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1 **Do Bayesian methods lead to more precise chronologies?**

2 **'BayLum' and a first OSL-based chronology for the**

3 **Palaeolithic open-air site of Mirak (Iran)**

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15
16 **Abstract**

17 Bayesian inference has been applied extensively to chronologies in archaeological science
18 since it provides several advantages over the (classic) frequentist approach. One of the most
19 important aspects of applying Bayesian methods is their capacity to consider the stratigraphic
20 relationship in the final ages. More specifically, in luminescence dating, a crucial motivation
21 for applying Bayesian modelling is the ability to address the systematic shared uncertainty.
22 The recently deployed R package 'BayLum' was developed to ameliorate luminescence-based
23 chronologies by employing Bayesian modelling. Our contribution aims at estimating the
24 impact of stratigraphic order and systematic shared uncertainty on the age results.

25 In this paper, for the first time, we present a comprehensive luminescence-based chronology
26 for the Middle-Upper Palaeolithic site of Mirak. The open-air site is located in the northern
27 fringes of the Iranian Central Desert, which is considered to be one of the dispersal corridors
28 for hominins (Neanderthal and modern human) living across Western and Central Asia. We
29 compare chronologies derived by frequentist and Bayesian methods to discuss the effect of
30 stratigraphic order and addressing the correlation between samples due to systematic shared

31 uncertainty. Our investigations indicate that applying the stratigraphic order when age
32 uncertainty overlap one another plays a fundamental role in reducing the uncertainty.
33 The obtained Bayesian chronology considering the stratigraphic order for the layer containing
34 predominately Upper Palaeolithic techno-complex results in [21–28] ka. The age of the
35 intermediate layer is in the range of [26–33] ka, and the lowermost layer containing middle
36 Palaeolithic assemblage gives the age-range of [43–55] ka. These results indicate that Late
37 Pleistocene humans have exploited the site during MIS 2–3. Furthermore, the chronology
38 gives further evidence to the hypothesis that the Iranian Central Plateau served as a
39 frequently used habitat and dispersal corridor for human groups populating Western and
40 Central Asia.

41

42 **Keywords: Bayesian modelling; Luminescence dating; Chronology; Palaeolithic; Iran**

43

44 1. Introduction

45 A reliable chronology is an indispensable component for studying Palaeolithic sites. Optically
46 stimulated luminescence (OSL, Huntley et al., 1985) on sediments is one of the chronological
47 methods applied in archaeological science (e.g., Roberts et al., 2015; Liritzis, 2017). The age
48 is the product of several separate stages of computation, fusing a considerable amount of
49 measurements and variables (e.g., Aitken, 1985; Zink, 2013). Each stage estimates parameters
50 with their uncertainties, hence, making the statistical data analysis an integral part of such
51 chronological studies.

52 Generally, two schools of statistics, frequentist (classic) and Bayesian can be applied (e.g.,
53 Buck and Millard, 2004). Classic statistical inference 'prefers' reproducible experiments,
54 where the probability of observing an unknown variable is determined after repeated runs
55 under similar conditions (Gelman et al., 2014; Carlin and Louis, 2000). However, such an
56 approach may not be the proper paradigm where *one-off* (non-repeatable) events are the
57 study subjects or where the number of observations is small (Buck and Meson, 2015).
58 Geochronology and archaeological science are the fields in which the classic inference does
59 not always seem to be the most judicious approach to data analysis (Buck and Meson 2015;
60 Buck et al., 1998). This circumstance may be seen as one of the reasons why Bayesian
61 inference has become prevalent. However, to date, classic statistical inference dominates the
62 data treatment in luminescence dating, but Bayesian statistics has gained some attention
63 (e.g., Rhodes et al., 2003; Huntriss., 2008; Zink, 2013; 2015; Combès et al., 2015; Mercier et
64 al., 2016; Philippe et al., 2018). Applying Bayesian modelling potentially prevents information
65 loss between analysis steps by deploying a model that runs simultaneously overall parameters
66 of the measurements, leading to more consistent results, which better reflect original data
67 (Combès et al., 2015). For instance, in the case of OSL dating, a single instrument may have
68 been used for all measurements; consequently, the source of systematic uncertainty (e.g.,
69 the calibration of the radioactive source) is identical to all samples. In such a situation
70 Bayesian inference should be used due to its capability to address different kinds of
71 uncertainty (Huntriss, 2008; Zink, 2015). Moreover, Bayesian modelling may provide an
72 option to include independent ages in specific situations, and with higher precision, such as

73 available for ^{14}C dating, to reduce uncertainties and thus result in an improved overall age
74 precision (Rhodes et al., 2003; Lanos and Philippe, 2018).

75 However, the advantages of applying Bayesian inference in dating applications are not solely
76 restricted to the improvement of the precision, but it also allows considering fundamental
77 knowledge of the dating process. The stratigraphic order is such kind of pre-knowledge ('prior
78 belief') which results in chronologies consistent with the stratigraphy. This allows to include
79 data that belong to different parts of the site, given that their stratigraphic sequence is well
80 known and unbiased, to provide a synthetic chronology (Buck and Millard 2004).

81 The R (R Core Team, 2019) package 'BayLum' based on Combès *et al.* (2015), Combès and
82 Philippe (2017) and implemented by Philippe *et al.* (2018) claims to play out the power of
83 Bayesian methods by employing hierarchical Bayesian models to analyse OSL signals and
84 estimate palaeodoses. Heydari and Guérin (2018) already showed in two laboratory-
85 controlled experiments that the Bayesian models result in most accurate estimations of the
86 palaeodose when compared to conventional methods, and Lahaye *et al.* (2019) reported the
87 first application of it in a dating study. Beyond, a full-scale application of 'BayLum' in a large
88 dating study under 'non-perfect' conditions is still uncharted territory raising the question of
89 whether "these new Bayesian methods do lead to more precise chronologies" and it leads to
90 the here presented threefold contribution:

91

- 92 1. First, we present a large set of luminescence dating using frequentist statistics for the
93 open-air site of Mirak, which has been excavated by the Joint Franco-Iranian
94 Palaeoanthropological Project (FIPP) between 2015 and 2017. The site is located in
95 12 km south of the city of Semnan in a belt-like region bordered by two natural
96 barriers, the Alborz Mountains to the north and the Iranian central desert to the south
97 (Rezvani 1990; Rezvani and Vahdati Nasab, 2010; Vahdati Nasab *et al.*, 2013; 2019)
98 (Fig. 1). First results of the multidisciplinary investigations indicate that Humans
99 occupied the area several times during Late Pleistocene (Vahdati Nasab *et al.*, 2019).
100 our work here provides the first comprehensive chronological framework for the
101 palaeoenvironmental of this area that has been unknown so far. A few preliminary
102 results, were already published using frequentist approach (Vahdati Nasab *et al.*,
103 2019).

- 104 2. We apply, for the first time, Bayesian models as implemented in ‘BayLum’ on
105 combined stratigraphic sequences from the Palaeolithic open-air site of Mirak. We
106 test different scenarios on the data set and discuss the application of Bayesian
107 modelling as implemented in ‘BayLum’. In particular, we test whether stratigraphic
108 ordering and addressing the correlation between samples caused by systematic
109 uncertainty results in a chronology, statistically indistinguishable to the ‘conventional’
110 frequentist approach (H_0) or indeed yields to a more precise chronology (H_A).
111 3. The first investigation clarified three main *in situ* archaeological layers in the site
112 (Vahdati Nasab et al., 2019) in which the uppermost and the lowermost layers indicate
113 characteristics associated to Upper and Middle Palaeolithic affinities. In addition, the
114 intermediate assemblage indicates a mixed nature comprising characteristics of both
115 Upper and Middle Palaeolithic lithic affinities. Hints in the intermediate deposit
116 implying the existence of two separated sub-layers. Thus, here, using the determined
117 chronological framework, we discuss whether these two sub-layers may address two
118 distinct Palaeolithic assemblages or they both may be considered as one
119 archaeological layer.

120

121 In summary, by combining dating application with methodological research, our study
122 responds to the high demand for reliable chronologies, and the question of whether Bayesian
123 methods may be of advantage to tackle this task. Finally, we contribute to the understanding
124 of the local Palaeolithic cultures by deciphering the environmental and occupation history of
125 the northern edge of the Iranian Central Plateau.

126 2. **Mirak open-air site in a prehistorical context**

127 The Iranian plateau is essential for tracking the routes of human dispersal during the Late
128 Pleistocene due to its particular location on a prehistoric intersection connecting Africa and
129 Europe to central Asia (Bar-Yosef and Belfer-Cohen, 2001).

130 Discovered in the last century, human remains close to the borders of this plateau
131 emphasize the notability of this region: for instance, the unique set of Neanderthal
132 skeletons in Shanidar (Solecki, 1955; Trinkaus, 1983) in the Iraqi Kurdistan, as well as the

133 skeleton of a Neanderthal child in Teshik Tash (Okladnikov, 1949), south of Uzbekistan.
134 However, so far, the Late Pleistocene human remains in Iran (Trinkaus and Biglari, 2006;
135 Zanolli et al., 2019) are scarce. On the contrary, considerable lithic assemblages associated
136 to the Middle Palaeolithic (Zagros Mousterian; Dibble, 1984) and Upper Palaeolithic (Zagros
137 Aurignacian: Olszewski and Dibble, 1994; Baradostian: Solecki, 1958; Rostamian: Conard and
138 Ghasidian, 2011) are known to be concentrated in the Zagros foothills (mainly in caves and
139 rock shelters) (e.g., Biglari, 2001; Otte et al., 2007; Shidrang et al., 2016; Bazgir et al., 2017;
140 Heydari-Guran and Ghasidian, 2017). Beyond the Zagros foothills, several open-air sites in
141 stratigraphic context have recently been discovered in the northern and western edges of
142 the Iranian Central plateau, as well as the central Alborz (e.g., see Berillon et al., 2007;
143 Berillon and Asgari Khaneghah, 2016; Conard et al. 2009; Heydari-Guran et al. 2014; Vahdati
144 Nasab and Hashemi 2016; Vahdati Nasab et al., 2013; 2019). Notwithstanding this abundant
145 archaeological evidence, the debate suffers from a lack of chronological data for this area.

146 2.1. **Geomorphological and stratigraphic setting**

147 The Palaeolithic site of Mirak lies in a flat-dissected plain, which extends from the southern
148 part of the Alborz Mountains to the margin of the central desert (*Dasht-i Kavir*) (Fig. 1). In
149 this area, unusual Holocene nebkha (i.e. shadow dunes; mounds) are located in the flat plain
150 composed of Pleistocene alluvial deposits (see Jamet and Akhavan Kharazian in Berillon et
151 al., 2017 and Akhavan Kharazian et al., 2018 for details; synthesis in Vahdati Nasab et al.,
152 2019). The lithic artefacts on the surface are exposed by deflation close to the mounds. The
153 presence of the nebkhas with vegetation on top played a fundamental role in the
154 preservation of three archaeological levels in the underlying Pleistocene alluvial deposits.
155 One of those mounds (mound no. 8) at an altitude of 1,035 m (a.s.l.) and surrounded by the
156 highest concentration of lithic artefacts, was selected for this study.
157 Besides, the presence of a nearby illegal pit, henceforth named S2, has provided a unique
158 possibility for primary investigations on *in situ* archaeological material. Having proved the
159 presence of in situ deposit, three main trenches have then been excavated in the northern,
160 eastern and southern slopes of the mound no. 8 with excavation areas of 19 m², 12 m² and 5
161 m² respectively; ¼m² has been excavated at the bottom of S2 (Berillon et al., 2017; Vahdati
162 Nasab et al., 2019) (see Fig. The one I attached).

163 Figures 2 and 3 show the synthetic stratigraphy based on sedimentological observations. The
164 upper part of the northern stratigraphy (ca. 4 m) exhibits aeolian sands (units 0 to 3) due to
165 Holocene windblown activity. The windblown deposits are reduced in the eastern
166 stratigraphy (ca 1.5 m). The lower part of the synthetic stratigraphy exhibits an alluvial
167 sequence composed of silty clay deposits (units 4, 6 & 8) with very fine intercalated sands
168 (units 5 & 7). The Late Pleistocene alluvial plain recorded frequent flood events due to the
169 channel overflow characterising the sediment as a shallow-water deposit.

170 **2.1.1. *In situ* archaeological assemblages**

171 The stratigraphic logs of the northern and eastern sections are shown in Figs. 2 and 3.
172 The archaeological assemblage in Mirak consists mostly of lithic artefacts, which are spread
173 extensively over the surface and within the *in situ* archaeological deposits. Indeed, a
174 considerable number of *in situ* artefacts have been recorded during the three seasons of
175 excavations in Mirak (in total 2,709 pieces); they were mainly discovered in the 3 main areas
176 of excavations (Northern, Southern and Eastern trenches) as well as in the lowest part of the
177 S2 sequence.

178 In the east trench where the excavation has been the more extensive (both in surface and
179 depth) three distinct *in situ* assemblages have been identified. Their vertical distribution is
180 displayed in Fig. 3. Typo-technological investigations indicate that the lower assemblage (level
181 3) mainly corresponds to Middle Palaeolithic characteristics, while the intermediate
182 assemblage (level 2) shows mixed characteristics of Upper and Middle Palaeolithic. However,
183 this level is spread over 50 cm of depth and may be divided into two sublevels. Finally, the
184 upper assemblage (level 1) has evident Upper Palaeolithic affinities although very few
185 artefacts represent it (see Vahdati Nasab et al., 2019 for details).

186 **3. Material and methods**

187 **3.1. Sampling**

188 The sediment sampling for Mirak was carried out during three field campaigns between 2015
189 and 2017. Each year, a series of sediment samples, in total 20, were extracted for OSL dating
190 using opaque tubes hammered into the stratigraphic sections (Figs. 2 and 3).

191 In 2015, five sediment samples were taken from the north trench. The first two samples were
192 recovered from the top of the mound, Mk15-1 from the vegetated surface (unit 1) and Mk15-
193 4 downwards from the wind-blown deposits (unit 3) on the top of the Palaeolithic layers.
194 Additionally, Mk15-5 was sampled from unit 4a containing the Upper Palaeolithic assemblage,
195 while Mk15-6 was taken from unit 4b. Finally, Mk15-7 originated from unit 8 beneath the
196 Middle Palaeolithic level 3. Moreover, an additional sample, Mk15-8, was extracted from one
197 of the clandestine pits (S2) attributable to the sedimentological unit 6.

198 In 2016, five luminescence samples were taken from the eastern trench and one from the
199 southern ditch. In the eastern trench, sampling started from unit 4a, which contains Upper
200 Palaeolithic artefacts (Mk16-6). The next sample (Mk16-4) came from the bottom of unit 5,
201 which includes intermediate archaeological layer featuring artefacts with mixing
202 characteristics attributable to both, the Upper and Middle Palaeolithic, periods. Mk16-5
203 originated from the archaeologically-sterile unit 6. Finally, two samples were extracted from
204 the bottom of unit 7 (Mk16-2) and from top of unit 8 (Mk16-3) framing the layer which
205 contains Middle Palaeolithic assemblage. Additionally, one sample was taken from the
206 corresponding geological unit 6 from the south trench (Mk16-1).

207 In 2017, a last series of samples were taken again from the east trench. The purpose of this
208 sampling was not only to access the lowest unit of the mound, but also to detail the
209 chronological study to obtain a better understanding of the Palaeolithic settlements. We took
210 two samples from unit 3b (Mk17-2 and Mk17-3) from the top of Upper Palaeolithic layer and
211 one sample from the bottom of the same layer in the geological unit 4a (Mk17-1). Then
212 sample Mk17-7 was taken from the bottom of geological unit 4b. We continued by taking two
213 samples from the top and bottom of the unit 5 containing intermediate assemblage (Mk17-6
214 and Mk17-5) and one sample from the very top of unit 6 (Mk17-4). Finally, the last sample
215 (Mk17-10) was taken from the lowest excavated unit 8.

216 3.2. **Sample preparation**

217 The samples were prepared using routine procedures for luminescence dating (e.g., Preusser
218 et al., 2008). Subdued orange (ca 589 nm, sodium vapour lamp) light conditions prevented
219 any unwanted loss of luminescence signal during sample preparation. Wet sieving was carried
220 out to extract grains between 80 μm to 140 μm , which is the dominant grain size fraction

221 according to grain size analyses. HCl (10 %) and H_2O_2 (30 %) were used to eliminate
222 carbonates and organic materials, respectively. To separate quartz and feldspar grains,
223 lithium heteropolytungstates (LST) heavy-liquid based density separation was applied
224 (densities: 2.70 g cm^{-3} and 2.62 g cm^{-3}). The quartz fraction was treated with HF (40 %) for
225 40 min, not only to remove any probable feldspar contamination, but also to minimize the
226 luminescence signal produced by alpha particles. The feldspar grains were etched with HF
227 (10 %) for 10 min to remove the outer part of the grains believed to be affected α -particles.
228 The last series of samples were taken from the eastern trench (Mk17-1 to Mk17-10) for which
229 we planned to carry out the measurements only on the quartz fraction, were not treated with
230 LST, and the sediments were soaked in HF (40 %) for 40 min to remove all feldspar grains and
231 purify quartz. Finally, the grains were rinsed in HCl (15%) overnight to remove Ca-fluorides
232 and sieved with the smaller-sized meshes to remove fragmented grains only (e.g., Porat et al.,
233 2015).

234 3.3. Instrumentation

235 Luminescence measurements were carried out on a Freiberg Instruments *lexsyg* SMART
236 TL/OSL system (Richter et al., 2015) and Freiberg Instruments *lexsyg research* readers (ca 15 %
237 of the measurements) (Richter et al., 2013). Both readers were equipped with a $^{90}\text{Sr}/^{90}\text{Y}$ -
238 source delivering ca 9.3 Gy min^{-1} and 7.08 Gy min^{-1} respectively (calibrated for coarse-grain
239 quartz on stainless steel cups using Risø calibration quartz batch 90; Hansen et al., 2015). For
240 signal stimulation, the *lexsyg* SMART system facilitates 10 green LEDs ($525 \Delta 20 \text{ nm}$, max. 70
241 mW cm^{-2}) and 5 infrared LEDs ($850 \Delta 3 \text{ nm}$, max. 300 mW cm^{-2}), set to 40 mW cm^{-2} (green)
242 and 100 mW cm^{-2} (infrared) during continuous wave (CW) stimulation. Optically stimulated
243 luminescence was detected through a UV filter set (Schott BG 3, 3mm and Delta BP 365/50
244 EX; green-OSL) in front of a Hamamatsu H7360-02 photomultiplier tube (PMT). For signal
245 stimulation, the *lexsyg research* system facilitates five blue LEDs ($458 \Delta 3 \text{ nm}$, max. 100 mW
246 cm^{-2}) and five infrared LEDs ($850 \Delta 3 \text{ nm}$, max. 300 mW cm^{-2}). They were set to 40 mW cm^{-2}
247 (blue) and 130 mW cm^{-2} (infrared) during continuous wave (CW) stimulation. A UV filter set
248 (Schott BG 3, 3mm and Delta BP 365/50 EX) was used for signal detection. Several hundred
249 grains, either quartz or feldspar, were mounted on the stainless-steel cups using silicon oil

250 and a mask of diameter 5 mm (medium size). We measured up to 15 aliquots per sample for
251 the feldspar and up to 40 aliquots for the quartz fractions.

252 3.4. Dose rate determination

253 Energy is stored in the minerals such as quartz and feldspar due to natural ionising radiation
254 in terms of alpha-, beta-particles, and gamma-photons as well as cosmic-rays (Aitken, 1985).
255 In this study, the size of the grains lies between 80–140 μm . We assume that the outer rim of
256 the grains, which was affected by alpha particles, was removed by the HF etching. Hence, the
257 alpha-dose rate contribution is assumed negligible. Furthermore, the dose rate absorbed by
258 the natural dosimeters (quartz and feldspar grains) consists of two parts: the internal dose
259 rate due to the activity of radionuclides inside the dosimeters and the external dose rate
260 because of the activity of the radionuclides outside the dosimeters.

261 3.4.1. Internal dose rate

262 The concentration of radionuclides inside the quartz grains is low in comparison to
263 environmental radionuclides concentrations. For our samples, we considered an internal dose
264 rate of $0.06 \pm 0.03 \text{ Gy ka}^{-1}$, following Mejdahl (1987). The internal dose-rate of K-feldspar
265 grains was calculated based on a potassium content of $12.5 \pm 0.5\%$ (Huntley and Baril, 1997).
266 The conversion factors after Guerin et al. (2011) were applied, and the self-dose fraction was
267 taken from Guerin et al. (2012), which resulted in an internal dose rate of $0.42 \pm 0.04 \text{ Gy ka}^{-1}$.

268 3.4.2. External dose rate

269 The main sources for external beta and gamma-radiation are radionuclides of ^{40}K , ^{232}Th , and
270 ^{238}U series. High-resolution, low background gamma-ray spectrometry was employed to
271 measure their concentrations (Guibert and Schvoerer, 1991). Therefore, the sediment was
272 first dried to measure the remaining water content. The water content estimated for each
273 sample, ranging from $2 \pm 1\%$ to $19 \pm 8\%$ was used to correct the dose rate for the effect of
274 water. The value for sample Mk16-2 is $5 \pm 3\%$; thus, it seems to be underestimated in
275 comparison with other values obtained for the bottom of the east trench. For the final age
276 calculation of this sample, we used an average water content of $10 \pm 5\%$ (Table 1).

277 Then the dried samples were crushed following sieving using a mesh size of 2 mm and packed
278 into sealed plastic boxes to avoid the loss of radon. In the following, the crushed and sealed

279 samples were stored over a minimum of four weeks to ensure a radioactive equilibrium
280 between ^{226}Rn and its daughter nuclides (e.g., Guibert and Schvoerer, 1991) before running
281 the measurements. The concentration of the radionuclides was converted to beta-dose rate
282 using the conversion factors by Guerin et al. (2011). The beta-dose rates were then corrected
283 for the intrinsic attenuation due to the grain size of the quartz and feldspar grains after Guerin
284 et al. (2012). The effect of HF etching, as well as the effect of moisture on beta-dose rates,
285 were corrected after Nathan (2011) and Nathan and Mauz (2008), respectively. The
286 concentration of the U, Th and K contents are shown in Table 1. The concentrations of K and
287 Th for entire samples fall between 1.26% to 2.32 %, and 4.67 ppm to 12.45 ppm, respectively.
288 Besides, the concentrations of U determined from the top of the chain range from 1.80 ppm
289 to 3.28 ppm. The concentration derived from the bottom of the chain lie between 1.75 ppm
290 to 9.42 ppm (this high U concentration is belonged to sample Mk15-8 from the clandestine
291 pit S2, if we exclude this value, then the highest value would be 4.30 ppm (from Mk17-4)).
292 The disequilibrium in the U chain is discussed below. The external beta dose rates for entire
293 sample range from 1.20 Gy ka^{-1} to 2.10 Gy ka^{-1} . It contributes 55% to 59 % to the total dose
294 rate.

295 The gamma-dose rate was also calculated from K, Th and U concentrations using conversion
296 factors by Guerin et al. (2011) and correction for water content after Guérin and Mercier
297 (2012). The gamma dose rates fall between 0.70 Gy ka^{-1} to 1.39 Gy ka^{-1} and they contribute
298 around 35 % of the total dose rate (Table 1).

299 Finally, the cosmic-dose rate was calculated using the *calc_CosmicDoseRate()* function
300 available in the R (R Core Team, 2019) package 'Luminescence' (Kreutzer et al., 2012; 2017)
301 applying the approach after Prescott and Stephan (1982) and Prescott and Hutton (1994). For
302 calculating the total dose rate (D_r), we used a self-written *Excel* sheet (results were compared
303 against *DRAC*, Durcan et al., 2015). The final dose rates for quartz grains range from 2.18 Gy
304 ka^{-1} to 3.69 Gy ka^{-1} ; correspondingly for K-feldspar grains it lies between 2.51 Gy ka^{-1} to 4.02
305 Gy ka^{-1} (Table 1).

306 **3.4.3. Radioactive disequilibrium**

307 Radioactive disequilibria in the decay chain of ^{238}U can be problematic for dating since it may
308 imply dose-rate evolution, while the basic requirement of the age equation is dose rate

309 stability. Substantial disequilibria can be caused, e.g., by leaching of U and Ra (due to the
310 chemical mobility of the U and Ra) (Aitken, 1985), and the influx of ^{210}Pb through ground and
311 rainwater and loss of Rn because of its gas form (Guibert et al., 2009). The equivalent ^{238}U
312 content is estimated from three different parts of the decay chain, where a possibility for a
313 disequilibrium exists: first, from the initial part of the chain, by calculating the value from
314 ^{234}Th , $^{234\text{m}}\text{Pa}$ and ^{234}U emissions; second, immediately after ^{226}Ra (by considering ^{214}Pb and
315 ^{214}Bi) and finally after ^{210}Pb . Figure 4 shows the ratio of ^{238}U concentrations from the top and
316 the bottom of the U-series divided by ^{232}Th , which is chemically immobile (Guibert et al.,
317 2009). Explicitly, the equivalent ^{238}U concentrations, which were derived from the bottom of
318 the decay chain, were about 1.5 to 3.7 times larger in comparison with values estimated from
319 the top for five samples (MK15-6, MK15-8, MK16-6, MK17-4, and MK17-5). These findings
320 represent disequilibria in the U-series. Since Ra is soluble and chemically active, accumulation
321 of Ra could be a reason for these disequilibria. We here assume that these disequilibria
322 developed gradually during burial time. As a result, the average of the effective ^{238}U
323 concentrations estimated from the top and the bottom (average uptake scenario) is
324 considered instead of the preliminary effective ^{238}U concentration from the bottom of the
325 chain and applied to these samples. Applying the average-uptake scenario results in older
326 ages (in comparison to a non-average scenario); the most impacts are observed for samples
327 Mk15-8 and Mk17-5 for which the ages are increased by 16 % to 7%. The ages of the rest of
328 the samples are increased between 3 % to 4%.

329 3.5. Luminescence signal measurements

330 3.5.1. Quartz UV signal

331 We applied the single aliquot regenerative (SAR) dose protocol (Murray and Wintle, 2000) to
332 determine the equivalent dose (D_e). The protocol parameters for the Mirak samples were
333 obtained from conventional tests such as examining the presence of a fast decaying signal
334 component, preheat plateau and dose recovery tests (Wintle and Murray, 2006). OSL signal
335 measurements were started with samples MK15-1 and Mk15-4. These two samples belonged
336 to the believed Holocene period, and their equivalent doses vary around 1 Gy to 3 Gy,
337 respectively. Due to the low luminescence signal intensity of these two samples, blue OSL was

338 preferred to improve the signal to noise ratio, and these settings were also used for the rest
339 of the samples taken in 2015 (MK15-5, MK15-6, MK15-7 and MK15-8).

340 Meanwhile, we carried out further luminescence tests (see Sec. 3.5.2 and Sec. S1) which
341 indicated a possible, but unwanted, medium component contamination of the OSL signal. This
342 led us to perform all subsequent measurements with green stimulated luminescence (GSL). A
343 few GSL measurements were also repeated for samples MK15-5, MK15-6, MK15-7 and MK15-
344 8 and the final equivalent dose is the average of blue and green stimulation (see below for
345 discussion). For the blue OSL we used initial channels 1–4 (0.64 s) for the signal and subtracted
346 early background using channels 5–15 (1.6 s).

347 **3.5.2. Testing the fast component**

348 Quartz OSL signals usually consist of several first-order kinetic exponential components,
349 which are related to specific electron traps (e.g., McKeever, 1991; Chen et al., 1991; Bailey,
350 2001). The so-called fast component has the advantage to be easily bleached in natural
351 environments and is believed to be suitable for the SAR protocol. Therefore, the first step was
352 to test whether Mirak samples show a dominant fast component. We first compared the
353 Mirak OSL signal with a signal from ‘calibration quartz’, which is known to be dominated by a
354 fast component (Fig. S1). Besides, we used a linearly modulated OSL method (LM-OSL) (Bulur,
355 1996) to deconvolve individual signal components. The LM-OSL results and details of our
356 investigation are shown in the supplementary material (Figs. S2 and S3). The results indicate
357 that the Mirak samples contain a medium component in addition to the fast and several slow
358 components. However, the medium component may exhibit unwanted luminescence
359 characteristics (Wintle and Murray 2006; Bailey 2010); thus, it should be separated from the
360 OSL signal. To better separate the fast component in our quartz samples, we applied green
361 stimulated OSL (Bailey et al., 2011). The OSL signal was measured at 125° C for 40 s following
362 a preheat at 260 ° C for 10 s. The test dose was measured following a cut heat at 220 ° C.

363 Additionally, for 30 aliquots of one sample (Mk17-6), we tested the dependence of the
364 equivalent dose on the signal integration times (Figs. S4), to determine whether our choice
365 for the signal integral may have biased the final D_e . The Figs. S4 illustrated that an appropriate
366 channel integration (believed to be represented by a plateau) varies from one sample to
367 another (Figs. S4). Therefore, we determined the individual D_e values for each aliquot using

368 the best channel integral, which lies in the plateau. Then we compared the average of the so
369 determined D_e with the various channel integration, with the average value of D_e determined
370 after applying the channel integration limit of 1-45 to all aliquots. While single D_e values may
371 vary with the chosen signal integral, averaged results derived for different signal integrals
372 provide values indistinguishable from 1% of unity, justifying the finally applied signal channel
373 range for GSL of 1–45 (7.2 s) and 280–399 (19.2 s) for the background. Additionally, the test
374 indicates that any medium component does not affect our final D_e s.

375 **3.5.3. SAR protocol parameters**

376 The SAR protocol was applied to determine the D_e for multi-grain aliquots of quartz. Five
377 regenerative points, approximately 31 Gy, 61 Gy, 122 Gy, 245 Gy and 490 Gy, were used to
378 construct the dose-response curves. The test dose was set to 31 Gy. The recuperation ratio
379 after delivering a zero dose was always below 5%. The first regenerative dose after the
380 recuperation test was used to check the efficiency of correction for sensitivity change
381 (recycling ratio). The recycling ratio was not taken into account as a rejection criterion
382 following Thomsen et al. (2016) and Guérin et al. (2015). However, we calculated the average
383 of the recycling ratio for each sample; the minimum and the maximum were 0.85 ± 0.7 and
384 1.02 ± 0.12 , respectively. The possibility of contamination with feldspar was examined by
385 applying the IR depletion ratio test (Duller 2003). This ratio was within 10 % of unity for all
386 samples. Therefore, we observed no significant evidence for a feldspar contamination of our
387 quartz samples. Typical TL curves, green stimulated shine-down curves, and corresponding
388 dose-response curves are shown for sample Mk17-1 as an example in Fig. S6.

389 The preheat temperature was varied in order to check the independency of the D_e from this
390 parameter (preheat plateau test). The result of typical preheat plateau for one sample (Mk16-
391 1) is shown in Fig. S5A. Each point represents the average of equivalent dose (D_e) for six
392 aliquots for the temperature ranges of 220 °C to 280 °C (20 °C steps). We selected 260 °C as
393 the preheat temperature for the SAR protocol since it was located in the middle of the
394 plateau.

395 Additionally, we performed a dose-recovery test on six aliquots of sample Mk15-5 (Fig. S5B).
396 The aliquots first were bleached for 100 s with a blue light at room temperature in the reader
397 to empty the natural luminescence signal. This was followed by a 10,000 s pause that allows

398 the decay of the 110°C peak (Wintle and Murray, 2006). The samples were then bleached for
399 a second time to deplete charges in the fast component related trap, potentially transferred
400 from the shallow 110°C trap during the pause. Finally, samples received a beta-dose of 111
401 Gy (close to the expected equivalent doses), and the SAR protocol was applied. The mean
402 recovered dose based on the measurement of six aliquots was 100 ± 5 Gy. Therefore, the
403 dose-recovery ratio was 0.90 ± 0.04 , which was consistent with unity and validated the chosen
404 SAR protocol parameters. We assumed similar behaviour for the rest of the samples; thus, we
405 applied the SAR protocol with the same parameters to all samples.

406 For the conventional data analysis, we employed the software *Analyst* (Duller, 2015; v4.53)
407 for determining the D_e . An exponential plus linear function was used for the dose-response
408 curve fitting. Selection criteria for the aliquot were based only on the relative uncertainty of
409 the first (natural) test signal, fixed to $< 20\%$, following Thomsen et al. (2016) and Guérin et al.
410 (2015).

411 We used the arithmetic mean to determine the palaeodose and the standard deviation of the
412 mean is calculated for representing the uncertainty on each palaeodose (Table 2). Except for
413 palaeodoses of samples M15-1 and Mk15-4 that are less than 3 Gy, the determined
414 palaeodoses for the rest of the samples laid between 76 Gy to 216 Gy (Table 2).

415 For the feldspar samples, the pIRIR₂₉₀ protocol (Thomsen et al., 2008; protocol settings after
416 Buylaert et al., 2012) was applied to five samples from the east trench, one sample from the
417 south trench, as well as five samples from the north trench and one sample from the
418 clandestine pit (S2). Typical TL curves, infrared light stimulated shine-down curves, and
419 corresponding dose-response curve from the pIRIR₂₉₀ signal are shown for sample Mk16-3.
420 Following quartz data treatments, here the palaeodoses are determined using the arithmetic
421 mean, and their uncertainties show based on standard deviation of the mean. Except for the
422 samples Mk15-1 and Mk15-4 for which the determined palaeodoses are less than 8 Gy, the
423 palaeodoses of the rest of the samples fall between 113 Gy to 454 Gy (Table 2). The Abanico
424 plots for illustrating the distribution of the D_e and their uncertainties for one sample (Mk16-
425 3) are provided for both green OSL on quartz and infrared light on feldspar (Fig. S8).

426 3.6. Bayesian chronology using ‘BayLum’

427 The Bayesian modelling was carried out using the R (R Core Team, 2019) package ‘BayLum’
428 (Philippe et al., 2018; Christoph et al., 2019). For the calculation process, we used a multi-core
429 workstation where subfolders were created containing the required input information, i.e.
430 BIN/BINX-files, the reader dose rate, the environmental dose rate, as well as the position of
431 the selected aliquots. The function *AgeS_Computation()* was applied to provide the
432 chronology for several samples, including information on the stratigraphic order. For our
433 study, the dose-response curves were fitted with an exponential plus linear equation through
434 the option *LIN_fit = TRUE*. Then the argument *distribution = c("gaussian")* was used to assume
435 a Gaussian distribution for the palaeodose for each sample (based on the study by Heydari
436 and Guérin, 2018). The argument *priorAge* allows including pre-knowledge about ages of the
437 sample before running the measurements.

438 Moreover, the stratigraphic order can be imposed on the data by calling the function
439 *StratiConstraints()*. The function called *create_ThetaMatrix()* helps to express and address the
440 systematic shared uncertainties between the samples. After determining the Bayesian
441 chronology, the *plot_Scatterplots()* function can be used to create bivariate plots of age
442 densities for every two samples. These plots illustrate the correlation between samples
443 caused by the shared systematic uncertainties.

444 The applied R script, as well as the convergence plots of the Monto Carlo Markov Chain
445 (MCMC) sampler are provided in the supplementary material (Sec. S5.1 and S5.3). To reach
446 convergence, 4,000,000 iterations were employed on the thirteen samples of the eastern
447 trench. The calculations were run on a local multi-core workstation. Depending on the setting,
448 each calculation took roughly a week.

449 3.6.1. Theta matrix

450 To address shared systematic uncertainty, ‘BayLum’ applies the basic statistical concept of a
451 covariance matrix in the form of a so-called Theta (Θ) matrix. Diagonal elements of the matrix
452 refer to the systematic and individual (statistical) uncertainty mainly on the dose-rate
453 estimation as well as the systematic uncertainty on the determined palaeodose of each
454 sample and non-diagonal elements of this matrix refer to the systematic uncertainty shared

455 between two samples, or in other words, it shows the correlation between them (Combès
456 and Philippe, 2017).

457 The source of the systematic uncertainty for our study is dominated by uncertainties in the
458 concentration of U, K and Th (which are used for calibration of the gamma-ray
459 spectrometers), the uncertainty on the internal-dose rate (the same value is applied to all
460 samples) as well as the uncertainty on the beta-source dose rate in the OSL reader. We detail
461 the background of the Theta (Θ) matrix and how it can be created in 'BayLum' after Guèrin et
462 al. (in prep.) for readers not familiar with this topic in the supplement (see Sec. S4). A
463 dedicated function to create the Theta matrix in R (*create_ThetaMatrix()*) was written for this
464 study and is now part of 'BayLum'.

465 4. Results

466 4.1. Comparison of quartz and feldspar ages derived by frequentist approach

467 Figures 5a–b show the ages determined with the frequentist statistic from feldspar and quartz
468 for the north and the east trenches respectively within 2σ uncertainty (95% confidence
469 interval). Both quartz and feldspar ages increase with depth. However, the feldspar ages are
470 systematically older than the quartz ages. The top of the north trench starts with the quartz
471 ages of samples Mk15-1 and Mk15-4, which are [0.4–0.8] ka and [0.8–1.6] ka, respectively.
472 The quartz ages of samples Mk15-5 and Mk15-6 ([25–31] ka, [24–32] ka) are in agreement
473 with the corresponding feldspar ages of [29–36] ka and [29–34] ka, respectively. The feldspar
474 ages determined from samples Mk15-8 and Mk15-7 ([46–52] ka, [64–78] ka) are significantly
475 older than the associated quartz ages ([33–41] ka, [44–56] ka). The quartz ages from the east
476 trench start from the top with sample Mk17-3, [21–26] ka, and increase gradually with depth,
477 ending up with sample Mk17-10, which represents the oldest age of the whole sequence, at
478 [55–74] ka. Here also the feldspar ages are older than the quartz ages. The feldspar ages for
479 samples Mk16-6, Mk16-4, Mk16-1 (the only sample from the south trench) and Mk16-2 are
480 between 30 % to 70 % older than the quartz ages. The feldspar ages of samples Mk16-5 and
481 Mk16-3 are not only two times older than the quartz ages, but also the dispersion between
482 the aliquots is much higher than for the rest of the pIRIR₂₉₀ ages. An Abanico plot (Dietze et

483 al., 2016) is used to illustrate the dispersion in quartz and pIRIR₂₉₀ palaeodose distributions
484 for sample Mk16-3, as an example (Fig. S8).

485 This discrepancy between the quartz and feldspar ages may be explained by the different
486 bleaching rates of the OSL quartz in comparison to the pIRIR₂₉₀ signal (~100 s vs ~1,000 s;
487 Murray et al., 2012). We know that the geological units 4 down to 8 are part of an alluvial
488 deposit. Units 4, 6 and 8, in particular, have repetitively experienced flood events. The
489 turbidity of the water during the flood may have caused insufficient bleaching of the feldspar
490 grains on the top of the, potentially, short light exposure due to the high transport energy.
491 The observed discrepancies between the feldspar ages and the quartz ages especially for
492 samples Mk16-5 and Mk16-3, which are taken from units 6 and 8 may be attributable to such
493 rapid sediment transport process. Guérin et al. (2015) reported a similar observation where
494 feldspar grains suffer from insufficient bleaching, but quartz grains are believed to be
495 bleached completely, showing age's consistency with the ¹⁴C age control. Here we do not
496 have any independent age control. However, we have no indication that the quartz ages are
497 unreliable, contrary to the feldspar ages which are likely to be overestimated.

498 4.2. Unravelling the Bayesian chronology

499 Bayesian modelling was investigated on samples from the east trench. The aim of this
500 investigation was to apply different options available in the 'BayLum' package to our dataset
501 and compare and discuss the obtained chronologies to highlight the effect of each of these
502 options. We defined four modelling scenarios. In **scenario I**, we ran the Bayesian model
503 without considering any stratigraphic constraints and without any input for the Theta matrix.
504 Henceforth, we call this scenario the *simplistic* Bayesian model (Fig. 6a). In **scenario II**, we add
505 the correlation between samples, i.e. taking the Theta matrix into account (Fig. 6b). Contrary,
506 in **scenario III** the Bayesian model was applied to the samples considering the stratigraphic
507 constraints, but without any inference on the statistical correlation between the samples (no
508 Theta matrix; Fig. 6c). Finally, in **scenario IV**, we considered the stratigraphic order in
509 conjunction with the Theta matrix to address the correlation between the samples (Fig. 6d).
510 We plot the frequentist chronology alongside the four Bayesian chronology scenarios (Figs.
511 6a–d). The estimated ages are quoted in a 95% confidence interval for the frequentist
512 approach and a 95% credible interval for the Bayesian approach. The point in the credible

513 interval (Fig. 6) corresponds to the highest probability density (HPD) estimation, i.e. the Bayes
514 estimate in Bayesian approach and the point in the middle of the confidence interval
515 corresponds to the average of the distribution in the frequentist approach.

516 **4.2.1. Scenario I**

517 The results of the simplistic Bayesian model do not indicate significant discrepancies for the
518 most of the samples compared to the frequentist approach obtained (Fig. 6a). The average in
519 the frequentist approach and the HDP in Bayesian do not differ by more than 2 % while the
520 uncertainties of the Bayesian estimates are reduced compared to the frequentist estimates.
521 This uncertainty reduction is significant only for samples Mk17-1 and Mk17-5 (reduction by
522 26 % and 41 %, respectively).

523 **4.2.2. Scenario II**

524 Figure 6b shows almost complete agreement between the frequentist chronology and the
525 Bayesian model when the Theta matrix (only) is considered. The only exception is sample
526 Mk17-5 for which the Bayesian model leads to a roughly 30 % reduction in the credible
527 interval in comparison with the confidence interval.

528 **4.2.3. Scenario III**

529 Figure 6c presents the Bayesian chronology applying the stratigraphic constraint with no
530 consideration of the correlations between the dose rates or equivalent dose estimates. The
531 most striking observation is the significant reduction of the uncertainty for the Bayesian
532 estimates. We observed reductions of 24 % to 53 % in uncertainty for the set of samples
533 located at the beginning of the sequence (Mk17-3 to Mk 16-5). At the bottom of the
534 sequence, sample Mk16-3 showed a 33 % uncertainty reduction. There appears to be no
535 significant change of the centre of the intervals: the Bayesian HPDs for samples Mk17-3,
536 Mk17-2, Mk17-1 and Mk16-5 were between 3 % to 7 % younger than the corresponding
537 averages, while, on the contrary, Bayesian HDPs of samples Mk16-6, Mk17-6, Mk16-4 and
538 Mk16-3 were 4 % to 11 % older in comparison to the frequentist averages.

539 **4.2.4. Scenario IV**

540 The last plot (Fig. 6d), which refers to the application of stratigraphic order and correlation
541 between samples (Theta matrix) results in a reduced credible interval from 5% (Mk17-10) up

542 to a maximum of 33 % (Mk17-1) compared to the confidence intervals. Moreover, for five
543 samples (out of 13), the Bayesian ages moved towards the older ages (up to 14%) in
544 comparison to the frequentist ages. The Bayesian age for one sample (Mk17-1) is younger
545 than the frequentist age by 6%. For the rest of the samples, the Bayesian ages render almost
546 the same ages as frequentist approach.

547 **4.2.5. Further results**

548 Figure 7 shows the bivariate plots of the probability densities for the age estimates. Each point
549 corresponds to the estimated ages for two samples as sampled from the MCMC. We indicated
550 the bivariate plots only for five samples. For the complete plots containing all of the samples,
551 we refer to the supplementary material (Figs. S11–S13). Figure 7a shows the results after
552 applying the *simplistic* Bayesian model (scenario I). The Mk17-3 is the youngest sample and
553 Mk17-7 is the oldest one. The symmetric shape of the distribution is almost present for all the
554 plots, which indicates no specific correlation between the samples. Figure 7b is related to
555 Fig. 6c where the stratigraphic constraints affect the final chronology, but neither the
556 correlation within the dose-rate data nor within the equivalent-dose data (scenario III) were
557 considered. For some of the plots, we observed a truncation in the top-left corner letting the
558 distribution appear asymmetric. For instance, the bivariate plots of two ages like Mk17-
559 3/Mk17-2, Mk17-2/Mk16-6, Mk17-1/Mk17-7 and Mk17-3/Mk16-6 are truncated. The last
560 bivariate plots are displayed in Fig. 7c, where both, the stratigraphic correlations and the
561 correlations on the systematic errors are considered (scenario IV). In this figure, all bivariate
562 plots appear graphically in a prolate shape and show a similar truncation to the one observed
563 in Fig. 7b.

564 **5. Discussion**

565 **5.1. Improvement of the precision**

566 Besides the rough comparison between frequentist chronology and different Bayesian
567 modelling scenarios in the previous section, here we present the kernel density distributions
568 of the relative uncertainties for all scenarios to visualise the changes in the obtained age
569 uncertainties (Fig. 8). All these distributions (except for scenario II) illustrate uncertainties
570 smaller for the Bayesian scenarios than with the frequentist approach, as observed in Sec. 4.

571 Moreover, the two models that employ stratigraphic constraints (scenarios III and IV) show
572 the lowest relative uncertainty in comparison to the frequentist results. To determine
573 whether these results are also statistically significant, we performed a one-sided paired Welch
574 *t*-test with the results listed in Table 3. For a significance level of 0.01, all scenarios except
575 scenario II exhibit that the uncertainty distribution has a statistically lesser mean than the
576 frequentist results, *i.e.* the OSL ages calculated with 'BayLum' are more precise than those
577 calculated with the conventional approach. Although, the rough comparison between
578 Bayesian and frequentist chronology for scenario I appeared to not to be considerable (see
579 section 4.2.1).

580 With regard to the initially formulated objective (2) (see Sec. 1) of our work, it appears that
581 we must reject H_0 . Thus, applying Bayesian models results in a chronology distinguishable
582 from the frequentist approach. Nevertheless, this conclusion alone allows no statement
583 about the best suitability of a particular scenario and why results differ between the
584 scenarios.

585 5.2. **Bayesian chronology: stratigraphic order and the correlation between samples**

586 While the different scenarios were proposed in order to unravel the effect of stratigraphic
587 constraint and statistical correlation, it must be emphasized that scenario III, while it shows
588 the best improvement of the precision, is inappropriate for discussing the final chronology
589 due to not considering the existing correlation between the data (Fig. 7c). For example, the
590 plot with samples Mk17-1 and Mk17-7 shows a strong positive correlation, *i.e.* if the age of
591 sample Mk17-1 is getting older, the age of sample Mk17-7 is likely to get older likewise.
592 However, this correlation is not observed in Fig. 7b, since scenario III does not take into
593 account correlations between the data. The Bayesian model in that scenario treats all of the
594 errors as random. Therefore, particularly when the ages of the two successive (in the
595 stratigraphy) samples overlap one another, the model reduces the uncertainty to satisfy the
596 stratigraphic order. In other words, such a model has the highest impact in the absence of
597 systematic shared uncertainty where samples do not correlate but overestimate the
598 precision.

599 Consequently, to address properly the effect of the stratigraphic order for our data (which
600 include systematic shared uncertainties), the Theta matrix should be applied and scenario III

601 cannot be considered. However, if the systematic error is added to the result of this scenario,
602 then the result can be considered following Rhodes et al. (2003).

603 5.3. **Bayesian chronology: effect of stratigraphic order and the question of accuracy**

604 It was shown that scenarios III and IV result in a considerable reduction in the age
605 uncertainties in comparison with the results obtained using the frequentist approach. Both
606 these Bayesian models take the stratigraphic order into account. Figures 6c–d display that the
607 maximum reduction in the uncertainties observe from sample Mk16-6 to Mk16-4 where their
608 confidence intervals overlap one another. The frequentist age of sample Mk16-6 does not
609 follow the stratigraphy order, but when the stratigraphic order applies, the credible interval
610 shifts towards the older part of the confidence interval to satisfy the imposed ordering.

611 Consequently, the rest of the samples from Mk17-1 to Mk16-4 which roughly place between
612 24–29 ka should follow this ordering; thus, the credible intervals decrease significantly in both
613 scenarios. Rhodes et al. (2003) already mentioned that Bayesian modelling might lead to
614 substantial improvements in the precision where the sampling resolution is high enough, so
615 that ages overlap each other. Contrary, if the age's intervals do not overlap, the Bayesian
616 chronology considering the stratigraphic order does not render results more precise than the
617 frequentist chronology (see for example the Bayesian ages of samples Mk16-2 and Mk17-10
618 in Figs. 6c–d). Moreover, Figs. 6c–d show that part of the obtained frequentist-age intervals
619 are 'discarded' when the stratigraphic order is imposed. For instance, for sample Mk17-6,
620 more than 50 % of the uncertainty interval is 'eliminated' pushing the credible interval out of
621 the average of the frequentist model.

622 The same pattern is observed for Mk16-6, where the Bayesian age shifts by 11 % towards an
623 older age. The estimated credible interval does not overlap the first part of the frequentist
624 confidence interval and results in a smaller uncertainty (38 % reduction) in comparison with
625 the frequentist approach.

626 This shift towards older ages almost affects the entire dataset; thus, result in the ages, which
627 are older or younger than frequentist ages (see Mk16-4, Mk17-4, Mk16-3).

628 Therefore, in particular scenarios, stratigraphic constraints should be applied with caution
629 since they affect all age estimates within a sequence. In other words, here, it is not only the

630 question of precision, but also the question of accuracy that matters when the application of
631 such a model is attempted.

632 5.4. **Technical issues**

633 The ideal way to address systematic uncertainty with Bayesian modelling is a rigorous
634 experimental design, using one well-known instrument each, for estimation of the
635 palaeodose and the dose rate. Unfortunately, experimental reality proves differently. For our
636 measurements, which were carried out over more than two years, different OSL readers were
637 employed (Freiberg Instruments *lexsyg SMART* and *research* readers, see above) limited by
638 the technical availability of the machines. The systematic uncertainty from the source-dose
639 rate of the OSL readers varies typically between 2 % to 3 %, or even more (see discussion in
640 Tribolo et al., 2019). However, it is also not clear whether the dose source uncertainty affects
641 the entire ages toward one direction (higher or lower value). It can result in higher dose in
642 one machine but lower in another. Nevertheless, in our case, the systematic errors are
643 correlated since we used the same calibration standard for the calibration of the OSL reader
644 sources.

645 Furthermore, it should be noted that variations of the systematic error could also occur if only
646 one machine was used. For our modelling, we applied a 2% systematic uncertainty, and we
647 provided the Theta matrix based on that value. Additionally, we also provide the Theta matrix
648 with 3% uncertainty on the source-dose rate (OSL reader) and compare the Bayesian
649 chronology of both (2% vs 3%; see supplement Fig. S15 and Table S1–S2). Our results suggest
650 that both values, for our samples and our assumptions, result in plots indistinguishable from
651 each other and the minor differences are likely being introduced by the stochastic process
652 itself, which indicates that the application of our modelling was generally justified. Similarly,
653 we employed two different gamma-ray spectrometers in our lab to estimate the radionuclide
654 concentration; however, we consider the differences in the systematic errors between both
655 systems negligible in particular due to the used identical material for the calibration of those
656 spectrometers.

657 **5.5. Further remarks**

658 The entire dataset from the Late Pleistocene geological units consist of thirteen samples from
659 the east trench, 3 samples from the north trench, one sample from the southern trench, and
660 finally, one sample from the clandestine pit known as S2.

661 Since the stratigraphic relationship between the different trenches is not consistent, we
662 applied Bayesian models separately on the samples from the east and the north trenches; the
663 later results are shown in the supplementary material (Figs. S9-S10).

664 Our observation showed that the Bayesian model in scenario IV results in more precise
665 chronology compared to the frequentist model. For the final archaeological age
666 interpretation, we present and discuss the results from scenario IV alongside the frequentist
667 chronology.

668 **5.6. The obtained chronology in the prehistoric context**

669 One of our aim for this study was to provide a chronology for Upper, Intermediate and
670 Middle Palaeolithic assemblages in the open-air site of Mirak.

671 The Bayesian and the frequentist age of sample Mk15-5 from the north trench, which
672 originated from the Upper Palaeolithic assemblage layer (level 1; geological unit 4a), results
673 in [25–28] ka and [25–31] ka, respectively. In the east trench, four samples (Mk17-3, Mk17-
674 2, Mk16-6, Mk17-1) were taken from the layer containing the Upper Palaeolithic
675 assemblage (level 1; geological units 3a and 4a). The Bayesian ages of those samples are
676 [21–25], [22–26], [23–26] and [25–28] ka while the frequentist results give [21–26], [22–27],
677 [19–24] and [26–30] ka. Hence, the Upper Palaeolithic occupation of Mirak is defined by the
678 samples lying between [21–28] ka (95 % credible interval, Bayesian approach) and [19–31]
679 ka (95 % confidence interval, frequentist approach). The geographical nearest Upper
680 Palaeolithic site to Mirak for which an absolute chronology is available is Garm Roud 2. This
681 site is located in the southern foothills of the Alborz mountains in the province Mazandaran
682 (Berillon et al., 2007; Berillon and Asgari Khaneghah, 2016). Radiocarbon dating results for
683 the site of Garm Roud 2 yielded [28–35] cal. ka BP (Antoine et al., 2016) which seems to be
684 slightly older than Bayesian and frequentist chronology for the Upper Palaeolithic layer of
685 Mirak; although the frequentist age interval overlap with the determined age interval of the
686 site of Garm Roud 2. However, the Bayesian approach leads to a more precise chronology in

687 comparison to the frequentist approach. Interestingly, our results from Mirak, like those for
688 the site of Garm Roud 2, exhibit ages for the Upper Palaeolithic that are younger than the
689 reported ages of the same period for the Zagros region. Indeed, ^{14}C dating has been applied
690 on the Upper Palaeolithic period of various sites, such as Shanidar cave in the north of
691 Zagros foothills which resulted in [29–40] cal. ka BP (original data: Solecki 1963; Hole and
692 Flannery, 1968; recalculated data: Becerra-Valdivia et al., 2017; Ghasidian et al., 2019). ^{14}C
693 dating was also applied for the Kaldar cave in central Zagros (Bazgir et al., 2017; [37–54] cal.
694 ka BP), Yafteh cave in the west-central Zagros (Otte et al., 2011; [29–42] cal. ka BP), and
695 Ghāre-Boof in the southern Zagros (Ghasidian, 2014; Becerra-Valdivia et al., 2017; [35–42]
696 cal. ka BP). The geographical location of the mentioned sites is shown in Fig. 1B. The
697 temporal period, engulfing all of these four age ranges is around [35–40] cal. ka BP, which
698 renders an earlier Upper Palaeolithic occupation than presumed for Mirak ([21–28] ka).
699 However, the chronology of Mirak aligns better with the chronology of Garm Roud 2 (south
700 of Alborz). Although, it is worth mentioning that the concentration of the lithic artefacts
701 attributable to the Upper Palaeolithic period is very scarce in Mirak, the younger Upper
702 Palaeolithic chronologies for the Central Alborz region (Mirak and Garm roud2) in
703 comparison with the chronologies of Upper Palaeolithic assemblages in the Zagros echo
704 some temporal differences between the two areas, which may be also translated into
705 cultural variabilities (Berillon et al., 2007; Chevrier in Berillon et al., 2016; Vahdati Nasab et
706 al., 2019).

707 The intermediate assemblage (level 2, east trench; Fig. 3) appears to be spread over two
708 sub-layers in Mirak, which raises the question of the existence of two distinct assemblages.
709 Indeed, the preliminary study of the lithic material of this layer highlighted a mix of Upper
710 and Middle Palaeolithic affinities that potentially characterise a transitional phase likely
711 related to early Aurignacian industries of the Zagros (Vahdati Nasab et al., 2019). One issue
712 was thus to know based on a refined chronology whether these apparent sub-layers
713 correspond to 2 distinct occupations; and if so, our interpretation of this apparently mix
714 assemblage should be reconsidered. The Bayesian and the frequentist age of sample Mk17-
715 7, which was taken from the top of sub-layer 1 (geological unit 4b), result in [25–28] ka and
716 [24–29] ka. The Bayesian and the frequentist ages of sample Mk17-6, which was taken
717 directly from sub-layer 1 (geological unit 5), result in [26–29] ka and [22–28] ka,

718 respectively. Moreover, the ages of Mk16-4 and Mk17-5, which were taken from the sub-
719 layer 2 (geological unit 5), yield to [26–30] ka and [28–33] ka for the Bayesian, and [24–29]
720 ka and [27–34] ka for the frequentist model. The Bayesian ages of samples Mk16-5 and
721 sample Mk17-4 from the geological unit 6, just below the sub-layer 2, result in [32–38] ka
722 and [34–40] ka while the frequentist ages yield [31–39] ka and [33–39] ka.

723 In summary, the Bayesian age for the sub-layer 2 in 95 % credible interval frames [26–33] ka
724 and the frequentist age results in [24–34] ka (95 % confidence interval). Here again the
725 Bayesian approach leads to smaller uncertainties in comparison with the frequentist
726 approach providing a more precise age. Moreover, the Bayesian age for sub-layer 1 [26–
727 29] ka agrees to the [26–30] ka (sample Mk16-4) in sub-layer 2. Therefore, it appears likely
728 that the two sub-layers relate more or less to one another and should be considered as a
729 single archaeological assemblage; this interpretation reinforces the hypothesis of the
730 existence in Mirak of an intermediate phase between Middle and Upper Palaeolithic periods
731 (Vahdati Nasab et al., 2019) which may be seen as transitional. However, this finding does
732 not indicate an occupation by a single group of people. The MIS 3 is a period with
733 millennial-scale fluctuations in climatic-environmental regime at the global and regional
734 scales (e.g., Bond et al. 1997; Dansgaard et al. 1993; Heinrich 1988; Wolff et al. 2010;
735 Mehterian et al. 2017; Vlaminc 2018) and thus, the site may have been frequently
736 abandoned and reoccupied during the age-ranges (Hashemi et al. 2018). In addition, the
737 results for the intermediate layer indicate that, despite some cultural differences, this layer
738 features a close chronology with that of the layer 1 allocated to the Upper Palaeolithic [21–
739 28] ka. Interestingly, the Bayesian age of [28–33] ka, which is the oldest age from sub-layer
740 2, agrees with the age of [28–35] ka cal. BP for the Upper Palaeolithic assemblages of the
741 open-air site of Garm Roud 2. Our results thus imply that the chronological interval of [26–
742 33] ka (comprising sub-layers 1 and 2) in Mirak is most likely an original cultural entity in the
743 region with subsequent and sub-contemporaneous cultures, some with clear Upper
744 Palaeolithic affinities (Mirak layer 1 and Garm Roud 2) and some with mixed characteristics
745 featuring likely a transitional entity (Mirak layer 2).

746 Finally, the Bayesian ages for samples Mk16-2 and Mk16-3, which were taken from the
747 layers that contain the Middle Palaeolithic assemblage (archaeological layer 3; end of unit 7
748 and beginning of unit 8 in the sedimentological log), result in [43–51] ka and [44–55] ka,

749 respectively, while the frequentist ages for these two samples exhibit [42–51] ka and [39–
750 55] ka. Here again, the Bayesian modelling provides ages more precise than the frequentist
751 ages. The determined ages for the Middle Palaeolithic layer of the site Mirak align with the
752 period of Middle-Upper Palaeolithic transition in Shanidar [39–49] cal. ka BP (Becerra-
753 Valdivia et al., 2017) as well as with the Neanderthal occupation layer in the Shanidar Cave,
754 which was dated to ca [46-60] cal. ka BP (Becerra-Valdivia et al., 2017; Solecki and Solecki,
755 1993). However, this age-range is close to the temporal limit of ^{14}C dating and, thus, should
756 be treated cautiously. Our results strengthen the idea of a cultural context that is highly
757 complex in the area, with the potential contemporaneity of Middle and Upper Palaeolithic
758 cultures in some parts of the region (Iranian Plateau) during MIS2 to MIS3 (age-boundaries
759 according to Lisiecki and Raymo, 2005); an hypothesis that needs further investigations and
760 the one which imply the likely contemporaneous presence of both Neanderthals and
761 modern humans in the region (see Zeitoun, 2016).

762 6. Conclusions

763 We applied and tested various Bayesian modelling scenarios to the chronological samples
764 taken from the east and north trenches of the open-air Palaeolithic site of Mirak and
765 presented the results of each model. Additionally, we provided the first complete numerical
766 chronology from late Holocene [0.8–1.6] ka (samples Mk15-1 and Mk15-4) to late Pleistocene
767 [56–73] ka (Bayesian age of oldest sample Mk17-10) for the site of Mirak in Iran. We conclude
768 that:

- 769 - Our study suggests that Bayesian modelling generally results in a statistically
770 significant improvement of the age precision (except scenario II), which discards our
771 initially formulated H_0 (scenario I and scenario IV). The best improvement was
772 achieved when the uncertainty of the samples overlap one another (scenario IV).
773 However, applying stratigraphic relationship to the model results in strong impact on
774 the final ages; therefore, for such a case the stratigraphic ordering should be
775 understood clearly which otherwise it leads to age under- or over-estimations.
- 776 - Although providing the Theta matrix addresses systematic errors, in the absence of
777 independent chronologies, with a higher temporal resolution than luminescence

778 dating (e.g., ^{14}C dating), it does not result in improved chronological precision and the
779 obtained result is almost indistinguishable from the frequentist approach (scenario II).
780 - The Bayesian chronology for the Upper Palaeolithic occupation of the site of Mirak is
781 attributed to [21–28] ka. The Bayesian chronology for the intermediate layer, provides
782 the age of [26–29] ka for sub-layer 1 and the ages of [26–33] ka for the sub-layer 2.
783 Therefore, based on our chronology, it is highly probable that the two distinct sub-
784 layers can be considered as a one individual layer with the age of [26–33] ka. The
785 Bayesian chronology for Middle Palaeolithic assemblage result in [43–55] ka.

786

787 In summary, based on our observations, it appears that the advantages of Bayesian modelling
788 have the strongest impact when a stratigraphic order is applied to the samples for which age
789 uncertainties overlap. Hence, in the absence of explicit stratigraphic constraints, applying the
790 frequentist approach may be favoured compared to the time-consuming and error-prone
791 Bayesian modelling (over several weeks on a multi-core workstation). However, it should be
792 mentioned that for this study, we did not access ^{14}C dating as an independent age control of
793 the site. Such combination can be the topic of future work. Although Bayesian ages provide
794 smaller age intervals compared to ages obtained by the frequentist approach, in a prehistoric
795 context, the determined ages from both approaches lead to a similar interpretation. Both
796 approaches provide valuable chronological evidence that Late Pleistocene Humans frequently
797 used the site of Mirak during MIS 3 and 2. However, fluctuations in climatic-environmental
798 characteristics on continental and regional scales likely impacted the site of Mirak (e.g.,
799 oscillations between arid and semi-arid landscapes; Dennell (2017)). Therefore, human
800 groups most likely lived in the region in temporally-discontinuous fashion. Further
801 investigation is needed to shed light on the issue of millennial- and larger-scale fluctuations
802 in climate and their impacts on the regions such as the Iranian Central Plateau during late
803 Pleistocene.

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822

823 **Table 1:** Environmental dose rates

824

Sample name	K (%)	σ	U Top (ppm)	σ	U Bottom (ppm)	σ	Th (ppm)	σ	water content (%)	σ	Beta (Gy/ka)	Σ	Gamma (Gy/ka)	σ	Cosmic (Gy/ka)	σ	Quartz total (Gy/ka)	σ	Feldspar total (Gy/ka)	σ
Mk15-1	1.26	0.01	1.91	0.06	2.10	0.02	4.67	0.04	9	4	1.20	0.04	0.70	0.02	0.22	0.02	2.18	0.05	2.51	0.07
Mk15-4	1.41	0.02	2.02	0.08	2.37	0.02	5.18	0.05	6	3	1.37	0.03	0.80	0.01	0.16	0.02	2.39	0.05	2.72	0.07
Mk15-5	2.16	0.02	2.27	0.09	2.60	0.02	8.76	0.08	9	4	1.96	0.06	1.13	0.03	0.15	0.02	3.29	0.07	3.62	0.09
Mk15-6	2.06	0.03	2.07	0.17	4.00	0.05	9.36	0.12	6	3	1.97	0.05	1.21	0.02	0.14	0.02	3.37	0.06	3.70	0.08
Mk15-7	2.10	0.02	2.31	0.06	2.89	0.02	9.25	0.06	13	5	1.87	0.08	1.12	0.03	0.12	0.02	3.16	0.09	3.49	0.10
Mk15-8	1.81	0.02	2.57	0.12	9.42	0.06	7.08	0.07	4	1	2.04	0.03	1.39	0.02	0.20	0.02	3.69	0.05	4.02	0.07
Mk16-1	1.72	0.02	2.05	0.07	1.75	0.02	6.68	0.05	2	1	1.65	0.02	0.92	0.01	0.16	0.02	2.78	0.04	3.14	0.05
Mk16-2	1.73	0.02	1.93	0.09	1.95	0.02	6.93	0.07	10	5	1.53	0.07	0.88	0.03	0.16	0.02	2.63	0.08	2.99	0.08
Mk16-3	2.24	0.02	2.42	0.09	2.94	0.02	9.41	0.08	13	5	1.94	0.08	1.16	0.04	0.16	0.02	3.32	0.10	3.68	0.10
Mk16-4	1.66	0.02	1.98	0.08	2.41	0.02	6.49	0.06	2	1	1.65	0.02	0.97	0.01	0.17	0.02	2.84	0.04	3.20	0.05
Mk16-5	1.97	0.02	2.19	0.08	2.78	0.02	7.08	0.06	6	3	1.83	0.04	1.06	0.02	0.17	0.02	3.12	0.06	3.48	0.06
Mk16-6	2.18	0.02	2.24	0.10	3.39	0.03	9.15	0.08	4	2	2.08	0.04	1.23	0.02	0.20	0.02	3.57	0.05	3.93	0.06
Mk17-1	2.07	0.04	2.39	0.19	2.24	0.04	8.55	0.12	2	1	2.01	0.03	1.15	0.01	0.20	0.02	3.42	0.05	3.78	0.06
Mk17-2	2.10	0.03	2.44	0.16	2.32	0.03	8.62	0.10	3	1	2.02	0.03	1.16	0.01	0.20	0.02	3.44	0.05	3.80	0.06
Mk17-3	2.12	0.03	2.41	0.17	2.80	0.04	8.78	0.11	2	1	2.10	0.03	1.24	0.01	0.20	0.02	3.60	0.05	3.96	0.06
Mk17-4	1.87	0.03	1.80	0.19	4.30	0.06	7.01	0.12	6	2	1.77	0.05	1.06	0.02	0.17	0.02	3.05	0.06	3.41	0.07
Mk17-5	1.60	0.03	2.14	0.15	3.13	0.04	6.14	0.09	3	1	1.61	0.03	0.96	0.01	0.17	0.02	2.79	0.05	3.15	0.05
Mk17-6	1.83	0.03	2.30	0.18	2.45	0.04	7.34	0.11	3	1	1.80	0.03	1.05	0.01	0.18	0.02	3.09	0.05	3.45	0.06
Mk17-7	2.03	0.04	2.38	0.19	2.79	0.04	8.26	0.12	4	1	1.97	0.04	1.16	0.02	0.18	0.02	3.37	0.05	3.73	0.06
Mk17-10	2.32	0.04	3.28	0.22	2.60	0.04	12.45	0.15	19	8	1.95	0.11	1.20	0.05	0.14	0.02	3.35	0.13	3.75	0.13

825

826 **Table2:** The estimated luminescence ages based on the frequentist approach

Sample name	Quartz				Feldspar			
	De (Gy)	σ	Age (ka)	Σ	De (Gy)	Σ	Age (ka)	σ
Mk15-1	1.2	0.2	0.6	0.1	4.4	0.3	1.7	0.1
Mk15-4	2.9	0.4	1.2	0.2	7.6	0.3	2.8	0.1
Mk15-5	92	4	28	1	118	4	32	2
Mk15-6	95	6	28	2	116	3	31	1
Mk15-7	159	6	50	3	249	9	71	4
Mk15-8	135	6	37	2	197	4	49	2
Mk16-1	114	6	41	2	179	9	57	3
Mk16-2	123	4	47	2	193	8	65	3
Mk16-3	156	11	47	4	454	52	123	15
Mk16-4	76	3	27	1	144	10	45	3
Mk16-5	110	5	35	2	258	52	74	15

Mk16-6	77	4	21	1	113	3	29	1
Mk17-1	96	3	28	1				
Mk17-2	83	4	24	1				
Mk17-3	84	3	23	1				
Mk17-4	110	3	36	1	39			
Mk17-5	84	4	30	2	40			
Mk17-6	77	3	25	1	29			
Mk17-7	90	3	27	1	29			
Mk17-10	216	12	64	5	29			

827

828

829 **Table 3:** Test results Welch one-sided paired *t*-test for relative uncertainty distribution

830

DATASET	SCENARIO	<i>t</i> -value	Df	<i>p</i> -value
East trench	SCENARIO I	-3.347	12	2.91E-03*
East trench	SCENARIO II	-1.732	12	5.45E-02
East trench	SCENARIO III	-6.709	12	1.08E-05*
East trench	SCENARIO IV	-7.442	12	3.91E-06*

831 * Statistically significant to a significance value of 0.01

832 H_0 : this scenario has similar or larger mean than the frequentist results (identical or lower
833 precision)

834 H_A : this scenario has a lower mean than the frequentist results (higher precision)

835

836

837 **Figure captions**

838 **Figure 1:** (A) Location of the open-air site Mirak between the Alborz Mountains to the north
839 and the Iranian Central Desert to the south. (B) Location of the Palaeolithic sites mentioned
840 in the text and the site of Mirak. (C) Mirak in the landscape. The red rectangle in (B) displays
841 the enlarged area in (A).

842 **Figure 2:** Synthetic stratigraphic record for the north trench in Mirak (the age of samples
843 Mk15-1 and Mk15-4 were calculated using the frequentist approach only. Figure redrawn
844 with modifications from Vahdati Nasab et al., 2019).

845 **Figure 3:** Synthetic stratigraphic record for the east trench, plus 2D dispersion of the
846 coordinated archaeological finds and the location of luminescence samples in the east
847 trench. Stratigraphic sketches by G. Jamet; 2D picture and projection by G. Berillon).

848 **Figure 4:** Evaluation of the disequilibrium in the decay chain of ^{238}U . The ratio of $^{238}\text{U}(\text{post-}^{226}\text{Ra})/^{232}\text{Th}$ and $^{238}\text{U}(\text{pre-}^{226}\text{Ra})/^{232}\text{Th}$ is shown for all the samples. The ratios for most of
849 the samples are close to the equilibrium line except, MK15-6, MK15-8, MK16-6, MK17-4,
850 and MK17-5.
851

852 **Figure 5:** Comparison of quartz OSL ages with post IR-IRSL 290 °C ages from the north (left
853 plot) (except Mk15-8 from pit S2) and the east (right) sector (except Mk 16-1 from the south
854 trench). All ages are quoted with 2σ uncertainty. The quartz and feldspar ages increase with
855 depth. The discrepancy between the two ages is significant for Mk16-3 (right figure).

856 **Figure 6:** Comparison of the different Bayesian and the frequentist chronologies for the 13
857 quartz samples from the east trench. Top left: Simplistic Bayesian model (for definition, see
858 main text). Top right: Bayesian chronology considering Theta matrix only (for definition,
859 please see the text). Bottom left: Bayesian chronology imposing the stratigraphic order.
860 Bottom right: Bayesian chronology imposing the stratigraphic order and applying the Theta
861 matrix, which addresses systematic shared errors.

862 **Figure 7:** Example of scattering plots (here so-called hexagon plots) for samples Mk17-3,
863 MK-17-2, Mk16-6, Mk17-1 and Mk17-7. The full plots are shown in Figs. S11–S13. The
864 figures illustrate the probability densities of the age estimations for two samples for which

865 the hexagons bin the estimated ages of two samples. a: The bivariate plots of probability
866 densities age estimation with the simplistic Bayesian model. b: applying the stratigraphic
867 constraints. c: applying stratigraphic constraints and modelling systematic error with the
868 Theta matrix. In this last figure, a positive correlation is observed for each plot, which
869 reflects the shared systematic errors. The top left corner truncation in each square
870 illustrates the effect of stratigraphic constraint.

871 **Figure 8:** Kernel density plots comparing relative age uncertainties for the applied modelling
872 scenarios. Here shown are the results for the east trench.

873

874

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