Do Bayesian methods lead to more precise chronologies? ‘BayLum’ and a first OSL-based chronology for the Palaeolithic open-air site of Mirak (Iran)

Maryam Heydari, Guillaume Guérin, Sebastian Kreutzer, Guillaume Jamet, Mohammad Akhavan Kharazian, Milad Hashemi, Hamed Vahdati Nasab, Gilles Berillon

To cite this version:

Maryam Heydari, Guillaume Guérin, Sebastian Kreutzer, Guillaume Jamet, Mohammad Akhavan Kharazian, et al.. Do Bayesian methods lead to more precise chronologies? ‘BayLum’ and a first OSL-based chronology for the Palaeolithic open-air site of Mirak (Iran). Quaternary Geochronology, 2020, 59, pp.101082. 10.1016/j.quageo.2020.101082 . hal-02568013

HAL Id: hal-02568013
https://hal.science/hal-02568013

Submitted on 27 Nov 2020

Do Bayesian methods lead to more precise chronologies? 'BayLum' and a first OSL-based chronology for the Palaeolithic open-air site of Mirak (Iran)

Maryam Heydari[1*], Guillaume Guérin[1], Sebastian Kreutzer[1], Guillaume Jamet[2], Mohammad Akhavan Kharazian[3,4], Milad Hashemi[3] and Hamed Vahdati Nasab[3] and Gilles Berillon[4]

[1]IRAMAT-CRP2A, UMR 5060, CNRS-Université Bordeaux Montaigne, Maison de l'Archéologie, 33607 Pessac cedex, France

[2]GéoArchÉon/UMR CNRS 8591, Laboratoire de géographie physique, 75016 Meudon, France

[3]Department of Archaeology, Tarbiat Modares University, Tehran, Iran

[4]UMR7194 MNHN–CNRS–UPVD/Département Homme et Environnement, Musée de l'Homme, Palais de Chaillot, 75016 Paris, France

**Corresponding author*: mariheyd@gmail.com

Abstract

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

In this paper, for the first time, we present a comprehensive luminescence-based chronology for the Middle-Upper Palaeolithic site of Mirak. The open-air site is located in the northern fringes of the Iranian Central Desert, which is considered to be one of the dispersal corridors for hominins (Neanderthal and modern human) living across Western and Central Asia. We compare chronologies derived by frequentist and Bayesian methods to discuss the effect of stratigraphic order and addressing the correlation between samples due to systematic shared uncertainty. Our investigations indicate that applying the stratigraphic order when age uncertainty overlap one another plays a fundamental role in reducing the uncertainty. The obtained Bayesian chronology considering the stratigraphic order for the layer containing predominately Upper Palaeolithic techno-complex results in [21–28] ka. The age of the intermediate layer is in the range of [26–33] ka, and the lowermost layer containing middle Palaeolithic assemblage gives the age-range of [43–55] ka. These results indicate that Late Pleistocene humans have exploited the site during MIS 2–3. Furthermore, the chronology gives further evidence to the hypothesis that the Iranian Central Plateau served as a frequently used habitat and dispersal corridor for human groups populating Western and Central Asia.

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

1. **Introduction**

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

Generally, two schools of statistics, frequentist (classic) and Bayesian can be applied (e.g., Buck and Millard, 2004). Classic statistical inference 'prefers' reproducible experiments, where the probability of observing an unknown variable is determined after repeated runs under similar conditions (Gelman et al., 2014; Carlin and Louis, 2000). However, such an approach may not be the proper paradigm where *one-off* (non-repeatable) events are the study subjects or where the number of observations is small (Buck and Meson, 2015). Geochronology and archaeological science are the fields in which the classic inference does not always seem to be the most judicious approach to data analysis (Buck and Meson 2015; Buck et al., 1998). This circumstance may be seen as one of the reasons why Bayesian inference has become prevalent. However, to date, classic statistical inference dominates the data treatment in luminescence dating, but Bayesian statistics has gained some attention (e.g., Rhodes et al., 2003; Huntriss., 2008; Zink, 2013; 2015; Combès et al., 2015; Mercier et al., 2016; Philippe et al., 2018). Applying Bayesian modelling potentially prevents information loss between analysis steps by deploying a model that runs simultaneously overall parameters of the measurements, leading to more consistent results, which better reflect original data (Combès et al., 2015). For instance, in the case of OSL dating, a single instrument may have been used for all measurements; consequently, the source of systematic uncertainty (e.g., the calibration of the radioactive source) is identical to all samples. In such a situation Bayesian inference should be used due to its capability to address different kinds of uncertainty (Huntriss, 2008; Zink, 2015). Moreover, Bayesian modelling may provide an option to include independent ages in specific situations, and with higher precision, such as available for ^{14}C dating, to reduce uncertainties and thus result in an improved overall age precision (Rhodes et al., 2003; Lanos and Philippe, 2018).

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

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

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

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

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

2. Mirak open-air site in a prehistorical context

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

Discovered in the last century, human remains close to the borders of this plateau emphasize the notability of this region: for instance, the unique set of Neanderthal skeletons in Shanidar (Solecki, 1955; Trinkaus, 1983) in the Iraqi Kurdistan, as well as the skeleton of a Neanderthal child in Teshik Tash (Okladnikov, 1949), south of Uzbekistan. However, so far, the Late Pleistocene human remains in Iran (Trinkaus and Biglari, 2006; Zanolli et al., 2019) are scarce. On the contrary, considerable lithic assemblages associated to the Middle Palaeolithic (Zagros Mousterian; Dibble, 1984) and Upper Palaeolithic (Zagros Aurignacian: Olszewski and Dibble, 1994; Baradostian: Solecki, 1958; Rostamian: Conard and Ghasidian, 2011) are known to be concentrated in the Zagros foothills (mainly in caves and rock shelters) (e.g., Biglari, 2001; Otte et al., 2007; Shidrang et al., 2016; Bazgir et al., 2017; Heydari-Guran and Ghasidian, 2017). Beyond the Zagros foothills, several open-air sites in stratigraphic context have recently been discovered in the northern and western edges of the Iranian Central plateau, as well as the central Alborz (e.g., see Berillon et al., 2007; Berillon and Asgari Khaneghah, 2016; Conard et al. 2009; Heydari-Guran et al. 2014; Vahdati Nasab and Hashemi 2016; Vahdati Nasab et al., 2013; 2019). Notwithstanding this abundant archaeological evidence, the debate suffers from a lack of chronological data for this area.

2.1. **Geomorphological and stratigraphic setting**

The Palaeolithic site of Mirak lies in a flat-dissected plain, which extends from the southern part of the Alborz Mountains to the margin of the central desert (*Dasht-i Kavir*) (Fig. 1). In this area, unusual Holocene nebkha (i.e. shadow dunes; mounds) are located in the flat plain composed of Pleistocene alluvial deposits (see Jamet and Akhavan Kharazian in Berillon et al., 2017 and Akhavan Kharazian et al., 2018 for details; synthesis in Vahdati Nasab et al., 2019). The lithic artefacts on the surface are exposed by deflation close to the mounds. The presence of the nebkhas with vegetation on top played a fundamental role in the preservation of three archaeological levels in the underlying Pleistocene alluvial deposits. One of those mounds (mound no. 8) at an altitude of 1,035 m (a.s.l.) and surrounded by the highest concentration of lithic artefacts, was selected for this study.

Besides, the presence of a nearby illegal pit, henceforth named *S2,* has provided a unique possibility for primary investigations on *in situ* archaeological material. Having proved the presence of in situ deposit, three main trenches have then been excavated in the northern, eastern and southern slopes of the mound no. 8 with excavation areas of 19 m², 12 m² and 5 m² respectively; ¼m² has been excavated at the bottom of S2 (Berillon et al., 2017; Vahdati Nasab et al., 2019) (see Fig. The one I attached).

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

2.1.1. *In situ* archaeological assemblages

The stratigraphic logs of the northern and eastern sections are shown in Figs. 2 and 3.

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

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

3. Material and methods

3.1. Sampling

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

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

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

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

3.2. Sample preparation

The samples were prepared using routine procedures for luminescence dating (e.g., Preusser et al., 2008). Subdued orange (ca 589 nm, sodium vapour lamp) light conditions prevented any unwanted loss of luminescence signal during sample preparation. Wet sieving was carried out to extract grains between 80 µm to 140 µm, which is the dominant grain size fraction according to grain size analyses. HCl (10 %) and H_2O_2 (30 %) were used to eliminate carbonates and organic materials, respectively. To separate quartz and feldspar grains, lithium heteropolytungstates (LST) heavy-liquid based density separation was applied (densities: 2.70 g cm^{-3} and 2.62 g cm^{-3}). The quartz fraction was treated with HF (40 %) for 40 min, not only to remove any probable feldspar contamination, but also to minimize the luminescence signal produced by alpha particles. The feldspar grains were etched with HF (10 %) for 10 min to remove the outer part of the grains believed to be affected α-particles. The last series of samples were taken from the eastern trench (Mk17-1 to Mk17-10) for which we planned to carry out the measurements only on the quartz fraction, were not treated with LST, and the sediments were soaked in HF (40 %) for 40 min to remove all feldspar grains and purify quartz. Finally, the grains were rinsed in HCl (15%) overnight to remove Ca-fluorides and sieved with the smaller-sized meshes to remove fragmented grains only (e.g., Porat et al., 2015).

3.3. **Instrumentation**

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

3.4. **Dose rate determination**

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

3.4.1. Internal dose rate

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

3.4.2. External dose rate

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

Then the dried samples were crushed following sieving using a mesh size of 2 mm and packed into sealed plastic boxes to avoid the loss of radon. In the following, the crushed and sealed samples were stored over a minimum of four weeks to ensure a radioactive equilibrium between ^{226}Rn and its daughter nuclides (e.g., Guibert and Schvoerer, 1991) before running the measurements. The concentration of the radionuclides was converted to beta-dose rate using the conversion factors by Guerin et al. (2011). The beta-dose rates were then corrected for the intrinsic attenuation due to the grain size of the quartz and feldspar grains after Guerin et al. (2012). The effect of HF etching, as well as the effect of moisture on beta-dose rates, were corrected after Nathan (2011) and Nathan and Mauz (2008), respectively. The concentration of the U, Th and K contents are shown in Table 1. The concentrations of K and Th for entire samples fall between 1.26% to 2.32 %, and 4.67 ppm to 12.45 ppm, respectively. Besides, the concentrations of U determined from the top of the chain range from 1.80 ppm to 3.28 ppm. The concentration derived from the bottom of the chain lie between 1.75 ppm to 9.42 ppm (this high U concentration is belonged to sample Mk15-8 from the clandestine pit S2, if we exclude this value, then the highest value would be 4.30 ppm (from Mk17-4)). The disequilibrium in the U chain is discussed below. The external beta dose rates for entire sample range from 1.20 Gy ka^{-1} to 2.10 Gy ka^{-1}. It contributes 55% to 59 % to the total dose rate.

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

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

3.4.3. Radioactive disequilibrium

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

3.5. **Luminescence signal measurements**

3.5.1. Quartz UV signal

We applied the single aliquot regenerative (SAR) dose protocol (Murray and Wintle, 2000) to determine the equivalent dose (*D_e*). The protocol parameters for the Mirak samples were obtained from conventional tests such as examining the presence of a fast decaying signal component, preheat plateau and dose recovery tests (Wintle and Murray, 2006). OSL signal measurements were started with samples MK15-1 and Mk15-4. These two samples belonged to the believed Holocene period, and their equivalent doses vary around 1 Gy to 3 Gy, respectively. Due to the low luminescence signal intensity of these two samples, blue OSL was preferred to improve the signal to noise ratio, and these settings were also used for the rest of the samples taken in 2015 (MK15-5, MK15-6, MK15-7 and MK15-8).

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

3.5.2. Testing the fast component

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

Additionally, for 30 aliquots of one sample (Mk17-6), we tested the dependence of the equivalent dose on the signal integration times (Figs. S4), to determine whether our choice for the signal integral may have biased the final D_e. The Figs. S4 illustrated that an appropriate channel integration (believed to be represented by a plateau) varies from one sample to another (Figs. S4). Therefore, we determined the individual D_e values for each aliquot using the best channel integral, which lies in the plateau. Then we compared the average of the so determined D_e with the various channel integration, with the average value of D_e determined after applying the channel integration limit of 1-45 to all aliquots. While single D_e values may vary with the chosen signal integral, averaged results derived for different signal integrals provide values indistinguishable from 1% of unity, justifying the finally applied signal channel range for GSL of 1–45 (7.2 s) and 280–399 (19.2 s) for the background. Additionally, the test indicates that any medium component does not affect our final D_es.

3.5.3. SAR protocol parameters

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

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

Additionally, we performed a dose-recovery test on six aliquots of sample Mk15-5 (Fig. S5B). The aliquots first were bleached for 100 s with a blue light at room temperature in the reader to empty the natural luminescence signal. This was followed by a 10,000 s pause that allows the decay of the 110°C peak (Wintle and Murray, 2006). The samples were then bleached for a second time to deplete charges in the fast component related trap, potentially transferred from the shallow 110°C trap during the pause. Finally, samples received a beta-dose of 111 Gy (close to the expected equivalent doses), and the SAR protocol was applied. The mean recovered dose based on the measurement of six aliquots was 100 ± 5 Gy. Therefore, the dose-recovery ratio was 0.90 ± 0.04, which was consistent with unity and validated the chosen SAR protocol parameters. We assumed similar behaviour for the rest of the samples; thus, we applied the SAR protocol with the same parameters to all samples.

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

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

For the feldspar samples, the pIRIR$_{290}$ protocol (Thomsen et al., 2008; protocol settings after Buylaert et al., 2012) was applied to five samples from the east trench, one sample from the south trench, as well as five samples from the north trench and one sample from the clandestine pit (S2). Typical TL curves, infrared light stimulated shine-down curves, and corresponding dose-response curve from the pIRIR$_{290}$ signal are shown for sample Mk16-3. Following quartz data treatments, here the palaeodoses are determined using the arithmetic mean, and their uncertainties show based on standard deviation of the mean. Except for the samples Mk15-1 and Mk15-4 for which the determined palaeodoses are less than 8 Gy, the palaeodoses of the rest of the samples fall between 113 Gy to 454 Gy (Table 2). The Abanico plots for illustrating the distribution of the D_e and their uncertainties for one sample (Mk16-3) are provided for both green OSL on quartz and infrared light on feldspar (Fig. S8).

3.6. Bayesian chronology using 'BayLum'

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

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

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

3.6.1. Theta matrix

To address shared systematic uncertainty, 'BayLum' applies the basic statistical concept of a covariance matrix in the form of a so-called Theta (Θ) matrix. Diagonal elements of the matrix refer to the systematic and individual (statistical) uncertainty mainly on the dose-rate estimation as well as the systematic uncertainty on the determined palaeodose of each sample and non-diagonal elements of this matrix refer to the systematic uncertainty shared between two samples, or in other words, it shows the correlation between them (Combès and Philippe, 2017).

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

4. Results

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

Figures 5a–b show the ages determined with the frequentist statistic from feldspar and quartz for the north and the east trenches respectively within 2σ uncertainty (95% confidence interval). Both quartz and feldspar ages increase with depth. However, the feldspar ages are systematically older than the quartz ages. The top of the north trench starts with the quartz ages of samples Mk15-1 and Mk15-4, which are [0.4–0.8] ka and [0.8–1.6] ka, respectively. The quartz ages of samples Mk15-5 and Mk15-6 ([25–31] ka, [24–32] ka) are in agreement with the corresponding feldspar ages of [29–36] ka and [29–34] ka, respectively. The feldspar ages determined from samples Mk15-8 and Mk15-7 ([46–52] ka, [64–78] ka) are significantly older than the associated quartz ages ([33–41] ka, [44–56] ka). The quartz ages from the east trench start from the top with sample Mk17-3, [21–26] ka, and increase gradually with depth, ending up with sample Mk17-10, which represents the oldest age of the whole sequence, at [55–74] ka. Here also the feldspar ages are older than the quartz ages. The feldspar ages for samples Mk16-6, Mk16-4, Mk16-1 (the only sample from the south trench) and Mk16-2 are between 30 % to 70 % older than the quartz ages. The feldspar ages of samples Mk16-5 and Mk16-3 are not only two times older than the quartz ages, but also the dispersion between the aliquots is much higher than for the rest of the pIRIR$_{290}$ ages. An Abanico plot (Dietze et al., 2016) is used to illustrate the dispersion in quartz and pIRIR$_{290}$ palaeodose distributions for sample Mk16-3, as an example (Fig. S8).

This discrepancy between the quartz and feldspar ages may be explained by the different bleaching rates of the OSL quartz in comparison to the pIRIR$_{290}$ signal (~100 s vs ~1,000 s; Murray et al., 2012). We know that the geological units 4 down to 8 are part of an alluvial deposit. Units 4, 6 and 8, in particular, have repetitively experienced flood events. The turbidity of the water during the flood may have caused insufficient bleaching of the feldspar grains on the top of the, potentially, short light exposure due to the high transport energy. The observed discrepancies between the feldspar ages and the quartz ages especially for samples Mk16-5 and Mk16-3, which are taken from units 6 and 8 may be attributable to such rapid sediment transport process. Guérin et al. (2015) reported a similar observation where feldspar grains suffer from insufficient bleaching, but quartz grains are believed to be bleached completely, showing age's consistency with the ^{14}C age control. Here we do not have any independent age control. However, we have no indication that the quartz ages are unreliable, contrary to the feldspar ages which are likely to be overestimated.

4.2. Unravelling the Bayesian chronology

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

4.2.1. Scenario I

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

4.2.2. Scenario II

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

4.2.3. Scenario III

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

4.2.4. Scenario IV

The last plot (Fig. 6d), which refers to the application of stratigraphic order and correlation between samples (Theta matrix) results in a reduced credible interval from 5% (Mk17-10) up to a maximum of 33 % (Mk17-1) compared to the confidence intervals. Moreover, for five samples (out of 13), the Bayesian ages moved towards the older ages (up to 14%) in comparison to the frequentist ages. The Bayesian age for one sample (Mk17-1) is younger than the frequentist age by 6%. For the rest of the samples, the Bayesian ages render almost the same ages as frequentist approach.

4.2.5. Further results

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

5. Discussion

5.1. Improvement of the precision

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

maryam.heydari@u-bordeaux-montaigne.fr

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

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

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

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

Consequently, to address properly the effect of the stratigraphic order for our data (which include systematic shared uncertainties), the Theta matrix should be applied and scenario III cannot be considered. However, if the systematic error is added to the result of this scenario, then the result can be considered following Rhodes et al. (2003).

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

It was shown that scenarios III and IV result in a considerable reduction in the age uncertainties in comparison with the results obtained using the frequentist approach. Both these Bayesian models take the stratigraphic order into account. Figures 6c–d display that the maximum reduction in the uncertainties observe from sample Mk16-6 to Mk16-4 where their confidence intervals overlap one another. The frequentist age of sample Mk16-6 does not follow the stratigraphy order, but when the stratigraphic order applies, the credible interval shifts towards the older part of the confidence interval to satisfy the imposed ordering.
Consequently, the rest of the samples from Mk17-1 to Mk16-4 which roughly place between 24–29 ka should follow this ordering; thus, the credible intervals decrease significantly in both scenarios. Rhodes et al. (2003) already mentioned that Bayesian modelling might lead to substantial improvements in the precision where the sampling resolution is high enough, so that ages overlap each other. Contrary, if the age's intervals do not overlap, the Bayesian chronology considering the stratigraphic order does not render results more precise than the frequentist chronology (see for example the Bayesian ages of samples Mk16-2 and Mk17-10 in Figs. 6c–d). Moreover, Figs. 6c–d show that part of the obtained frequentist-age intervals are 'discarded' when the stratigraphic order is imposed. For instance, for sample Mk17-6, more than 50 % of the uncertainty interval is 'eliminated' pushing the credible interval out of the average of the frequentist model.

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

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

Therefore, in particular scenarios, stratigraphic constraints should be applied with caution since they affect all age estimates within a sequence. In other words, here, it is not only the question of precision, but also the question of accuracy that matters when the application of such a model is attempted.

5.4. **Technical issues**

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

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

5.5. Further remarks

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

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

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

5.6. The obtained chronology in the prehistoric context

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

The Bayesian and the frequentist age of sample Mk15-5 from the north trench, which originated from the Upper Palaeolithic assemblage layer (level 1; geological unit 4a), results in [25–28] ka and [25–31] ka, respectively. In the east trench, four samples (Mk17-3, Mk17-2, Mk16-6, Mk17-1) were taken from the layer containing the Upper Palaeolithic assemblage (level 1; geological units 3a and 4a). The Bayesian ages of those samples are [21–25], [22–26], [23–26] and [25–28] ka while the frequentist results give [21–26], [22–27], [19–24] and [26–30] ka. Hence, the Upper Palaeolithic occupation of Mirak is defined by the samples lying between [21–28] ka (95 % credible interval, Bayesian approach) and [19–31] ka (95 % confidence interval, frequentist approach). The geographical nearest Upper Palaeolithic site to Mirak for which an absolute chronology is available is Garm Roud 2. This site is located in the southern foothills of the Alborz mountains in the province Mazandaran (Berillon et al., 2007; Berillon and Asgari Khaneghah, 2016). Radiocarbon dating results for the site of Garm Roud 2 yielded [28–35] cal. ka BP (Antoine et al., 2016) which seems to be slightly older than Bayesian and frequentist chronology for the Upper Palaeolithic layer of Mirak; although the frequentist age interval overlap with the determined age interval of the site of Garm Roud 2. However, the Bayesian approach leads to a more precise chronology in comparison to the frequentist approach. Interestingly, our results from Mirak, like those for the site of Garm Roud 2, exhibit ages for the Upper Palaeolithic that are younger than the reported ages of the same period for the Zagros region. Indeed, ^{14}C dating has been applied on the Upper Palaeolithic period of various sites, such as Shanidar cave in the north of Zagros foothills which resulted in [29–40] cal. ka BP (original data: Solecki 1963; Hole and Flannery, 1968; recalculated data: Becerra-Valdivia et al., 2017; Ghasidian et al., 2019). ^{14}C dating was also applied for the Kaldar cave in central Zagros (Bazgir et al., 2017; [37–54] cal. ka BP), Yafteh cave in the west-central Zagros (Otte et al., 2011; [29–42] cal. ka BP), and Ghāre-Boof in the southern Zagros (Ghasidian, 2014; Becerra-Valdivia et al., 2017; [35–42] cal. ka BP). The geographical location of the mentioned sites is shown in Fig. 1B. The temporal period, engulfing all of these four age ranges is around [35–40] cal. ka BP, which renders an earlier Upper Palaeolithic occupation than presumed for Mirak ([21–28] ka). However, the chronology of Mirak aligns better with the chronology of Garm Roud 2 (south of Alborz). Although, it is worth mentioning that the concentration of the lithic artefacts attributable to the Upper Palaeolithic period is very scarce in Mirak, the younger Upper Palaeolithic chronologies for the Central Alborz region (Mirak and Garm roud2) in comparison with the chronologies of Upper Palaeolithic assemblages in the Zagros echo some temporal differences between the two areas, which may be also translated into cultural variabilities (Berillon et al., 2007; Chevrier in Berillon et al., 2016; Vahdati Nasab et al., 2019).

The intermediate assemblage (level 2, east trench; Fig. 3) appears to be spread over two sub-layers in Mirak, which raises the question of the existence of two distinct assemblages. Indeed, the preliminary study of the lithic material of this layer highlighted a mix of Upper and Middle Palaeolithic affinities that potentially characterise a transitional phase likely related to early Aurignacian industries of the Zagros (Vahdati Nasab et al., 2019). One issue was thus to know based on a refined chronology whether these apparent sub-layers correspond to 2 distinct occupations; and if so, our interpretation of this apparently mix assemblage should be reconsidered. The Bayesian and the frequentist age of sample Mk17-7, which was taken from the top of sub-layer 1 (geological unit 4b), result in [25–28] ka and [24–29] ka. The Bayesian and the frequentist ages of sample Mk17-6, which was taken directly from sub-layer 1 (geological unit 5), result in [26–29] ka and [22–28] ka, respectively. Moreover, the ages of Mk16-4 and Mk17-5, which were taken from the sub-layer 2 (geological unit 5), yield to [26–30] ka and [28–33] ka for the Bayesian, and [24–29] ka and [27–34] ka for the frequentist model. The Bayesian ages of samples Mk16-5 and sample Mk17-4 from the geological unit 6, just below the sub-layer 2, result in [32–38] ka and [34–40] ka while the frequentist ages yield [31–39] ka and [33–39] ka.

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

Finally, the Bayesian ages for samples Mk16-2 and Mk16-3, which were taken from the layers that contain the Middle Palaeolithic assemblage (archaeological layer 3; end of unit 7 and beginning of unit 8 in the sedimentological log), result in [43–51] ka and [44–55] ka, respectively, while the frequentist ages for these two samples exhibit [42–51] ka and [39–55] ka. Here again, the Bayesian modelling provides ages more precise than the frequentist ages. The determined ages for the Middle Palaeolithic layer of the site Mirak align with the period of Middle-Upper Palaeolithic transition in Shanidar [39–49] cal. ka BP (Becerra-Valdivia et al., 2017) as well as with the Neanderthal occupation layer in the Shanidar Cave, which was dated to ca [46-60] cal. ka BP (Becerra-Valdivia et al., 2017; Solecki and Solecki, 1993). However, this age-range is close to the temporal limit of ^{14}C dating and, thus, should be treated cautiously. Our results strengthen the idea of a cultural context that is highly complex in the area, with the potential contemporaneity of Middle and Upper Palaeolithic cultures in some parts of the region (Iranian Plateau) during MIS2 to MIS3 (age-boundaries according to Lisiecki and Raymo, 2005); an hypothesis that needs further investigations and the one which imply the likely contemporaneous presence of both Neanderthals and modern humans in the region (see Zeitoun, 2016).

6. Conclusions

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

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

dating (e.g., ^{14}C dating), it does not result in improved chronological precision and the obtained result is almost indistinguishable from the frequentist approach (scenario II).

- The Bayesian chronology for the Upper Palaeolithic occupation of the site of Mirak is attributed to [21–28] ka. The Bayesian chronology for the intermediate layer, provides the age of [26–29] ka for sub-layer 1 and the ages of [26–33] ka for the sub-layer 2. Therefore, based on our chronology, it is highly probable that the two distinct sub-layers can be considered as a one individual layer with the age of [26–33] ka. The Bayesian chronology for Middle Palaeolithic assemblage result in [43–55] ka.

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

Acknowledgements

This work was financed by the LaScArBx LabEx supported by the ANR - n◦ ANR-10-LABX-52 and was performed in the framework of the PhD thesis of MH.

Chantal Tribolo is thanked for her constructive comments on an earlier version of the manuscript. We would like to thank the Research Center for Cultural Heritage and Tourism of Iran (RICHT) and the Iranian Center for Archaeological Research (ICAR) for granting the permit for conducting the Joint Iranian and French Project at Mirak, and authorizing the exportation of the OSL samples for analysis. We thank the Office of International Affairs at the RICHT for facilitating the VISA-granting process for the non-Iranian collaborators. We are greatly indebted to Mr. Khajeh Beidokhti, the director of the Iranian Cultural Heritage Organization (ICHO) office in Semnan Province at the time and his colleagues for providing logistics and comfort to conduct the fieldwork. The fieldwork and geological analyses have been co-funded by the office of governor of Semnan, the French Ministry of Europe and Foreign Affair (MEAE) and the UMR7194 CNRS-MNHN-UPVD (Paris); we are very grateful to them. Special thanks go to the field crew in alphabetical order: Alieh Abdollahi, Mahkameh Abolfathi, Laya Alinia, Benoit Chevrier, Nasim Feizi, Mozhgan Jayez, Mahyar Khademi, Ashghar Nateghi, Mona Oryat, Soroush Razi, Robabeh Sadeghinejad, Yashar Sadeghi, Sanaz Shirvani, Mohammad Javad Shoaee, and Marzieh Zareh Khalili.

Table 1: Environmental dose rates

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

Table2: The estimated luminescence ages based on the frequentist approach

	Quartz				Feldspar			
Sample name	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			

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

DATASET	**SCENARIO**	***t*-value**	**Df**	***p*-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*

** Statistically significant to a significance value of 0.01*

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

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

Figure captions

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

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

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

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

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

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

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

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

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

References

Aitken, M.J., 1985. Thermoluminescence Dating. Academic Press, London.

Akhavan kharazian, M., Jamet G., Puaud S., Heydari, M., Guérin, G., Hashemi M., Vahdati Nasab H., Berillon G., 2018. The geoarchaeological study of Paleolithic open-air site of Mirak (Semnan, IRAN) using sedimentological and physical-chemical analysis (in Persian). Quaternary Journal of Iran 4,273-290.

Antoine, P., Bahain, J.-J., Ghaleb, B., Mercier,N. 2016. The Chronostratigraphic framework at Garm Roud, In:Berillon, G., Asgari Khaneghah, A. (Eds.), Garm Roud: A Hunting place in Iran, Upper Paleolithic. Editions IFRI & @rchéo-éditions (French-English-Persian), 49-55.

Bailey, R.M., 2001. Towards a general kinetic model for optically and thermally stimulated luminescence of quartz. Radiation Measurements 33, 17-45.

Bailey, R.M., 2010. Direct measurement of the fast component of quartz optically stimulated luminescence and implications for the accuracy of optical dating. Quaternary Geochronology 5, 559–568.

Bailey, R.M., Yukihara, E.G., McKeever, S.W.S., 2011. Separation of quartz optically stimulated luminescence components using green (525 nm) stimulation. Radiation Measurements 46, 643–648. DOI: 10.1016/j.radmeas.2011.06.005

Bar-Yosef, O., Belfer-Cohen, A., 2001. From Africa to Eurasia-early dispersals. Quaternary Geochronology 75, 19–28.

Bazgir, B., Oll_e, A., Tumung, L., Becerra-Valdivia, L., Douka, K., Higham, T., van derMade, J., Picin, A., Saladi_e, P., L_opez-Garcí-a, J.M., Blain, H.Al, Allu_e, E., Fern_andez-García, M., Rey-Rodríguez, I., Arceredillo, D., Bahrololoumi, F., Azimi, M.,Otte, M., Carbonell, E., 2017. Understanding the emergence of modern humans and the disappearance of Neanderthals: Insights from Kaldar Cave (KhorramabadValley, Western Iran). Sci. Rep. 7, 43460.

Becerra-Valdivia, L., Douka, K., Comeskey, D., Bazgir, B., Conard, N.J., Marean, C.W., Oll_e, A., Otte, M., Tumung, L., Zeidi, M., Higham, T.F.G., 2017. Chronometric investigations of the Middle to Upper Paleolithic transition in the Zagros Mountains using AMS radiocarbon dating and Bayesian age modelling. Journal of Human Evolution 109, 57-69.

Berillon, G., Khaneghah, A.A., Antoine, P., Bahain, J.-J., Chevrier, B., Zeitoun, V., Aminzadeh, N., Beheshti, M., Chanzanagh, H.E., Nochadi, S., 2007. Discovery of new open-air Paleolithic localities in Central Alborz, Northern Iran. Journal of Human Evolution 52, 380–387. doi:10.1016/j.jhevol.2006.10.004

Berillon G., Asgari Khaneghah A., Antoine P., Auguste P., Bahain J.-J., Chausse C., Chevrier B., Ghaleb B., Jolly-Saad M.-C., Klaus S., Lebreton V., Limondin-Lozouet N., Mercier N., Senegas F., Vahdati Nasab H., Vercoutere C., Zeitoun V. (2016), Garm Roud. A Hunting place in Iran, Upper Palaeolithic. IFRI & @rchéo-éditions, French-English-Persian, 280 pp.

Berillon, G., Vahdati Nasab, H., Khaneghah, A. A., Jamet, G., Akhavan, M., Guérin, G., Heydari, M., Anvari, Z., Auguste, P., Bonilauri, S., Chevrier, B., Zeitoun, V., Mohammadkhani, K., Hashemi, M., Jayez, M., Darvishi, J., 2017. *Fouille du site Mirak 8:* Rapport Annuel. Programme Paléoanthropologique Franco-Iranien (FIPP).

Biglari, F., 2001. Recent finds of Paleolithic period from Bisotun, CentralWestern Zagros Mountains. Iranian Journal of Archaeology and History 28, 50–60 (in Persian).

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., Bonani, G. 1997. A pervasive millennial-scale cycle in north Atlantic Holocene and glacial climates. Science 278: 1257-65.

Buck, C. E., Cavanagh, W. G., Litton., 1998. Bayesian Approach to Interpreting Archaeological Data. American Journal of Archaeology, 102(1) 187-188.

Buck, C.E., Meson, B. 2015. On being a good Bayesian. World Archaeology 47 (4). 567– 584. ISSN 0043-8243

Buck, C.E., Millard, A.R., 2004. Tools for Constructing Chronologies - Crossing Disciplinary Boundaries. Springer.

Bulur, E., 1996. An alternative technique for optically stimulated luminescence (OSL) experiment. Radiation Measurement 26, 701–709.

Buylaert, J.-P., Jain, M., Murray, A.S., Thomsen, K.J., Thiel, C., Sohbati, R., 2012. A robust feldspar luminescence dating method for Middle and Late Pleistocene sediments. Boreas 41, 435-451.

Carlin, B.P. and Louis, T.A., 2000. Bayes and empirical Bayes methods for data analysis. CRC Press third edition.

Chervrier B., 2016, The lithic assemblage from Gram Roud. In Berillon G. and Asgari Khaneghah A. (eds), “Garm Roud. Hunting place in Iran. Upper Palaeolithic”, 63-69

Chen, R., Kirsh, Y., Townsend, P.D., 1991. Models for the sensitization of thermoluminescence in silica fibres. Nuclear Tracks and Radiation Measurements 18, 13–17.

Christoph, C., Philippe, A., Kreutzer, S., Guérin, G., 2019. BayLum: Chronological Bayesian Models Integrating Optically Stimulated Luminescence and Radiocarbon Age Dating. Version 0.1.4, http://github.com/crp2a/BayLum, https://cran.r-project.org/package=BayLum.

Combès, B., Philippe, A., 2017. Bayesian analysis of individual and systematic multiplicative errors for estimating ages with stratigraphic constraints in optically stimulated luminescence dating. Quaternary Geochronology 39, 24–34. doi:10.1016/j.quageo.2017.02.003.

Combès, B., Philippe, A., Lanos, P., Mercier, N., Tribolo, C., Guérin, G., Guibert, P., Lahaye, C., 2015. A Bayesian central equivalent dose model for optically stimulated luminescence dating 28, 62–70. doi:10.1016/j.quageo.2015.04.001.

Conard, N.J., Ghasidian, E., 2011. The Rostamian cultural group and thetaxonomy of the Iranian Upper Paleolithic. In: Conard, N.J., Drechsler, P., Morales, A. (Eds.), Between Sand and Sea. The Archaeology and Human Ecology of Southwestern Asia, 744. Kerns Verlag, Tübingen,Germany, pp. 33–52.

Conard, N.J., Ghasidian, E., and S. Heydari-Guran. 2009. The Open-Air late Paleolithic Site of Bardia and the Paleolithic Occupation of the Qaleh Gusheh Sand Dunes, Esfahan Province, Iran. In: Iran Paleolithic, Le Paléolithique d'Iran, M. Otte, F. Biglari, & Jaubert (eds.), pp. 141-154. Bar International Series.

Dansgaard, W., Johnson, S.J., Clausen, H.B., Dahl-Jensen, D., Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjörnsdottir, A.E., Jouzel, J., Bond, G. 1993. Evidence for general instability of past climate from a 250-kyr ice core record. Nature 364: 218-20.

Dennell, R., 2017. Human Colonization of Asia in the Late Pleistocene: The History of an Invasive Species. Current Anthropology 58(S17): S383-S396.

Dibble, H.L., 1984. The Mousterian Industry from Bisitun Cave (Iran). Paléorient 10 (2), 23-34.

Dietze, M., Kreutzer, S., Burow, C., Fuchs, M.C., Fischer, M., Schmidt, C., 2016. The abanico plot: visualising chronometric data with individual standard errors. Quaternary Geochronology 31, 12–18. doi:10.1016/j.quageo.2015.09.003

Duller, G.A.T., 2015. The Analyst software package for luminescence data: overview and recent improvements. Ancient TL 33, 35–42.

Duller, G.A.T., 2003. Distinguishing quartz and feldspar in single grain luminescence measurements. Radiation Measurements 37, 161–165. Doi: 10.1016/S1350-4487(02)00170-1

Durcan, J.A., King, G., Duller, Geoff A.T., 2015. DRAC: dose rate and age calculator for trapped charge dating. Quat. Geochronol. 28, 54–61.

Gelman, A., Carlin, J.B., Stern, H.S., Dunson, D.B., Vehtari, A., Rubin, D.B., 2014. Bayesian Data Analysis. CRC Press.

Ghasidian, E., Heydari Guran, Saman., Lahr, M.M., 2019. Upper Paleolithic cultural diversity in the Iranian Zagros Mountains. Journal of Human Evolution. 132,101-118.

and the expansion of modern humans into Eurasia

Ghasidian, E., 2014. The Early Upper Paleolithic Occupation at Gh_ar-e Boof Cave: A Reconstruction of Cultural Tradition in the Southern Zagros Mountains of Iran. Kerns Verlag, Tubingen.

Guèrin, G., Lahaye, C., Heydari, M., Christophe, C., Autzen, M., Buylaert, J. P., Guibert, P., Jain, M., Kreutzer, S., Murray, A.S., Thomsen, K.J., Tribolo, C., Urbanova, P., Philippe, A. under preparation. Towards an improvement of OSL age uncertainties: specifying the dose covariance matrix for modelling OSL ages with systematic errors, stratigraphic constraints and radiocarbon ages using the R package 'BayLum'. Geochronology, 1–84

Guérin, G., Frouin, M., Talamo, S., Aldeias, V., Bruxelles, L., Chiotti, L., Dibble, H.L., Hublin, J.J., Jain, M., Lahaye, C. 2015. A multi-method luminescence dating of the Palaeolithic sequence of La Ferrassie based on new excavations adjacent to the La Ferrassie 1 and 2 skeletons. Journal of Archaeological Science 58, 147-166.

Guérin, G., Mercier, N., 2012. Preliminary insight into dose deposition processes in sedimentary media on a grain scale: Monte Carlo modelling of the effect of water on gamma dose-rates. Radiat. Meas. 47, 541-547.

Guérin, G., Mercier, N., Adamiec, G., 2011. Dose-rate conversion factors: update. Ancient TL 29, 5–8.

Guérin, G., Mercier, N., Nathan, R., Adamiec, G., Lefrais, Y., 2012. On the use of the infinite matrix assumption and associated concepts: a critical review. Radiat. Meas. 47, 778-785.

Guibert, P., Lahaye, C., Bechtel, F., 2009. The importance of U-series disequilibrium of sediments in luminescence dating: a case study at the Roc de Marsal Cave(Dordogne, France). Radiation Measurements 44, 223-231.

Guibert, P., Schvoerer, M., 1991. TL-dating: Low background gamma spectrometry as a tool for the determination of the annual dose. Nuclear Tracks and Radiation Measurements, 14, 155-161.

Hansen, V., Murray, A.S., Buylaert, J.-P., Yeo, E.-Y., Thomsen, K.J., 2015. A new irradiated quartz for beta source calibration. Radiat. Meas. 81, 123–127.

Hashemi, M., Vahdati Nasab, H., Berillon, G., Jamet, G., Azizi, Q., Jayez, M., Guerin, G., Heydari, M., Akhavan Kharazian, M., Nateghi, A., and A. Abdollahi. 2018. The Late Pleistocene in the Northern fringes of Iranian Central Desert and the Formation of Archaeological Sites; Case Study: Mirak, Semnan. Quaternary Journal of Iran 3(12): 405-430 (in Farsi).

Heinrich, H., 1988. Origin and consequences of cyclic ice-rafting in the Northeast Atlantic Ocean during the past 130,000 years. Quaternary Research 29: 142–152.

Heydari-Guran, S., Ghasidian, E., 2017. The MUP Zagros Project: tracking the Middle Upper Palaeolithic transition in the Kermanshah region, west-central Zagros, Iran. Antiquity 91 (355), 1-7.

Heydari-Guran, S., Ghasidian, E., and N. Conard. 2014. Middle Paleolithic Settlements on the Iranian Central Plateau. In: Settlement Dynamics of the Middle Paleolithic and Middle Stone Age, Vol. IV, N. Conard, A. Delagnes (eds.). Pp. 171-203. Tübingen Publication in Prehistory.

Heydari, M., Guérin, G., 2018. OSL signal saturation and dose rate variability: Investigating the behaviour of different statistical models. Radiation Measurements 120, 96–103. doi:10.1016/j.radmeas.2018.05.005

Hole, F., Becerra Flannery, K.V., 1968. The prehistory of southwestern Iran: A preliminary report. Proc. Prehis. Soc. 33, 147–206.

Huntley, D.J., Baril, M.R., 1997. The K content of the K-feldspar being measured in optical dating or in thermoluminescence dating. Ancient TL 15, 11–13.

Huntley, D.J., Godfrey-Smith, D.I., Thewalt, M.L.W., 1985. Optical dating of sediments. Nature 313, 105–107.

maryam.heydari@u-bordeaux-montaigne.fr

Huntriss, A., 2008. A Bayesian analysis of luminescence dating. PhD thesis, University of Durham. http://etheses.dur.ac.uk/2928/1/2928-759.pdf?UkUDh:CyT

Kreutzer, S., Dietze, M., Burow, C., Fuchs, M.C., Schmidt, C., Fischer, M., Friedrich, J.,2017. Luminescence: Comprehensive Luminescence Dating Data Analysis. R Package, Version 0.7.5. https://CRAN.R-project.org/package=Luminescence.

Kreutzer, S., Schmidt, C., Fuchs, M.C., Dietze, M., Fischer, M., Fuchs, M., 2012. Introducing an R package for luminescence dating analysis. Ancient TL 30, 1–8.

Lahaye, C., Guérin, G., Gluchy, M., Hatté, C., Fontugne, M., Clemente-Conte, I., Santos, J.C., Villagran, X., Da Costa, A., Borges, C., Guidon, N., Boëda, E., 2019. Another site, same old song: the Pleistocene-Holocene archaeological sequence of Toca da Janela da Barra do Antonião-North, Piauí, Brazil. Quaternary Geochronology 49, 223-229.

Lanos, P., Anne, P., 2018. Event date model: a robust Bayesian tool for chronology building. CSAM 25, 131–157. doi:10.29220/CSAM.2018.25.2.131

Lisiecki, L. E., Raymo, M. E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic d^{18}O records, Paleoceanography 20, PA1003, doi:10.1029/2004PA001071.

Liritzis, I., 2017. Luminescence Dating in Archaeology, Anthropology, and Geoarchaeology. Springer. ISBN 10: 3319001698.

McKeever, S.W.S., 1991. Mechanisms of thermoluminescence production, some problems and a few answers. Nuclear Tracks and Radiation Measurements 18, 5-12.

Mehterian, S., Pourmand, A., Sharifi, A., Lahijani, H.A.K., Naderi, M., and P.K. Swart. 2017. Speleothem records of glacial/interglacial climate from Iran forewarn of future Water Availability in the interior of the Middle East. Quaternary Science Reviews 164: 187-198.

Mejdahl, V., 1987. Internal radioactivity in quartz and feldspar grains. Ancient TL 5, 10–17.

Mercier, N., Kreutzer, S., Christophe, C., Guérin, G., Guibert, P., Lahaye, C., Lanos,P., Philippe, A., Tribolo,C., 2016. Bayesian statistics in luminescence dating: The ’baSAR’-model and its implementation in the R package ’Luminescence’. Ancient TL 34 (2), 14–21.

Murray, A.S., Thomsen, K.J., Masuda, N., Buylaert, J.P., Jain, M., 2012. Identifying well-bleached quartz using the different bleaching rates of quartz and feldspar luminescence signals. Radiation Measurements 47, 688–695. doi:10.1016/j.radmeas.2012.05.006

Murray, A.S., Wintle, A.G., 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiation Measurements 32, 57–73.

Nathan, R.P., 2011. Numerical Modelling of the Environmental Dose-rate for Trapped Charge Dating DPhil thesis, University of Oxford. https://ora.ox.ac.uk/objects/ora:6421

Nathan, R.P., Mauz, B., 2008. On the dose-rate estimate of carbonate-rich sediments for trapped charge dating. Radiat. Meas. 43, 14-25.

Okladnikov, A. P., 1949. Investigations of the Mousterian site and the Neanderthal burial at the Teshik-Tash grotto, South Uzbekistan (Central Asia). In: Gremiatsky MA, Nesturkh MF, editors. Teshik Tash: paleolithic man. Moscow: Moscow State University. 7–85.

Olszewski, D.I., Dibble, H.L., 1994. The Zagros Aurignacian. Current Anthropology 35, 68–75.

Otte M, Shidrang S, Zwyns N, Flas D, 2011. New radiocarbon dates for the Zagros Aurignacian from Yafteh cave, Iran. J Hum Evol 61, 340–346.

Otte, M., Biglari, F., Flas, D., Shidrang, S., Zwyns, N., Mashkour, M., Naderi, R., Mohaseb, A., Hashemi, N., Darvish, J., Radu, V., 2007. The Aurignacian in the Zagros region: New research at Yafteh Cave, Lorestan, Iran. Antiquity 81, 82–96.

Philippe, A., Guérin, G., Kreutzer, S., 2018. ''BayLum'' an R package for Bayesian Analysis of OSL Ages: An introduction. Quaternary Geochronology 49, 16-24. doi: 10.1016/j.quageo.2018.05.009.

Porat, N., Faerstein, G., Medialdea, A., Murray, A.S., 2015. Re-examination of common extraction and purification methods of quartz and feldspar for luminescence dating. Ancient TL 33, 22–30.

Prescott, J.R., Hutton, J.T., 1994. Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long-term time variations. Radiation Measurements 23, 497-500.

Prescott, J.R., Stephan, L.G., 1982. The contribution of cosmic radiation to the environmental dose for thermoluminescence dating. Latitude, altitude and depth dependences. PACT 6, 17-25.

Preusser, F., Degering, D., Fuchs, M., Hilgers, A., Kadereit, A., Klasen, N., Krbetschek, M.R., Richter, D., Spencer, J.Q.G., 2008. Luminescence dating: basics, methods and applications. Eiszeitalter und Gegenwart (Quaternary Science Journal) 57, 95–149. doi:10.3285/eg.57.1-2.5

R Core Team, 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.URL http://www.R-project.org/.

Rezvani, H., 1990. Settlement patterns of prehistoric cultures in Semnan Province. In: Alizadeh, A., Majidzadeh, Y., Malek Shahmirzadi, S. (Eds.), 32 Articles in Memory of E. Negahban. Tehran University Press, Tehran, pp. 7-19.

Rezvani, H., Vahdati Nasab, H., 2010. A major Paleolithic open site at Mirak, Semnan Province, Iran. Antiquity 84 (323). Project Gallery.

Rhodes, E., Bronk Ramsey, C., Outram, Z., Batt, C., Willis, L., Dockrill, S., Bond, J., 2003. Bayesian methods applied to the interpretation of multiple OSL dates: high precision sediment ages from old scatness broch excavations, Shetland isles. Quat. Sci. Rev. 22, 1231-1244.

Richter, D., Richter, A., Dornich, K., 2013. Lexsyg — a new system for luminescence research. Geochronometria 40, 220–228.

Richter, D., Richter, A., Dornich, K., 2015. Lexsyg smart — a luminescence detection system for dosimetry, material research and dating application. Geochronometria 42, 202–209.

Roberts, R.G., Jacobs, Z., Li, B., Jankowski, N.R., Cunningham, A.C., Rosenfeld, A.B., 2015. Optical dating in archaeology: thirty years in retrospect and grand challenges for the future. Journal of Archaeological Science 56, 41–60. doi:10.1016/j.jas.2015.02.028

Shidrang, S., Biglari, F., Bordes, J.G., Jaubert, J., 2016. Continuity and Change in the Late Pleistocene Lithic Industries of the Central Zagros: A Typo-Technological Analysis of Lithic Assemblages from Ghar-E Khar Cave, Bisotun, Iran. Arheol. ètnogr. antropol. Evrazii 44, 27–38. doi:10.17746/1563-0110.2016.44.1.027-038

Solecki, R.S., 1955, "Shanidar Cave, A Palaeolithic Site in Northern Iraq", Smithsonian Institution Annual Report for 1954, pp. 389-425.

Solecki, R.S., 1958. The Baradostian industry and the Upper Palaeolithic in the Near East. Ph.D. thesis. Columbia University.

Solecki, R.S., 1963. Prehistory in Shanidar valley, northern Iraq. Science 139: 179-193.

Solecki, R.S., Solecki, R.L., 1993. The pointed tools from the Mousterian occupations of Shanidar Cave, northern Iraq. In: Olszewski, D., Dibble, H. (Eds.), The Paleolithic Prehistory of the Zagros-Taurus. The University Museum of Archaeology and Anthropology. University of Pennsylvania, Philadelphia, pp. 119-146.

Thomsen, K.J., Murray, A.S., Buylaert, J.-P., Jain, M., Helt-Hansen, J., Aubry, T., 2016. Testing single-grain quartz OSL methods using known age samples from the Bordes-Fitte rockshelter (Roches d'Abilly site, Central France). Quaternary Geochronology 31, 77–96.

Thomsen, K.J., Murray, A.S., Jain, M., Botter-Jensen, L., 2008. Laboratory fading rates of various luminescence signals from feldspar-rich sediment extracts. Radiation Measurements 43, 1474–1486.

Tribolo, C., Kreutzer, S., Mercier, N., 2019. How reliable are our beta-source calibrations? Ancient TL 37, 1–10.

Trinkaus, E., Biglari, F., 2006. Middle paleolithic human remains from Bisitun cave, Iran. Paleorient 32, 105-111.

Trinkaus,E., 1983. The Shanidar Neandertals. Academic press. DOI: https://doi.org/10.1016/C2013-0-11620-0.

Vahdati Nasab, H., Clark., G.A., Torkamandi, S., 2013. Late Pleistocene Dispersal Corridors across the Iranian Plateau: a Case Study from Mirak, a Middle Paleolithic Site on the Northern Edge of the Iranian Central Desert (Dasht-e Kavir). Quaternary International 300, 267–281.

Vahdati Nasab, H., and M. Hashemi. 2016. Playas and Middle Paleolithic settlement of the Iranian Central Desert: The discovery of the Chah-e Jam Middle Paleolithic site. Quaternary International 408 (part B): 140-152.

Vahdati Nasab,H., Berillon, G., Jamet, G., Hashemi, M., Jayez, M., Khaksar, S., Anvari, Z., Guérin, G., Heydari, M., Akhavan Kharazian,M., Puaud, S., Bonilauri, S., Zeitoun, V., Sévêque, N., Darvishi Khatooni, J., Asgari Khaneghah A., 2019. The open-air Paleolithic site of Mirak, northern edge of the Iranian Central Desert (Semnan, Iran): Evidence of repeatedhuman occupations during the late Pleistocene. Comptes Rendus Palevol 18(4), 465-478.

Vlaminck, S., 2018. Northeastern Iranian loess and its palaeoclimatic implications. PhD dissertation, Faculty of Mathematics and Natural Sciences, University of Cologne (Unpublished).

Wintle, A.G. and Murray A.S., 2006. A review of quartz optically stimulated luminescence characteristics and their relevance in single-aliquot regeneration dating protocols. Radiation Measurements (41), 369–391.

Wolff, E., Chappellaz, J., Blunier, T., Rasmussen, S., and A. Svensson. 2010. Millennial-scale variability during the last glacial: the ice core record. Quaternary Science Reviews 29: 2828-2838.1963.

Zanolli, C., Biglari, F., Mashkour, M., Abdi, K., Monchot, H., Debue, K., Mazurier, A., Bayle, P., Luyer, M., Rougier, H., Trinkaus, E., Macchiarelli, R., 2019. A Neanderthal from the Central Western Zagros, Iran. Structural reassessment of the Wezmeh 1 maxillary premolar. Journal of Human Evolution 135, 102643. doi.org/10.1016/j.jhevol.2019.102643

Zeitoun, V., 2016. Where palaeoanthropology and prehistory meet. In:Berillon, G., Asgari-Khaneghah, A. (Eds.), Garm Roud. A Hunting placein Iran, Upper Paleolithic. Éditions IFRI & @rchéo-éditions, Paris, pp.101–110.

Zink, A., 2013. A coarse Bayesian approach to evaluate luminescence ages. Geochronometria 40, 90–100. doi: 10.2478/s13386-013-0105-x

Zink, A.J.C., 2015. Bayesian analysis of luminescence measurements. Radiation Measurements 81, 71–77.