (Shelter), linked by a narrow trench (Link Trench; Figure S1). The deep sounding in the Main  
134 Area excavation has attained a depth of 1.9 m below surface without encountering bedrock.  
135 No subsurface Later Stone Age (LSA) material is preserved in the Main Area, and the entire  
136 deposit so far excavated can be assigned to the MSA. Still Bay and Howiesons Poort  
137 horizons occur in stratum I-04 near the top of the sequence (Figure S1) (18), underlain by  
138 extensive MSA (strata I-05 to I-09). Having previously described the material through to I-07  
139 (18), we concentrate here on the deepest excavated pre-Still Bay deposits in the Main Area,  
140 comprising two archaeological horizons – I-08 and I-09 – referred to for the purposes of this  
141 paper as the Lower Deposits.

142

143 The sedimentary sequence in the Main Area is composed of slope deposits with fine grained  
144 colluvium and coarser grained debris flow (Figure 2; for more detail see SI Geoarchaeology,

145 Figures S2-5). Deposition of non-archaeological clasts on the slope by debris flow and  
146 colluvial processes is indicated by a lack of sorting or orientation and the fine coating of  
147 some coarse grained materials, though the low incidence of soil aggregates (Figure 2, inset  
148 B) and the lack of rounded rocks from the plateau above the shelter suggests overall limited  
149 transport distances. The regular occurrence of microscopic lithic knapping debris, and the  
150 high incidence and broad size distribution of microscopic bones (Figure 2, inset A, B) are  
151 typical for occupation layers suggesting their initial deposition on the slope. The presence of  
152 gypsum in the deposits indicates an arid environment with high evaporation rates. Fabric  
153 analysis of elongated bone and stone objects (n=353) reveals a predominantly planar  
154 distribution, suggesting that archaeological materials in the Lower Deposits were discarded  
155 on the slope (Figure S6). Object dip does not deviate from the surface slope or the overlying  
156 strata, and orientation does not differ significantly from a uniform distribution (Rayleigh test,  
157  $p = 0.0008$ ). Similarly, the dip of the 12 identified lithic refit sets, mainly comprising  
158 sequential flake removals (n=9), generally follows the deposit slope (Figure S7).

159

160 The Lower Deposits have been dated using single-grain luminescence (pIRIR) on feldspar,  
161 and by U-series dating on ostrich eggshell (OES) fragments (Figure 2). Potassium feldspar  
162 extracted from four sediment samples distributed from near the top of I-08 to the base of I-09  
163 yielded stratigraphically consistent ages ranging from  $80.8 \pm 4.6$  ka ( $1\sigma$ ,  $\pm 9.2$  ka  $2\sigma$ ) to  
164  $89.9 \pm 5.0$  ka ( $1\sigma$ ,  $\pm 10.1$  ka  $2\sigma$ ) (Table S7). U-series dating on three fragments of OES from  
165 lower I-08 and upper I-09 used a novel approach termed  $^{230}\text{Th}/\text{U}$  burial dating (19). As OES  
166 fragments were not typically piece-plotted during excavations we used two samples from  
167 bucket aggregates that also yielded OES artefacts (VR003-9300, VR003-6612) (see below),  
168 and one well-preserved piece-plotted fragment (VR003-9085) (Figures S11-S15). OES  
169 fragment VR003-9300 yields a  $^{230}\text{Th}/\text{U}$  burial age of  $88.3 \pm 3.2$  ka ( $2\sigma$  error). OES fragment  
170 VR003-9085 yields concordant sub-sample ages consistent with rapid U uptake, defining a  
171 mean age of  $90.7 \pm 0.7$  ka in good agreement with the age determined for VR003-9300.  
172 VR003-6612 also yields concordant sub-sample ages, however, their mean age of  $74.5 \pm 1.4$   
173 ka is significantly younger than ages obtained for the two other OES, though it is within error  
174 of the luminescence ages at  $2\sigma$ . This may imply mixing either in the bucket aggregate from  
175 which the sample derived or via disturbance processes such as bioturbation (SI  
176 Geoarchaeology). A probability density function provides a combined age range for the  
177 Lower Deposits of 92-80 ka at  $1\sigma$  (SI Geochronology).

178

179 Archaeology: Phytoliths were analysed from nine samples distributed across stratigraphic  
180 units from I-09 to I-03 (SI Phytolith analysis, Tables S9 & S10, Figure S17). Abundance  
181 varies between samples, with highest concentrations in the Lower Deposits corresponding

182 with high proportions of Poaceae (grasses) relative to Restionaceae and non-graminoid  
183 (woody and shrubby) vegetation compared to overlying strata (Table S10). The ratio of C<sub>4</sub>  
184 (warm growing season) to C<sub>3</sub> (cool growing season) to grass phytoliths is low (<20.8),  
185 consistent with the region's winter rainfall regime. However, higher proportions of warm  
186 growing season C<sub>4</sub> grasses in the Lower Deposits (18.7±3.4) compared with the overlying  
187 strata (6.7±2.3) suggest a decrease in summer rain after ~80 ka. The decline in C<sub>4</sub>  
188 grasses—and grasses in general—is concurrent with a two-fold increase in Restionaceae  
189 and woody phytolith percentages. Combined these results are consistent with the marked  
190 increase in wind strength and upwelling along the west coast that began in MIS 5a (Figure 3)  
191 and the weakening of tropical systems in the southern continental interior under decreasing  
192 orbital eccentricity (20). These factors would have limited the incursion of summer rainfall  
193 systems in the region, resulting in increased rainfall seasonality (21). As Restionaceae is  
194 strongly linked to winter rainfall in the Cape, this may be further evidence for an overall shift  
195 toward a more dominant winter rainfall regime (see SI Phytoliths).

196

197 The preserved vertebrate sample of the Lower Deposits is small (NISP=524; SI  
198 Vertebrates, Table S11, which includes scientific names for the taxa mentioned below) and  
199 dominated by tortoises (n=352), most of which are angulate tortoises that feed on grasses,  
200 annual herbs, and succulents in sandy, coastal habitats and succulent scrublands (22).  
201 Bovids of all sizes are present, although only eland and grysbok/steenbok could be identified  
202 to taxon. Eland can tolerate a wide variety of habitats, including those with limited surface  
203 water, by consuming browse and grass (23). Steenbok are browsers that are adapted to  
204 open areas with some tall grass, bushes or scrub for shelter; grysbok may have extended  
205 this far north, but generally prefer denser cover (23, 24). Cape zebra was a grazer that  
206 would have consumed grasses in open areas (25). Consistent with the phytoliths, the faunal  
207 communities imply a relatively open, arid to semi-arid environment, offering graze and  
208 browse in diverse habitats. These taxa are also found higher in the sequence, along with  
209 springbok, wildebeest/hartebeest, and blue antelope, indicating that grasses persisted in the  
210 region; small sample sizes limit detailed comparisons.

211

212 In addition to mammals and reptiles, the Lower Deposits preserve 26 shellfish fragments.  
213 Limpets account for 77% of these, with granite limpets the dominant taxon, along with two  
214 black mussel fragments (SI Molluscs; Table S12, which includes scientific names). Other  
215 than a few isolated overlying examples, the majority of all marine shells at VR003 cluster in a  
216 band in the Lower Deposits (Figure 2). Given the luminescence and U-series results, relative  
217 sea level during the formation of the Lower Deposits would have been 25-40 m below



218 present (26), though due to off-shore topography this would not have substantially increased  
219 VR003's distance to shore (27). The molluscs were thus likely obtained at least 45-50 km  
220 from site. While limpets and mussels appear as an important food resource in other South  
221 African coastal MSA assemblages (28), they are rarely transported as food packages  
222 beyond 10 km (29), raising questions about whether the VR003 individuals were transported  
223 as food or as empty shells. The shells from the Lower Deposits are fragmented, but no ochre  
224 residues nor anthropogenic modifications were observed on them.

225

226 OES is abundant at VR003, consisting mainly of unworked fragments, most of which appear  
227 to have been heated (SI Ostrich eggshell, Table S9). Surface preservation is typically poor,  
228 and engraved OES is limited to one piece with parallel striations from a Howiesons Poort  
229 context in the Link Trench (Figure S1). From approximately halfway through the Lower  
230 Deposits, however, we recovered 21 flaked OES fragments (Figures 2 & 4; SI Ostrich  
231 eggshell, Table S14). All pieces show flaking in the form of precise percussive initiations that  
232 were truncated when the piece broke. Typically three or more initiations were used to form  
233 an arc consistent with a circular aperture of approximately 23.6 mm ( $\pm 6.1$  mm) that likely  
234 reflect circular perforations initially made on whole OES (Table S14). Such perforations are  
235 consistent in size, if not form, with laterally perforated ostrich eggshell flasks from the  
236 Holocene (30). Pieces with only one or two initiations may reflect the early stages of this  
237 perforation process (SI Ostrich eggshell).

238

239 Main Area excavations have produced 27 772 flaked stone artefacts; 3062 of these were  
240 recovered from the Lower Deposits (SI Lithics) in addition to a small sample of pigments (SI  
241 Pigments). Distinctive artefact markers for the Still Bay and Howiesons Poort are limited to  
242 the upper strata, mainly I-04 (Figure S1). Quartz accounts for 60.0% of all artefacts from I-07  
243 to I-03 (range: 54.2-65.4%), and silcrete for 10.9% (range: 7.2-16.1%) (18). In the Lower  
244 Deposits the proportion of quartz (29.8%) halves while silcrete (41.6%) becomes the  
245 dominant raw material for the only time in the sequence (Table S16). This change is most  
246 evident in the distribution of silcrete cores (Figure 2) which account for 61.5% of cores in the  
247 Lower Deposits.

248

249 These silcrete cores are small (max dimension mean= $43.7 \pm 10.2$  mm), typologically diverse  
250 (Table S22), and exclusively produced small flakes and blades (scar length mean= $17.4 \pm 6.9$   
251 mm). Cores with prepared platforms and no obvious management of the flaking surface are  
252 the most common identifiable type, though opportunistic and minimally worked cores  
253 account for about a quarter of the total. The average number of flake scars on silcrete cores

254 is 3.1, suggesting generally short reduction chains. Blade removals are not numerous but  
255 are concentrated on some cores (Figure 5, Figure S24), and with an average scar length of  
256 15.2 mm could be classified as bladelets. Blade production, however, generally seems to  
257 have been opportunistic (SI Lithics, Tables S17 & S18).

258

259 Heat shatter is unusually common in the Lower Deposits at VR003 (SI Lithics, Table S24,  
260 Figure S22), accounting for 24.2% of all silcrete artefacts (Tables S16); 62.3% of silcrete  
261 cores were made on such heat shattered fragments. Among those cores the mean scar  
262 count is only 2.3. Thus, the majority of silcrete cores in the Lower Deposits result from heat  
263 shattering of unworked pieces that were retrieved and used to produce a limited number of  
264 small flaking products prior to discard (Figure 5). Given the short reduction chains it is less  
265 likely that heat was used to improve the flaking characteristics of the rock than as an  
266 expedient means of creating small, angular core blanks.

267

## 268 **Discussion**

269 Geoarchaeological work combined with refit analysis suggests that strata I-08 and I-09 at  
270 VR003 are intact slope deposits, and two different geochronometric techniques produce  
271 largely concordant ages suggesting accumulation within the interval ~92-80 ka. Phytolith  
272 assemblages in these Lower Deposits indicate higher proportions of summer rain and limited  
273 fynbos taxa, giving way to an increasingly dominant winter rainfall regime across the MIS 5/4  
274 transition. Corresponding with these environmental changes, the archaeological  
275 assemblages in the Lower Deposits are distinctive both from those overlying them, but also  
276 from documented MSA assemblages elsewhere in southern Africa.

277

278 Though it is not possible to confirm that the flaked OES pieces are fragments of flasks, no  
279 comparable flaked OES artefacts have been reported from other MSA assemblages with  
280 large samples of OES (e.g., (9, 31, 32)). Potential OES flasks occur in the Howiesons Poort  
281 at Apollo 11 (33) and Diepkloof (4), but have not been reported from pre-Howiesons Poort  
282 contexts. The flask apertures at Diepkloof are also ground rather than flaked, consistent with  
283 LSA flasks. Thus, if the flaked OES from VR003 were flasks they were produced differently  
284 to other flasks from either MSA or LSA, and if they were not flasks then they reflect some  
285 other novel behaviour. In either case, use of OES as a raw material for artefact manufacture  
286 appears to be quite deep-rooted in the MSA.

287

288 Evidence for exploitation of edible shellfish species (e.g. limpets and mussels) occurs along  
289 the southern Cape coast as early as 164 ka (34); however transport of such species over  
290 >45 km is rare during the MSA and suggests movement of people between coastal and

291 interior southern Namaqualand during MIS 5b. Long-distance transportation of a small  
292 sample of shellfish during the MSA has been noted from Apollo 11 and Pockenbank, which  
293 are ~140 km and ~120 km from the modern coast respectively (35, 36); they are both  
294 located in southern Namibia, suggesting that this behaviour may have been widespread  
295 through arid regions of southern Africa. Elsewhere limited transport of marine shell over ~15  
296 km is found in the MSA at Diepkloof (31) and at Sibudu Cave (37).

297

298 The major component of the Lower Deposits lithic technology is characterised by focussed  
299 procurement of silcrete, use of heat shatter to create core blanks, and short core-reduction  
300 chains producing small flakes and blades. Comparable technological systems have not been  
301 described in the MSA elsewhere (for reviews see 1, 38, 39, and SI Lithics), including at the  
302 six Fynbos Biome sites that lie within 100 km of VR003 (Figure 1; SI Lithics, Table S24).  
303 Assemblages at those nearby sites are generally dominated by locally available quartzite or  
304 hornfels with systematic use of silcrete only after 75 ka (40-45). The exception is in MSA-  
305 Lynn at Diepkloof, which exhibits an increase in heat-treated silcrete and dedicated bladelet  
306 production leading in to the Still Bay (3). Heat shatter is rare in that assemblage, however,  
307 and none of the documented reduction processes feature the systematic use of core blanks  
308 made from heat shatter. The presence of bifacial and unifacial points in MSA-Lynn also  
309 suggests continuity with the overlying Still Bay, something that did not occur at VR003.

310

311 Results from VR003 suggest that the southern Succulent Karoo fostered a different set of  
312 adaptations to those characteristic of more humid areas to the south, including the  
313 manufacture of OES artefacts (possibly flasks), long distance transportation of marine shell,  
314 and the primary use of heat treatment to create core blanks for production of small flakes  
315 and blades. This package corresponds to a specific set of environmental conditions, and  
316 terminates around 80 ka with an apparent strengthening of regional winter rainfall systems.  
317 Though it lacks *fossile directeur* implements, the archaeological signature of the Lower  
318 Deposits is as distinctive in the VR003 MSA sequence as the Howiesons Poort or Still Bay.  
319 The difference between these phases is not in their innovativeness *per se*, but in their  
320 differing geographic extent. While the Howiesons Poort and Still Bay extend across much of  
321 southern Africa, the Lower Deposit package at VR003 appears to be a localised and  
322 environmentally-contingent adaptation.

323

324 These observations carry four significant implications for models of human behavioural  
325 evolution. First, they support arguments that the productive environments of the southern  
326 Cape coastal plains were not the sole locus of human innovation in southern Africa (9).  
327 Indeed, conversely, marginal environments likely required novel or at least distinct

328 technological solutions to enable persistent survivorship (46). Second, and following from the  
329 first, research emphasis on biogeographically limited regions of southern Africa has probably  
330 acted to exaggerate the extent of cultural similarities through the MSA (SI Lithics).

331

332 Third, cultural connectedness in southern Africa, if measurable by similarity in stone tool  
333 assemblages, was variable through the late Pleistocene. While VR003 is culturally in phase  
334 with sites across the Fynbos Biome at least after 71 ka, it was not between 92-80 ka. Fourth,  
335 arguments that widespread cultural interaction was a primary driver of innovation in southern  
336 Africa (e.g., (8)) are not supported. It is possible that strong cultural connections pertained  
337 across the arid and interior regions of the sub-continent during MIS 5, however available  
338 data are insufficient to substantiate this proposition. In any case, Still Bay and Howiesons  
339 Poort assemblages occur across these regions as well as more humid parts of southern  
340 Africa (2). More interesting is the apparent loss of innovations (production of OES artefacts,  
341 systematic use of heat shatter to create core blanks) at VR003 after 80 ka, preceding the  
342 spread of the Still Bay. In some cases at least, innovation was responsive to environmental  
343 conditions and neither driven by interaction nor inherently cumulative (47).

344

345 Though the suite of adaptations identified at VR003 is currently unique, the pattern of  
346 transient innovations is consistent with the broader evidence from the African MSA. This can  
347 be read in one of two ways. It could imply a pre-modern condition in which the capacity for  
348 innovation was latent but cultural behaviour itself was yet to become a major selective force  
349 (48). Subsequent developments may reflect stabilisation of high-fidelity information  
350 transmission in the human niche (49, 50), potentially supported by transformations in  
351 language efficacy (51). Alternatively, it may partly reflect the out-sized role played by durable  
352 materials in models of human behavioural evolution. Flask fragments are rare even in large  
353 LSA OES assemblages, and their identifying characteristics are—in contrast to the possible  
354 VR003 examples—quite subtle; ground surfaces representing fragments of apertures <15  
355 mm (30). In the small, fragmented OES assemblages from pre-Still Bay MSA contexts (9)  
356 and/or where surface preservation is poor (as at VR003) such artefacts would easily be  
357 masked. Thus, even if the flaked OES from the Lower Deposits are the remains of flasks,  
358 their disappearance does not necessarily reflect the loss of that capability but potentially its  
359 shift into a form that is less robust and visually obvious. Similarly, while the long-distance  
360 transportation of durable items is evident in the MSA by 200 ka (52); evidence for long-  
361 distance transport of perishable items, as with the shellfish at VR003, first appears much  
362 later for reasons that we consider more probably taphonomic than behavioural. Such  
363 preservation problems currently confound all models of human behavioural evolution (49, 53,  
364 54). Ultimately the archaeology of human behavioural evolution reflects the intersection of

365 four factors: capability to innovate (55), motivation to innovate (46), stabilisation of  
366 innovations (56, 57), and preservation of innovations (58). The record from VR003 speaks to  
367 the first two, highlighting the importance of obtaining data from diverse ecological regions.  
368 Disentangling the last two remains a key challenge going forward.

369

## 370 **Methods**

371 **Excavation.** Excavations at VR003 proceeded within stratigraphic units. Only selected items  
372 were individually piece plotted during excavations in 2009/2011, with most items recovered  
373 in 11 L buckets aggregates. In 2014, 2015, and 2016, during which seasons the Lower  
374 Deposits were excavated, all artefacts >20 mm and bones >25 mm were piece plotted.  
375 Elongate items were plotted with 2 points where possible to allow for fabric analysis.  
376 Modified OES was plotted regardless of size in these seasons. All bucket aggregates were  
377 sieved on site through nested 3 mm and 1.5 mm mesh sieves.

378

379 **Geoarchaeology.** Geoarchaeological analysis included grain size, loss on ignition, magnetic  
380 susceptibility, and micromorphology as well as fabric and refit analyses. Detailed results are  
381 presented in SI Geoarchaeology. Thin section analysis was conducted with a petrographic  
382 microscopic with magnification of up to 200x using oblique incidental (OIL), plane (PPL) and  
383 cross polarized (XPL) light. Micromorphological description follows terminology in (59, 60)  
384 and a detailed analysis is presented in SI Micromorphology. Fabric analysis was undertaken  
385 using the methods and code provided in (61).

386

387 **Single-grain luminescence dating.** Luminescence samples were obtained by hammering  
388 metal tubes into cleaned section faces. Samples were prepared under subdued red light at  
389 the Royal Holloway Luminescence Laboratory, yielding sand-sized quartz and potassium  
390 feldspar (K-feldspar) separates. All luminescence measurements were carried out using a  
391 Risø TL/OSL-DA-15 automated dating system, fitted with a dual-laser single-grain  
392 luminescence attachment. Quartz was measured using a standard single-aliquot  
393 regenerative-dose method whereas a post infrared, infrared stimulated luminescence  
394 procedure, intended to minimise the effect of “fading” (62) was used for K-feldspar. Individual  
395 grains were stimulated using either a focused 10 mW Nd:YVO<sub>4</sub> solid-state diode-pumped  
396 green (532 nm) laser for quartz or a 140 mW TTL modulated infra-red (IR, 830 nm) laser  
397 with a Schott RG 780 longpass filter mounted in the beamline for K-feldspar. Simultaneous  
398 illumination of all grains on a disc was carried out using either blue (470 nm) or IR (870 nm)  
399 light emitting diodes (LEDs). Luminescence was detected using an Electron Tubes Ltd  
400 9235QB15 photomultiplier tube shielded by Schott BG3 and BG39 filters. Irradiation was  
401 carried out using a 1.48 GBq <sup>90</sup>Sr/<sup>90</sup>Y beta source calibrated relative to the National Physical

402 Laboratory, Teddington  $^{60}\text{Co}$   $\gamma$ -source (63). Data analysis was carried out using functions  
403 within the *numOSL* and *Luminescence R* packages. K-feldspar ages were corrected for a  
404 measured fading rate (g-value normalised to 2 days) of  $1.9\pm 0.1$  %/decade (64).

405

406 **U-series dating of ostrich eggshell.** OES were analyzed in the Berkeley Geochronology  
407 Center's U-Daughter Lab. OES dating samples were screened using profiles of [U] and  $^{232}\text{Th}/\text{U}$   
408 obtained via laser ablation using a Photon Machines Analyte II excimer laser attached to a  
409 Thermo-Fisher NEPTUNE *Plus* inductively coupled mass spectrometer (ICP-MS). Selectively  
410 abraded subsamples of OES calcite from known positions in each OES fragment were  
411 analyzed in solution mode using the Thermo-Fisher NEPTUNE *Plus* ICP-MS. Laser ablation,  
412 solution analyses, data reduction, and calculation of  $^{230}\text{Th}/\text{U}$  burial ages followed techniques  
413 similar to those described in (19). Activity ratios and ages were calculated using the half-lives  
414 from (65-67). Ages and uncertainties were calculated using (68).

415

416 **Phytolith analysis.** Nine sediment samples were processed for phytoliths, covering strata  
417 from I-09 to I-03. Phytoliths were extracted from approximately 5 g of bulk fine fraction  
418 sediment. Samples were sieved through 125  $\mu\text{m}$  mesh; 2 g of each  $<125$   $\mu\text{m}$  subsample was  
419 treated for carbonate digestion using 10% HCl, followed by clay deflocculation aided by  
420  $\text{NaPO}_3$ . 10% KOH solution was used for digestion of organic matter, before another round of  
421 deflocculation. Samples were neutralized, centrifuged and decanted between all steps.  
422 Phytoliths were extracted by heavy liquid flotation, using a solution of sodium polytungstate  
423 ( $2.3 \text{ g/cm}^3$ ). Assemblages were pipetted onto coverslips, dried, and mounted to microscope  
424 slides using Entellan medium for identification and counting. Phytolith abundance was counted  
425 up to 300, with concentration per gram of sediment later estimated using the proportion of  
426 sample analysed and initial 2 g weight.

427

428 **Faunal analysis.** All faunal (vertebrate, mollusc, and eggshell) remains were examined,  
429 including those that were individually plotted ( $>25$  mm) as well as those recovered from the 3  
430 mm screens. The screened materials were rinsed with water before sorting. Specimens were  
431 identified using comparative material housed in the Department of Archaeology at the  
432 University of Cape Town and the Department of Anthropology and the Museum of Wildlife  
433 and Fish Biology at the University of California, Davis, and published manuals. Specimens of  
434 any size that could be identified to element and taxon were recorded in the MNISQL  
435 database program written by Richard G. Klein (Stanford University). All identified specimens  
436 were examined for surface modifications and preservation. Molluscs and eggshells were  
437 counted, weighed, and examined for surface modifications. Discoloration consistent with  
438 heating was also noted (69).

439

440 **Lithic analysis.** Basic methods of stone artefacts classification and analysis are described  
441 in (18). Additional data were acquired as follows. Core scars counts applied a scaled  
442 minimum scar size cut-off at 20% of core maximum dimension, and also a fixed value (15  
443 mm) presented separately in SI. Heat treatment was identified visually using methods  
444 described in (70). Silcrete is common and physically diverse around VR003 (71),  
445 complicating development of reference collections. For this reason we rely principally on  
446 visually-obvious heat-induced non-conchoidal fractures (HINC) (72) to identify the presence  
447 of thermal effects.

448

#### 449 **Data availability statement**

450 All data used in the present study are available from the corresponding author on reasonable  
451 request.

452

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467

#### 468 **Author contributions**

469 TES & AM directed excavations at VR003; dating by SJA (luminescence) and EMN & WDS  
470 (uranium-series); geoarchaeology by MCS (micromorphology), IM & RR (sedimentology),  
471 AFB (fabric analysis), and MAL (lithic refit); KB prepared and analysed the phytolith samples  
472 with environmental context provided by BMC; faunal analysis by TES & SL; TES & PJM  
473 analysed the ostrich eggshell, and CFK analysed the Iziko comparative sample; NM  
474 analysed the pigments; AM and CAO'D analysed the stone artefacts; AM, TES, SJA, EMN,  
475 WDS, MCS, AFB, KB, BMC, SL, NM, PJM, IM & JO wrote the manuscript.

476

477 **Competing Interests Statement**

478 The authors have no competing interests as defined by Nature Portfolio, or other interests  
479 that might be perceived to influence the results and/or discussion reported in this paper.

480

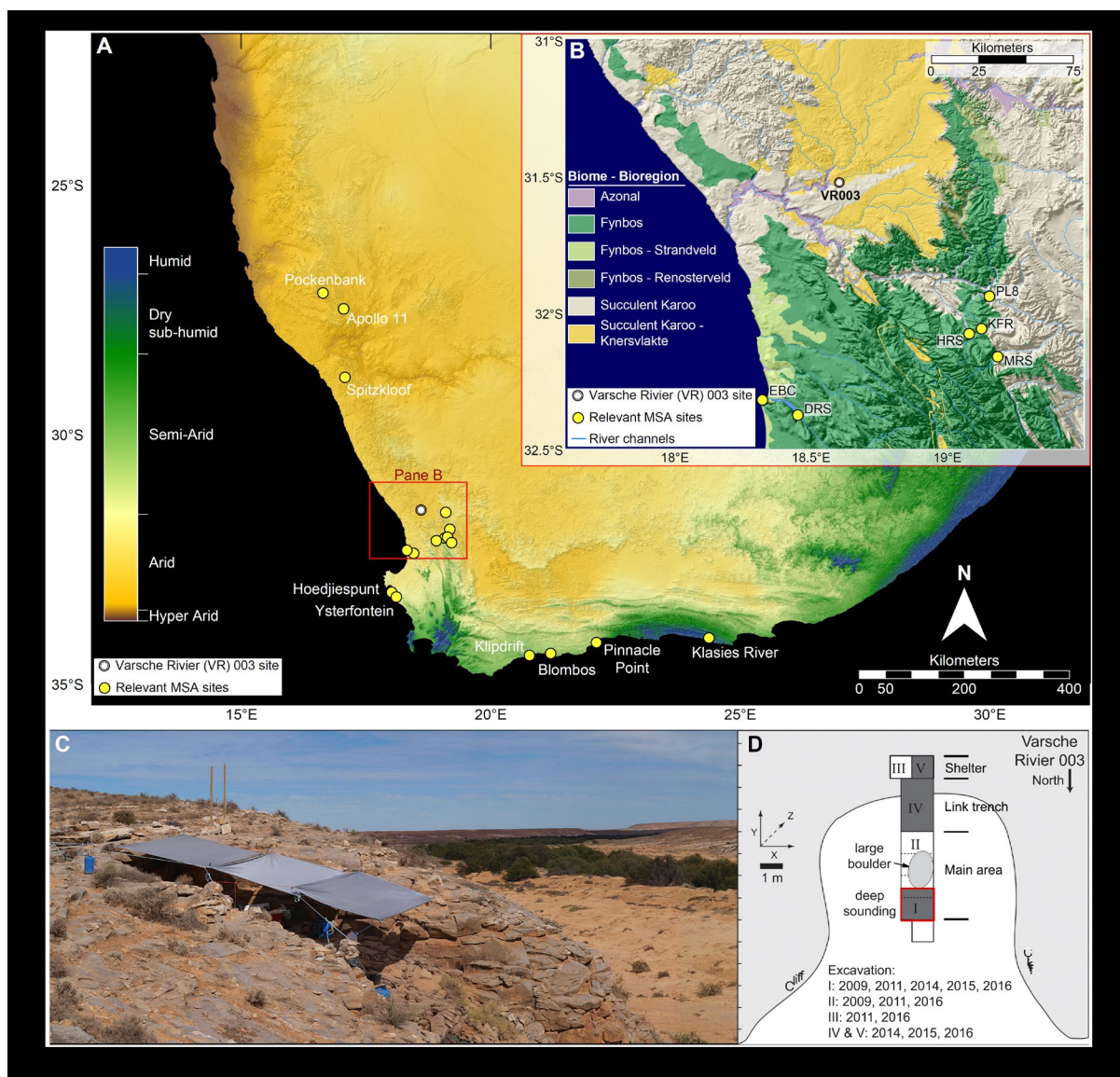
481 **Data Availability Statement**

482 The spatial, lithic, faunal and pigment data used in this paper are included in a  
483 supplementary file. Phytolith data are provided in tables in the Supplementary Information.

484 The VR003 collections are curated at University of Cape Town and Iziko Museums Cape  
485 Town, and can be accessed by arrangement with TES and AM.

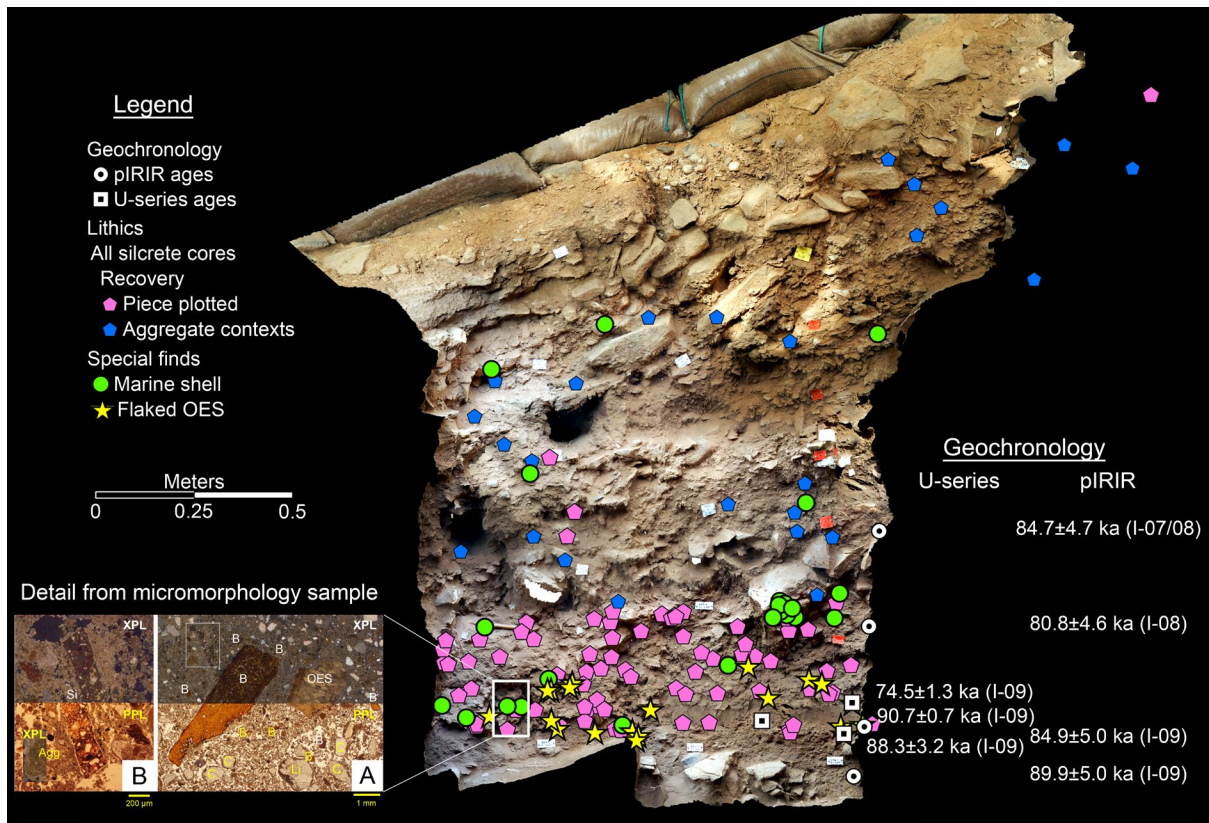
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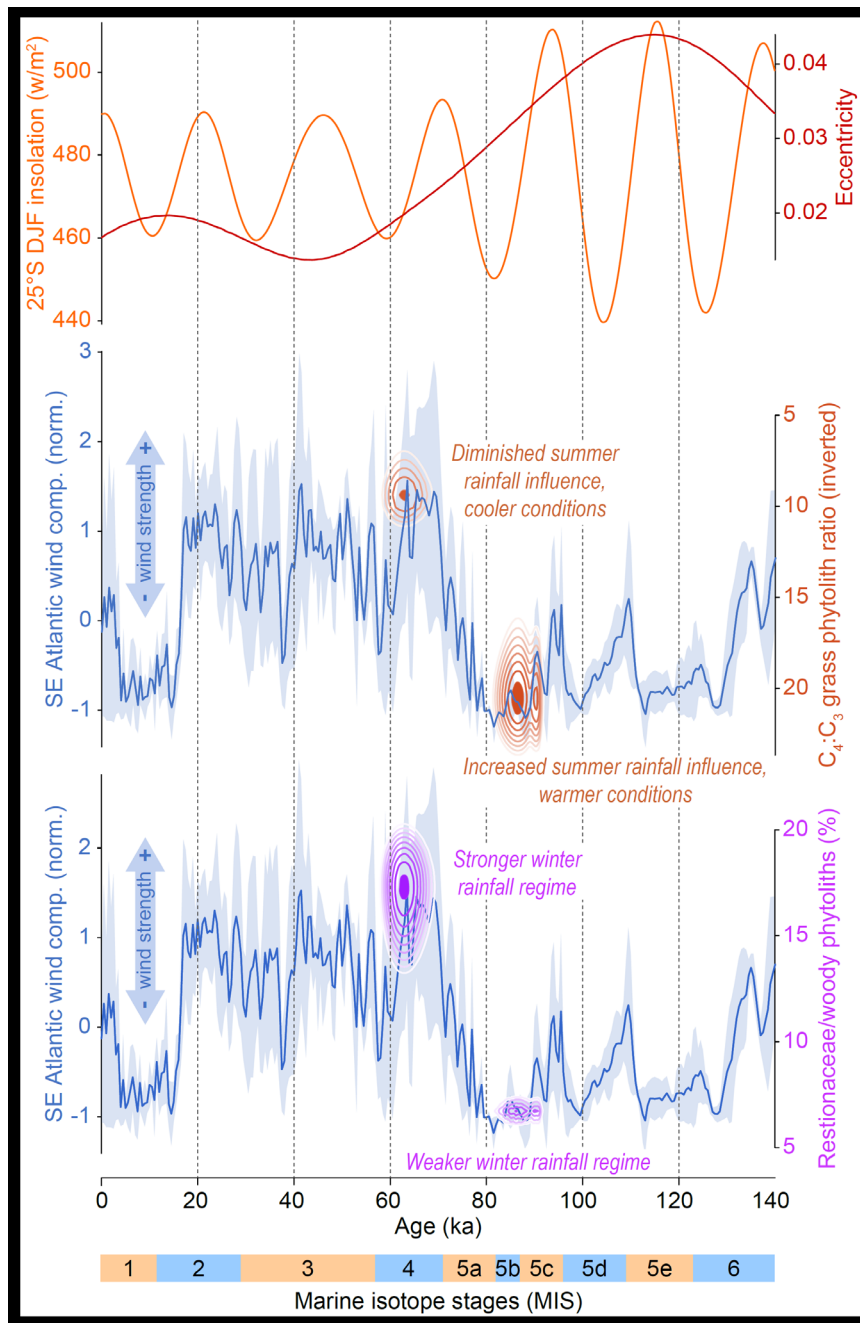
487  
 488 **Figure 1. (A)** Aridity map of southern Africa, with the Varsche Rivier 003 (VR003; white dot)  
 489 and relevant MSA sites referred to in the text (yellow dots) indicated. Aridity index data from  
 490 (73) with definitions according to (74). Red box shows location of inset map (B). **(B)** VR003  
 491 in relation to modern biome-bioregion boundaries from (75) and Fynbos Biome sites  
 492 immediately south: DRS=Diepkloof, EBC=Elands Bay Cave, HRS=Hollow Rock Shelter,  
 493 KFR=Klipfonteinrand 1, MRS=Mertenhof, PL8=Putslaagte 8. **(C)** Site photo of VR003 and  
 494 the Varsche Rivier 003 valley, looking west. **(D)** Excavation plan at conclusion of most recent  
 495 season in 2016. The original deep sounding is highlighted in red.

496



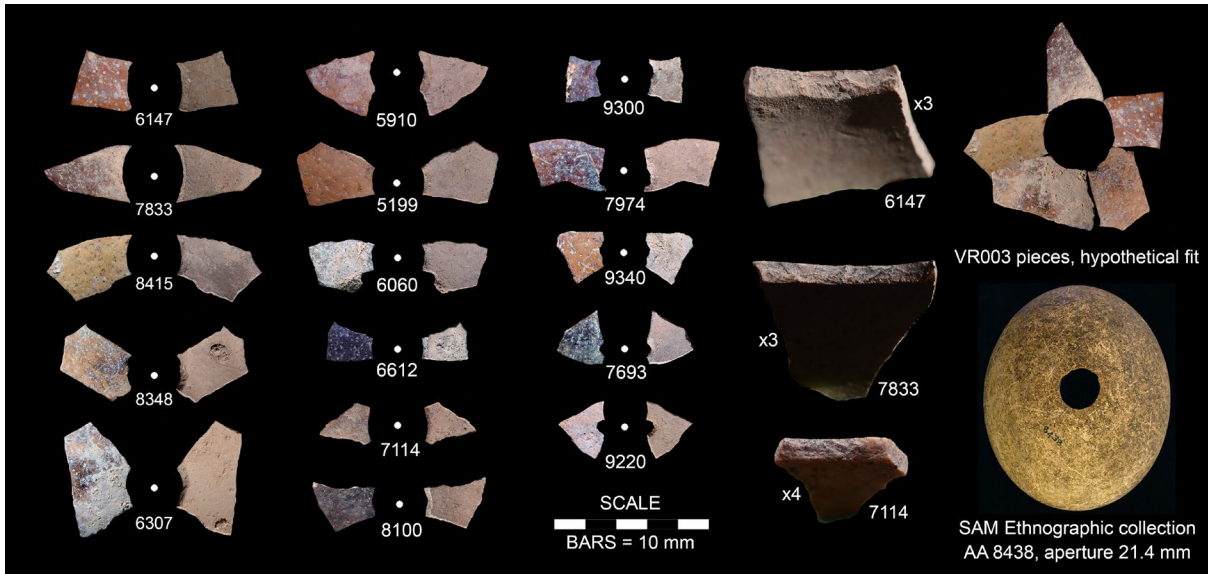
497

498 **Figure 2.** East section of deep sounding with key artefact type and location of  
 499 geochronology samples. Per convention, luminescence ages are presented here at 1 sigma  
 500 uncertainty, U-Th ages at 2 sigma. For artefacts, aggregate contexts refers to silcrete cores  
 501 recovered during the initial seasons (2009, 2011) during which individual artefacts were  
 502 typically not plotted. These cores were recovered from bucket aggregates and include up to  
 503 two cores in some cases. Inset bottom left: Microphotographs showing the typical  
 504 components and structure of I-08. **(A).** Bone (B) fragments range in size from gravel to sand.  
 505 Another typical anthropogenic component at the site is ostrich eggshell (OES). Note also the  
 506 coarse crystalline limestone (Li), and calcite crystals (C) and fine coating of these coarse  
 507 grains. **(B)** Microscopic silcrete (Si) knapping debris and rounded soil aggregates (Agg) from  
 508 the plateau above the site in a calcareous matrix.  
 509



510

511 **Figure 3.** Comparison of primary factors determining long-term regional climate dynamics  
 512 with VR003 phytolith data for 1)  $C_4:C_3$  grass ratios and 2) the percentage of Restionaceae  
 513 and woody taxa, a classification reflecting the abundance of fynbos vegetation (Cordova et  
 514 al., 2013; Esteban et al., 2017). Data for orbital parameters is from Laskar et al. (2004) and  
 515 the SE Atlantic wind strength composite is as calculated by Chase et al. (2019) using the  
 516 data of Farmer et al. (2005), Little et al. (1997), Pichevin et al. (2005) and Stuu et al. (2002).  
 517 The phytolith data are depicted as uncertainty spaces defined by the multiplication of  
 518 probability density functions derived from 1) stratigraphic unit ages and errors for the Lower  
 519 Deposits and Howiesons Poort layers and 2) aggregated phytolith data and the associated  
 520 standard deviation of sample values from these units (see SI for more detail).



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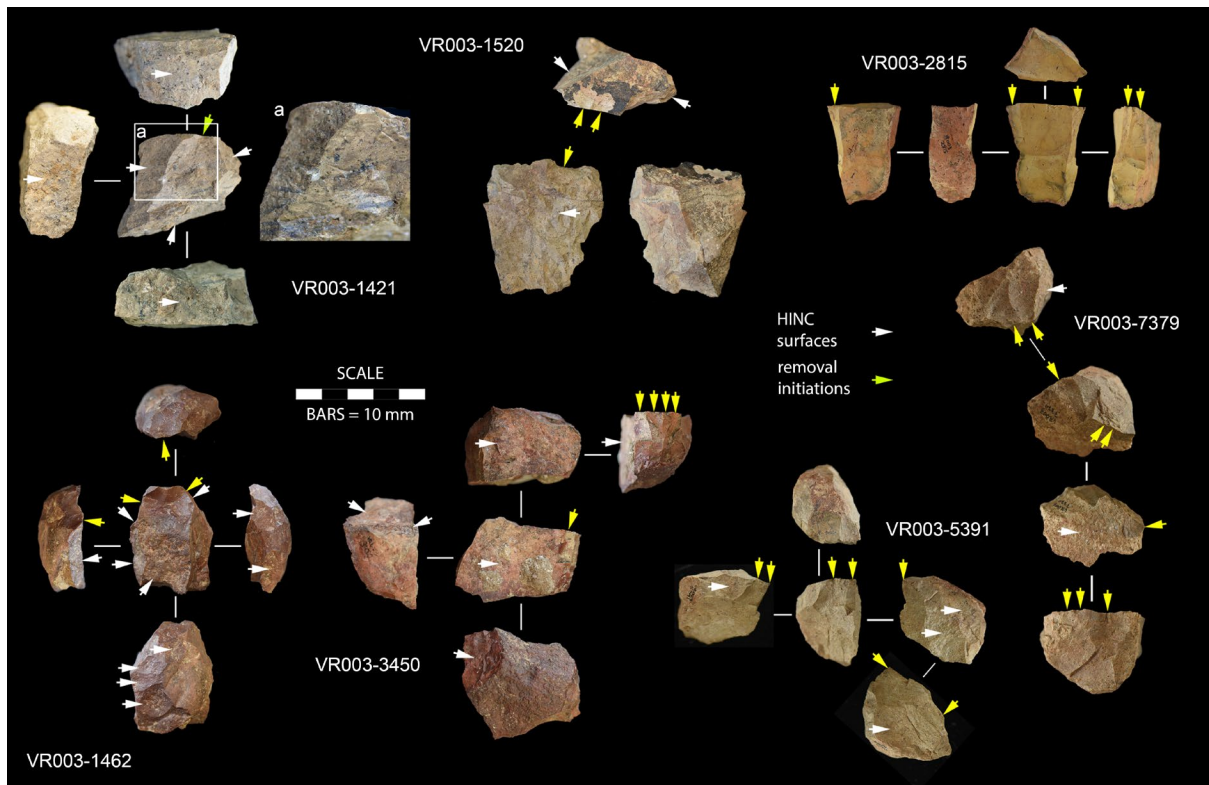
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531

**Figure 4.** Flaked OES fragments from the Lower Deposits. Artefacts 9220 and 7693 have simple perforations like those made by hyenas (76), but 9340, 7974, and 9300 show apparent elaborations of similar perforations through more extensive flaking. The artefacts in the central column may thus represent production stages leading to more finely ‘finished’ pieces in the left two columns. The ‘hypothetical fit’ in the top right is an indicative photo montage of VR003 samples 6147, 7833, 8415, 8348, and 6307. These pieces do not actually refit. Artefact AA8438 (bottom right) is from the Ethnographic Collection at Iziko Museums, and was recovered from Ysterfontein Village by G.E. Loedalf in June 1968 and donated to the museum in December 1968.



532

533 **Figure 5.** A selection of silcrete cores from the Lower Deposits (see also Figure S24). White  
 534 arrows indicate location of HINC surfaces; yellow arrows indicate location of flaking  
 535 initiations. All artefacts shown except 2815 were made on heat shatter. 1421: Minimal core  
 536 on heat shatter. Inset (a) shows the contact between the smooth post-heat removal and the  
 537 scalar features on the older shatter surface. 1462: Simple prepared platform core on heat  
 538 shatter. 1520: Minimal core on heat shatter. 3450: Single platform core with small laminar  
 539 removals on heat shatter. 5391: Prepared core on heat shatter with one laminar removal.  
 540 7379: Multiplatform core on heat shatter. 2815: Unheated single platform core with small  
 541 laminar removals.

542

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