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1 **Single grain TT-OSL ages for the Earlier Stone Age site of Bestwood 1 (Northern Cape**
2 **Province, South Africa)**

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15

16

17 **Abstract**

18 The transition from the Earlier Stone Age (ESA) to the Middle Stone Age (MSA) in
19 the interior of southern Africa is associated with the Fauresmith Industry. Major cultural
20 developments found in the Fauresmith include regular use of ochre and other coloured
21 minerals, prepared core technology including blade and point production, and the use of
22 hafted spears. Chronological control for the Fauresmith is weak so that critical questions
23 regarding the relationship of this industry to the evolution of modern humans remain
24 unresolved. Here we present ages for the Bestwood 1 site, an open-air locality in the Northern
25 Cape Province (South Africa) where an extensive Fauresmith occupation is found underlying
26 sand deposits.

27 Optically stimulated luminescence (OSL) was first applied to samples from the sands
28 overlying the Bestwood 1 occupation horizon, and from the occupation horizon itself, in order
29 to establish the chronology of the site. However, sediment mixing resulting from bioturbation
30 processes has been observed, causing post-depositional bleaching of the majority of the
31 grains, thus limiting the use of OSL. In addition, given the identification of the lithic
32 assemblage to the Fauresmith, it seems likely that the sands were beyond the dating range of
33 conventional OSL. Due to its hard-to-bleach properties, the thermally transferred-optimally

34 stimulated luminescence (TT-OSL) signal was deemed suitable for detecting the least-
35 bleached grains.

36 Single grain TT-OSL analyses combined with the finite mixture model (FMM) were
37 conducted in order to isolate the oldest grains that could be contemporaneous with the time of
38 deposition of the sediment associated with the ESA assemblage. High scattering of the
39 equivalent doses is consistent with bioturbation processes that mixed sediment; the
40 distribution of the equivalent dose values suggests that younger grains were incorporated into
41 the ESA layers, thus supporting the use of the oldest component determined using the FMM
42 to calculate the TT-OSL ages. This approach allowed us to establish the time for the
43 Fauresmith occupation at 366 ± 32 ka, and the age of the overlying sand deposits, spanning
44 from 350 ± 22 ka to 226 ± 13 ka.

45 **Key-words:** Earlier Stone Age; Fauresmith; Chronology; Luminescence; TT-OSL;
46 Bioturbation; Finite Mixture Model

47

48 1. Introduction

49

50 Luminescence dating has played a critical role in the archaeology of early modern
51 humans in Africa and the Middle East, and Neanderthals in Europe and the Middle East.
52 Optically stimulated luminescence (OSL) and thermoluminescence (TL) provide widely
53 applicable means of chronological control for periods as far back as 300 ka. For earlier sites,
54 there is a very real challenge in correlating the timing of the archaeological record with the
55 stages of hominin evolution leading up to the emergence of modern humans. In southern
56 Africa, the immediate challenge is to establish the chronology of the Fauresmith industry,
57 which represents the local transition between the Earlier Stone Age and the Middle Stone Age
58 (Chazan 2015a, see Herries 2011; see Underhill 2011 for critical discussion of the
59 Fauresmith). At Kathu Pan 1, the Fauresmith Stratum 4a is dated by OSL of quartz to $464 \pm$
60 47 ka and by U-series/ESR of tooth enamel to $542 +140/-107$ ka (Porat et al. 2010). The
61 Kathu Pan 1 archaeological assemblage is notable for the presence of ochre and specularite,
62 the use of a prepared core method of flake, point and blade production, and evidence for the
63 use of points as hafted spears (Wilkins et al., 2012; Watts et al., 2016). At Canteen Kopje,
64 Finite Mixture Model (FMM) OSL ages obtained for the base of the section, overlying the

65 Fauresmith layer, ranged from 164 ± 9 ka (CK7-6) to 167 ± 10 ka (CK7-5) (Chazan et al.
66 2013).

67 The site of Bestwood 1 (Northern Cape Province, South Africa, Fig. 1) is an extensive
68 locality situated in a north-facing valley between two hills on the western flank of the
69 Kuruman Hills (Chazan et al. 2012, Papadimitrios et al. 2019). Lithic material was first
70 identified at the edges of a sand quarry, leading to excavations at areas designated Block 1 (29
71 m²) and Block 2 (16 m²) at the southern end of the quarry. In both Block 1 and 2 a continuous
72 distribution of artefacts in fresh (unabraded) condition were found across the entire
73 excavation area lying on the top of a gravel deposit (with a thickness >20 m.) and below clean
74 sands. Similar sections were found in test pits excavated 250 and 800 m to the north. There is
75 a typological consistency across these excavation areas, with a combination of bifaces and
76 prepared core technology. Bestwood 1 thus represents an extensive hominin occupation
77 across a landscape which, based on Ground Penetrating Radar survey, is reconstructed as the
78 banks of a small stream (Papadimitrios et al., 2019).

79 For Middle Pleistocene deposits, the development of extended-range luminescence
80 methods, such as thermally transferred optically stimulated luminescence (TT-OSL), allowed
81 the dating of quartz beyond the limits of conventional OSL. TT-OSL is based on the transfer
82 of charge from deeper traps to the main OSL traps, induced after depleting the OSL signal and
83 preheating the sample to high temperature (i.e., 260°C). The TT-OSL signal was observed in
84 early luminescence dating studies (e.g., Aitken and Smith, 1988; Rhodes, 1988) but its use for
85 dating was proposed in 2006 (Wang et al., 2006a; Wang et al., 2006b). Two components have
86 been identified in the TT-OSL signal, named the Recuperated OSL (ReOSL) and the Basic
87 Transferred OSL (BT-OSL) (Aitken, 1998). The ReOSL is the signal used to construct the
88 dose response curve (DRC) and to obtain the equivalent dose (D_e) in TT-OSL dating studies;
89 the BT-OSL is a residual signal that remains after depletion of the ReOSL signal. Single
90 aliquot regeneration (SAR) protocols were thus proposed to isolate the BT-OSL (e.g., Wang
91 et al., 2007; Tsukamoto et al., 2008). However, a study led by Kim et al. (2009) suggests that
92 the BT-OSL signal contribution to the TT-OSL signal might be negligible and that its
93 subtraction does not impact significantly the DRC nor the D_e . A simplified protocol, which
94 does not involve a separate measurement of the BT-OSL signal but includes a depletion of
95 this component using heat treatment at 300°C at the end of the SAR cycle, was proposed by
96 Porat et al. (2009), and a modified protocol (after Adamiec et al., 2010) was applied in this
97 study.

98 The reliability of TT-OSL dating has been tested in a number of studies by comparing
99 results with independent or semi-independent dating methods, especially at the Atapuerca
100 sites in Spain (e.g., Arnold et al., 2015; Demuro et al., 2019). The sensitivity of the TT-OSL
101 signal to light exposure is much lower than the conventional OSL signal, resulting in slow
102 optical resetting rate (Porat et al., 2009; Jacobs et al., 2011). Indeed, only well-bleached
103 samples can be considered for TT-OSL, since bleaching experiments have shown that
104 exposure to daylight prior to deposition must be in the order of several weeks or months to
105 reset the signal and avoid age overestimation (Fig. 4 in Jacobs et al., 2011).

106 However, based on the assumption that the TT-OSL signal bleaches much slower than
107 the OSL signal, this property can be used in environments where bioturbation is predominant
108 and has been constant over time, limiting the use of conventional OSL. This is the case of the
109 open-air site of Bestwood 1. Preliminary OSL measurements revealed a high scatter in the D_e
110 distribution, whether using single or multi-grain analyses (SOM Tab. S1). Moreover, the
111 obtained ages were far too young for the industries found at the site. It is assumed that intense
112 bioturbation processes are responsible for this scatter. Indeed, ants and termites can cause
113 vertical and lateral displacement of grains, and favour the incorporation of bleached grains
114 originating from the top of the sequence, whose signal has been reset (e.g., Bateman et al.,
115 2007; Rink et al., 2013).

116 The use of single grain (SG) measurements can provide information on the dose
117 distribution, especially in environments where differential bleaching and sediment mixing is
118 expected. As the TT-OSL signal is bleached much slower than the OSL signal by several
119 orders of magnitude, we hypothesized that for some grains the signal might not have been
120 bleached during the intense bioturbation; these grains could be isolated by SG TT-OSL
121 measurements. This innovative application of SG TT-OSL, combined with the use of the
122 Finite Mixture Model (FMM, Galbraith and Green, 1990), allows to isolate the oldest grain
123 component, avoiding the bleached grains in the samples. This approach is fundamental in
124 establishing the chronology of Bestwood 1.

125

126 **2. Material and method**

127 Samples for luminescence dating were collected from the main section in the sand unit
128 (samples BSW-5 and 6), at the boundary between the sand and gravel units (BSW-7), and in

129 the gravel unit (BSW-8) in the excavated square, by hammering light-proof PVC pipes into
130 the section (Fig. 2).

131 **2.1. Sample preparation**

132 Sample preparation and all measurements were conducted at the Geological Survey of
133 Israel according to the procedure detailed in Faershtein et al. (2016). Wet sieving was
134 performed to extract the most abundant grain size, 125-150 μm . Quartz grains were purified
135 with 8% HCl to dissolve carbonates, followed by magnetic separation to remove heavy
136 minerals and most feldspars. The remaining feldspars were dissolved and the quartz etched to
137 eliminate the alpha dose component using 40% HF for 40 minutes, followed by overnight
138 soaking in 16% HCl to dissolve any fluorides which may have precipitated.

139 **2.2. Equivalent dose determination**

140 OSL analyses were first conducted on 2 mm aliquots using a modified single aliquot
141 regenerative (SAR) protocol (Murray and Wintle, 2000) (SOM Tab. S2). Dose recovery tests
142 over a range of preheats showed that a recovery dose ratio of 0.99 ± 0.05 can be obtained
143 using a preheat of 10 s at 260°C, a test dose of ~ 9.3 Gy with a preheat of 5 s at 200 °C. All
144 samples show good recycling ratios within 10% of 1.0 and negligible IR signals. However,
145 high overdispersion (OD) values and relatively young OSL ages (SOM Tab. S1) are
146 consistent with bioturbated sands. SG measurements of one sample further highlighted the
147 severe mixed and bleached character of the sample, giving an age of 60 ± 50 ka (SOM Tab.
148 S1). To isolate the oldest dose component, SG TT-OSL measurements were undertaken
149 following the SAR protocol of Porat et al. (2009), including a thermal bleach (310°C for 100
150 s) at the end of each cycle to remove the contribution from the BT-OSL component (Tab. 1).
151 Single-grain disks with 300 μm holes were loaded with 125-150 μm quartz grains. Using a
152 binocular microscope, it has been observed that up to three or four grains filled each hole,
153 thus increasing the yield compared to ideal SG measurements (Arnold et al., 2014; Arnold et
154 al., 2015). Indeed, the yield of grains accepted according to our selection criteria is high,
155 ranging from 12% to 20% (Tab. 2).

156 Equivalent doses were determined on a TL/OSL DA-20 Risø reader (Bøtter-Jensen
157 and Murray, 1999). A green laser was used for stimulation and the signal was detected with a
158 7.5-mm U-340 filter. Aliquots were irradiated using the inbuilt $^{90}\text{Sr}/^{90}\text{Y}$ beta-source with dose

159 rate to the SG disc of $0.049 \text{ Gy}\cdot\text{s}^{-1}$. The TT-OSL signal was normalised using the subsequent
160 OSL signal measured after delivering a test dose of $\sim 25 \text{ Gy}$ (Porat et al., 2009).

161 The data were processed using Analyst v.4.57 (Duller, 2007). The signal was
162 integrated using the first 0.125 s and background was subtracted from the last 0.25 s. The
163 following criteria were applied for D_e selection: a recycling ratio limit of 1 ± 0.25 ;
164 recuperation $< 20\%$ of the natural signal; maximum test dose error of 30% ; and a test dose
165 signal > 3 sigma above background. Equivalent doses were obtained using an exponential
166 fitting function. The statistical treatment of the D_e values was done using the Finite Mixture
167 Model (FMM, Galbraith and Green, 1990) using a sigma-b value of 0.15 based on single
168 grain measurements of the well-bleached Risø calibration quartz (OD = 11-22%), a good
169 analogue for the measured sands. However, instead of using the most frequent grain
170 population (e.g., Chazan et al., 2013), ages were calculated from the highest D_e population,
171 with the condition that this component represents at least 10% of the overall grains. This
172 threshold was selected so that the oldest component is not biased by very few outlying grains,
173 (e.g. Rodnight et al., 2005) and it is considered reasonable taking into account the number of
174 viable grains (> 100 grains).

175 **2.3. Dose rate determination**

176 Water content was estimated at $5 \pm 3\%$, due to the sandy and loose nature of the
177 sediment. Alpha, beta and gamma dose rates were derived from the radioactive content
178 measured by inductively coupled plasma-mass spectrometry (ICP-MS) for uranium and
179 thorium and inductively coupled plasma optical emission spectrometry (ICP-OES) for
180 potassium, using the conversion factors of Guérin et al. (2011). Uncertainties of 3% (K), 5%
181 (U) and 10% (Th) were derived from comparison to international standards and repeated
182 measurements. Cosmic dose rates were estimated from current burial depths according to the
183 equations of Prescott and Hutton (1988).

184

185 **3. Results**

186 The TT-OSL signals are mostly bright, and the DRC's are sub-linear (Fig. 3). The
187 chosen data processing results in ages in stratigraphic order. Dose rates, equivalent doses and
188 SG TT-OSL ages are presented in Tab. 2 and SOM Tab. S1. The alpha, beta and gamma dose
189 rates derived from U, Th and K contents are homogeneous within the sand unit, resulting in

190 dose rates that range from 0.58 to 0.67 Gy/ka for samples BSW-5 to 7 (Tab. 2 and SOM Tab.
191 1). Sample BSW-8 was collected from the gravel layers, for which the dose rate is slightly
192 higher (0.73 Gy/ka). Sampling depths ranges from 1.9 to 2.3 m, and even at such depths the
193 corresponding cosmic dose rate is significant, representing between 18% and 22% of the total
194 dose rate.

195 Since bioturbation processes have been observed along the sequence, the use of the
196 Central Age Model (Galbraith et al., 1999) is not appropriate. Indeed, the broad range of D_e
197 values (Fig. 4), the indistinguishable CAM ages along the sequence, and the high OD values
198 that range from 54 to 63% (SOM Tab. 1) even without the rejected “zero-age” grains, (SOM
199 Tab. 1) are consistent with the mixing of sediment by post-depositional processes. Instead of
200 using the Maximum Age Model, which is sensitive to anomalously high outliers, the Finite
201 Mixture Model (Galbraith and Green, 1990) was applied to isolate the significant D_e
202 components, using the BIC criterion (Galbraith and Roberts, 2012), and selecting the oldest
203 component that comprises more than 10% of the grains (see e.g. Rodnight et al., 2005 for a
204 similar selection criterion when choosing the youngest D_e component). Three components
205 were identified for each sample (Fig. 4 and SOM Tab. S3). The highest D_e component
206 represents the oldest grain population, assuming that for these grains the TT-OSL signal has
207 been least bleached during post-depositional processes. These D_e values are based on 11 to
208 42% of the grains (Tab. 2). The presence in all samples of “zero-age” grains that their TT-
209 OSL signal has been well bleached, indicates that bioturbation is an on-going process. These
210 grains did not pass the selection criteria and have a natural TT-OSL intensity close to 0, but
211 TT-OSL signals can be generated and a DRC constructed (Fig. 3A), providing D_e values close
212 to 0 Gy (< 5 Gy). The “zero-age” grains raise the possibility that even the oldest grain
213 component might underestimate the true age of the site because these grains could have been
214 exposed to sunlight and partially bleached. The cumulative light sum curves obtained are
215 similar for the four samples (Fig. 5). As for such curves obtained for SG OSL data (e.g. Duller
216 et al., 2000), the light distribution among the grains is not equal, meaning that a small number
217 of grains dominate the signal in multi-grains measurements.

218 Additionally, to assess the level of bleaching of the TT-OSL signal in such
219 environments, measurements were conducted on three Holocene samples from the
220 neighboring site of Kathu Pan (SOM Tab. S4), situated about 5 km away from Bestwood and
221 also constructed of sandy sediments (Lukich et al., 2020). These samples yielded low OSL D_e
222 (≤ 2 Gy) (Lukich et al., 2019; 2020). The TT-OSL signal was measured on three aliquots from

223 each sample, a total of 9 D_e determinations. Eight out of the nine aliquots were well bleached,
224 with TT-OSL D_e values ranging from 4.7-18 Gy, and an average of 9.9 ± 4.5 Gy (SOM Tab.
225 S4). This value is similar to the lowest value measured in “modern” samples by Duller and
226 Wintle (2012) and can be considered as the minimum residual. In addition to the “zero-age”
227 grains, these measurements support our assumption that the TT-OSL signal was well bleached
228 at the time the quartz grains were initially deposited at the site, but they also raise concerns
229 that even the oldest TT-OSL grains might have been exposed to some sunlight and partially
230 bleached. Hence the ages should be considered as minimum.

231 The ages obtained using the highest D_e component are (from bottom to top; Tab. 2)
232 366 ± 32 ka for the gravel layer (BSW-8), and 350 ± 22 ka (BSW-7), 295 ± 17 ka (BSW-6)
233 and 226 ± 13 ka (BSW-5) for the sand unit. These ages are in stratigraphic order and the one
234 obtained for the gravel layer, 366 ± 32 ka, provides a minimum age for the living surface
235 where artefacts were discovered.

236

237 **4. Discussion**

238 **4.1. Bioturbation processes and the use of single grain TT-OSL to extract the oldest** 239 **component**

240 Bioturbation has been reported in similar contexts at other sites, limiting the use of
241 optical dating of the sediment: the presence of different age populations among the dated
242 grains affects the accuracy of the ages and limits their precision (e.g., Tribolo et al., 2010), in
243 particular in unconsolidated sands (e.g., Schoville et al., 2009; Chazan et al., 2013; Kristensen
244 et al., 2015; Williams, 2019). Indeed, the lack of any sedimentary structures in the sands at
245 Bestwood indicates that bioturbation occurred. Nonetheless, the use of the FMM allows to
246 extract the oldest component, i.e. to discard younger grains that were likely bleached after
247 deposition.

248 The transportation of grains by ants or termites can lead to different scenarios, for
249 example, the introduction of younger grains from the top of the section through galleries or
250 the transportation of older grains from the lower levels to the surface by termites to construct
251 their mounds. Kristensen et al. (2015) studied the effect of termites bioturbation on the OSL
252 D_e values distribution and identified a few saturated grains in the upper 100 cm in termite
253 mounds in a savannah ecosystem in Ghana, interpreted as an occasional loss of grains by the
254 termites on the way to the surface. This is also suggested by Rink et al. (2013) for ants

255 activity. The authors also show that downward movement of grains occurred from the surface
256 to the depth, through galleries. The grain displacement may also occur laterally, representing
257 a major issue for the application of luminescence dating (e.g., Bateman et al., 2007; Rink et
258 al., 2013; Kristensen et al., 2015). On the one hand, these processes can lead to age
259 underestimation, when grains are transported downwards from the surface with their signal
260 reset. On the other hand, ages can also be overestimated appear when grains are brought
261 upward in the section but not to the surface (no zeroing), as evidenced by Rink et al. (2013),
262 and defined as “subterranean-transported”.

263 However, in the case of Bestwood 1, the majority of the grains dated using both
264 conventional OSL and TT-OSL were considered to be too young according to the
265 archaeological context of the deposit. Taking into account the minimum-maximum OSL or
266 TT-OSL age ranges and the average ages for each of the dated samples (SOM Table S1), the
267 young SG component clearly impacts the average D_e values. It suggests that the introduction
268 down-section of zeroed grains was the main consequence of bioturbation processes and that
269 any averaging would cause age underestimation for these samples; only the use of the FMM
270 to isolate the oldest component could circumvent age underestimations. In addition, the
271 presence of zero-age grains suggests that bioturbation is an ongoing process. That there are
272 also TT-OSL zero-age grains deep in the section gives an insight into the thorough resetting
273 of the quartz TT-OSL signal. Lastly, the SG TT-OSL ages calculated using the oldest
274 component are in stratigraphic order and in agreement with the archaeological record,
275 supporting the use of SG TT-OSL combined with the FMM to calculate ages for bioturbated
276 sandy deposits.

277

278 **4.2. Significance of the ages**

279 The chronology of the Fauresmith industry is, to date, not well defined. Similarly
280 bioturbated sediments at Canteen Kopje produced a Fauresmith industry but the use of OSL
281 dating was limited by sediment mixing (Chazan et al., 2013). At Canteen Kopje, the
282 Fauresmith was found right above the gravel (McNabb and Beaumont, 2011; Lotter et al.,
283 2016). Single-grain (micro-aliquot) OSL ages obtained for the base of the sandy section that
284 overlies the gravel unit can thus give a minimum age for the Fauresmith. Chazan et al. (2013)
285 used the FMM to select the largest SG population, and obtained ages of 167 ± 10 ka (CK7-5)
286 and of 164 ± 9 ka (CK7-6) for the lowermost samples. Following our approach to isolate the

287 oldest grain component and avoid the bleached grains in these samples, a re-analyses of the
288 SG OSL data from Chazan et al. (2013) gave ages of 307 ± 24 ka (CK7-5) and 292 ± 17 ka
289 (CK7-6). They are somewhat younger than the SG TT-OSL FMM ages obtained for
290 Bestwood 1, but they can be considered as minimum ages for the Fauresmith as they overly
291 the layers where this industry was found.

292 Other published age determinations for the Fauresmith are U-Th ages from the sites of
293 Rooidam and Wonderwerk Cave, which in both cases do not provide a conclusive age for the
294 occupation. At Rooidam, there are two U-Th ages on calcrete from strata overlying
295 Archaeological Stratum 9 (Unit B), which produced a rich archaeological assemblage
296 attributed to the Fauresmith (Butzer, 1974). Samples BUT 2 from Unit C and BUT 1 from
297 Unit G (two meters higher in the sequence) are dated to 108 ± 20 ka and 151 ± 35 ka,
298 respectively (Szabo and Butzer, 1979). The younger age of BUT 2 appears to be the result of
299 recrystallization of calcite. There is apparently a small assemblage also attributed to the
300 Fauresmith from Unit F, which underlies BUT 1. Thus, the Rooidam data supports a
301 chronology of the Fauresmith at greater than 150 kyr but does not provide an actual age for
302 the assemblage.

303 Beaumont and Vogel (2006) have published several U-Th ages from three excavation
304 areas in Wonderwerk Cave that are relevant to the age of the Fauresmith. From Excavations 6
305 at the back of the cave there is a single U-Th minimum age of 187 ± 8 ka on a speleothem
306 (sample U576). Although Beaumont and Vogel attribute the archaeological assemblage to
307 the MSA, it is most likely Fauresmith based on current understanding of this assemblage
308 (Chazan, 2015a). However, questions remain about the temporal relationship between this
309 speleothem and the depositional context in which it was found (Herries, 2011). Beaumont and
310 Vogel also report U-Th ages for Excavation 2 (U437 - 276 ± 29 ka; U499 - 278 ± 26 ka; U583
311 - 286 ± 29 ka) as coming from a Fauresmith context, however re-examination of the
312 associated archaeological assemblages does not find adequate indications to confirm this
313 cultural attribution. In Excavation 1, two speleothems from the top of the Acheulean sequence
314 (U427, U407; Stratum 6) produced ages of >350 ka. Typologically the associated assemblage
315 (Stratum 6) shows some characteristics that link it to the Fauresmith (Chazan, 2015).

316 Based on our TT-OSL data for Bestwood 1, on the reanalysed OSL data from Canteen
317 Kopje and on published data from Kathu Pan, the Fauresmith industry is older than ~ 350 ka.
318 The SG TT-OSL age obtained for the human occupation layer at Bestwood 1, of 366 ± 32 ka,

319 is in agreement with updated minimum ages for the industry at the base of the section at
320 Canteen Kopje, of around 300 ka. The ages are however younger than those obtained for the
321 Fauresmith industry at Kathu Pan, for which a minimum OSL age of 464 ± 47 ka and a
322 combined U-series–ESR age of $542 +140/-107$ were obtained (Porat et al., 2010).

323

324 **5. Conclusion**

325 Based on the observations that the TT-OSL signal bleaches much slower than the OSL
326 signal, single grain TT-OSL analyses were conducted in order to isolate the oldest grains, i.e.,
327 the grains that were the least affected by bioturbation and surface exposure. The slow optical
328 resetting rate of the TT-OSL signal is generally considered as an obstacle; nonetheless,
329 bioturbated sediment can benefit from this property, allowing to discard the younger grain
330 component whose signal has been partially reset during transportation and burrowing by ants
331 and termites.

332 At Bestwood 1, this innovative application combined with the use of the FMM, allows
333 to isolate the oldest component that is thought to be contemporaneous with the deposition
334 time of the sediment associated to the ESA assemblage. The age obtained for the human
335 occupation layer, of 366 ± 32 ka, allows to constrain human presence at the site during MIS
336 11-10. The chronology of the overlying sand deposits, spanning from 350 ± 22 ka to 226 ± 13
337 ka (MIS 10 to 8), suggest that the lower part of the stratigraphic section dated in this study
338 was deposited in less than 150 ka.

339 The regional chronology suggests that the Fauresmith industry appeared around 500
340 ka, according to ESR and OSL ages obtained at Kathu Pan. Our data from Bestwood 1, as
341 well as updated ages for Canteen Kopje, are consistent with such an early age but allow for a
342 persistence of the Fauresmith to at least ~ 360 ka. These new data confirm the overlap between
343 the timing of the Fauresmith and the first appearance of modern humans and predates the age
344 of the Florisbad fossil (Grün et al., 1996; Richter et al., 2017). Our approach to isolate the
345 oldest grains component, using single grain TT-OSL combined with FMM, opens new
346 perspectives in dating bioturbated sediment.

347

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357

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503

504 **Figures**

505 Fig. 1. Location map of Bestwood 1 and other sites discussed in the text. Black squares:
506 Modern towns and cities, OLF- Olifantshoek, KUR- Kuruman, KMB- Kimberley. Red
507 circles: Archaeological sites, BW- Bestwood, KP- Kathu Pan, WW- Wonderwerk Cave, CK-
508 Canteen Kopje, RD- Rooidam.

509 Fig. 2. The stratigraphic context of the OSL samples in relation to the archaeological horizon
510 at Bestwood 1, Block 1. A: Profile in exposure of overlying sands with OSL samples BSW-
511 1 to BSW-6. B: BSW-7. C: BSW-8. D: Stratigraphic column. E: Vertical projection facing
512 west showing OSL samples and archaeological artefacts. Note the association of samples
513 BSW-7 and BSW-8 with the archaeological horizon, which is flat and vertically constrained.
514 Units in meters. F: Vertical projection facing south showing OSL samples and archaeological
515 artefacts.

516 Fig. 3. Dose response curves for a “Zero-age” grain (A) and an old (B, 620 ± 40 Gy) grain
517 from sample BSW-8.

518 Fig. 4. Abanico plots for all samples. The dash lines represent the mean value; the solid red
519 lines the FMM components. Graphs produced using ‘RLumShiny’ (Burow et al., 2016).

520 Fig. 5. Cumulative light sum curves for all samples.

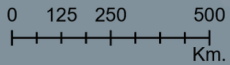
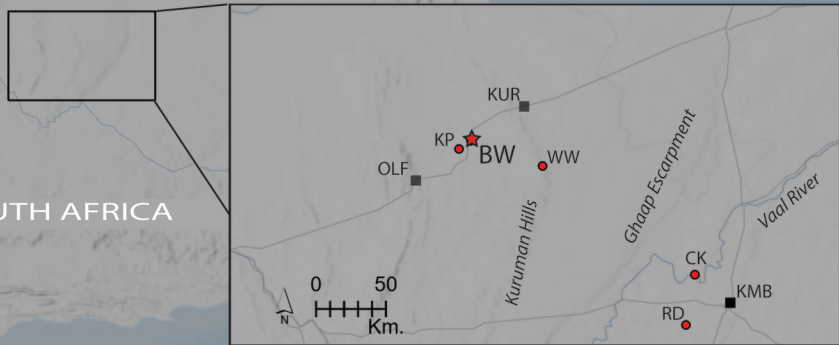
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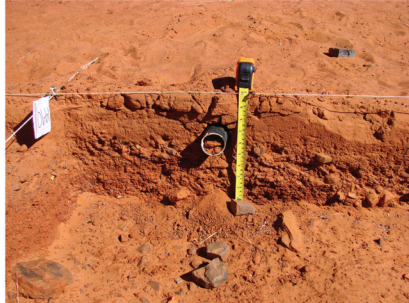
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Cape Town





A



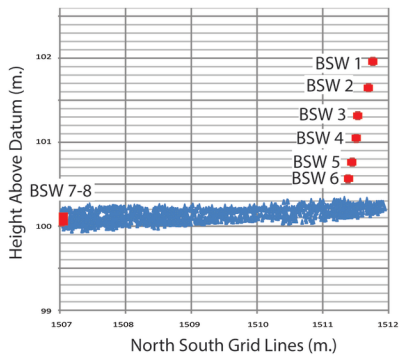
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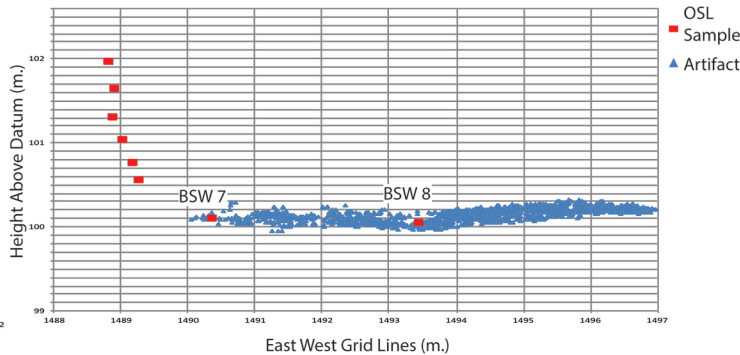
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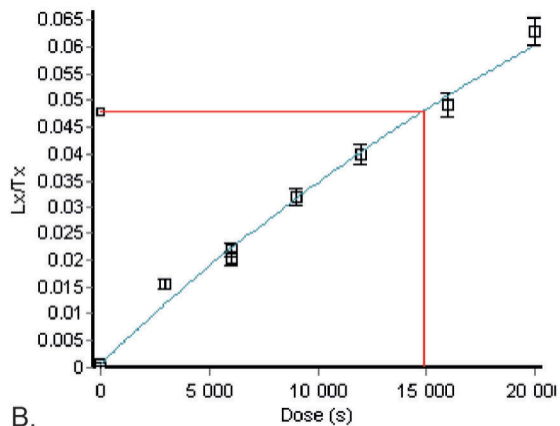
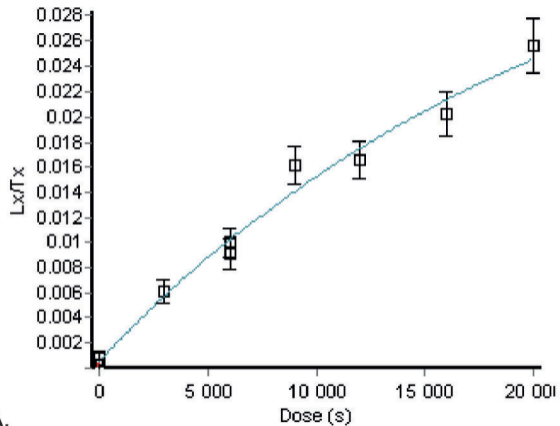
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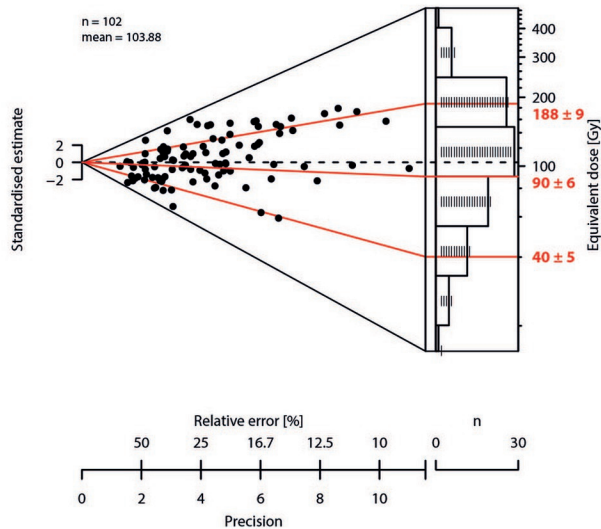
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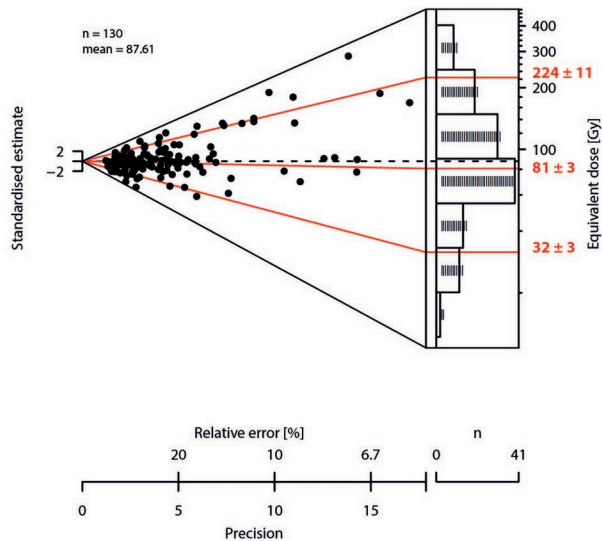
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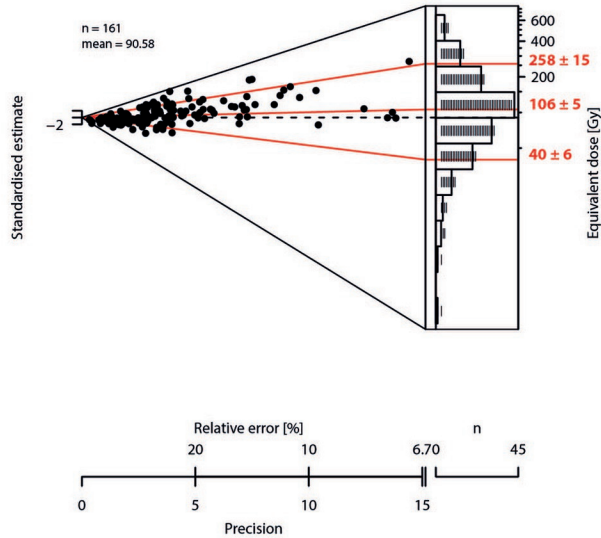
BSW-5



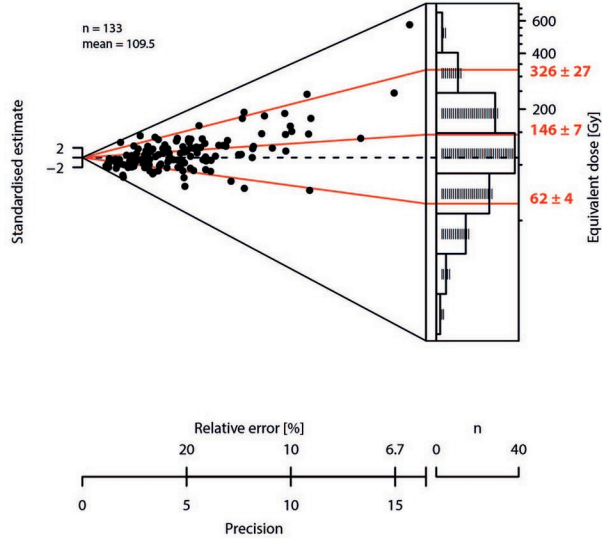
BSW-6

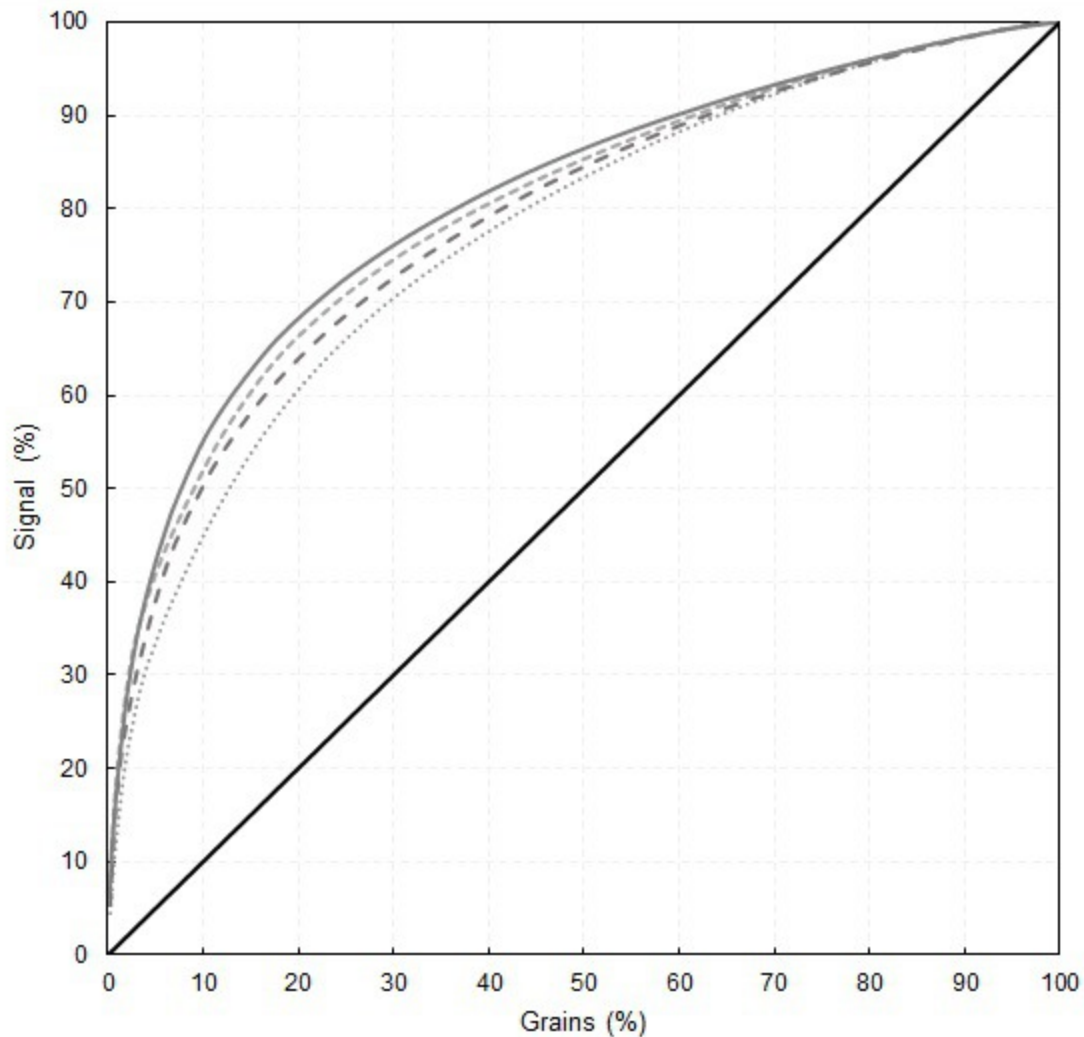


BSW-7



BSW-8





..... BSW-5 - - - - BSW-6 - . - . BSW-7 ——— BSW-8 ——— 1:1

Tables

Step	Treatment
1	Give a regenerative dose (for N, dose = 0)
2	Preheat at 260°C for 10 s
3	Blue LED stimulation at 125°C for 300 s
4	Preheat at 260°C for 10 s
5 (L_{TT-OSL})	SG Green laser stimulation at 125°C for 2 s
6	Give a test dose of ~25 Gy
7	Preheat at 220°C for 5 s
8 (T_{OSL})	SG Green laser stimulation at 125°C for 2 s
9	Deplete remaining signal with blue stimulation at 310°C for 100 s
10	Return to 1

Tab. 1. TT-OSL SAR measurement protocol applied to single grain (SG) quartz. Shaded steps were used to construct the dose response curve.

Sample	Burial depth (cm)	n/N	Yield (%)	Total dose rate (Gy/ka)	D _e (Gy)	Age (ka)
BSW-5	192	102/500	20	0.83 ± 0.02	188 ± 9	226 ± 13
BSW-6	215	130/1000	13	0.76 ± 0.02	224 ± 11	295 ± 17
BSW-7	218	161/1100	15	0.74 ± 0.02	258 ± 15	350 ± 22
BSW-8	233	133/1100	12	0.89 ± 0.03	326 ± 27	366 ± 32

Tab. 2. Single grain TT-OSL ages obtained for Bestwood 1. The D_e were measured using the standard 300 μm holes-disk, with 3-4 grains in each hole. Ages were calculated using the oldest component obtained from the Finite Mixture Model (SOM Tab. S3). Alpha, beta and gamma dose rates were calculated from the radioactive elements measured by ICP-MS (U, Th) and ICP-OES (K) and are provided in SOM Tab. S1. Cosmic dose rates were estimated from current burial depths (see text).