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Revising the oldest Oldowan: Updated optimal linear estimation models and the impact of Nyayanga (Kenya)

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1. Introduction

The Oldowan lithic industry represents the earliest known evidence of efficiently and expeditiously produced flake stone tools (Toth, 1985; Braun et al., 2019; Reti, 2016; Stout et al., 2019). Complex technological strategies were employed to produce these artefacts compared to earlier hominin stone tools, and potential organic tool-use behaviors inferred via parsimony with non-human primates (Braun et al., 2019; Boesch et al., 2020; Delagnes and Roche, 2005; Gürbüz and Lycett, 2021; Harmand et al., 2015; Lombard et al., 2018; Plummer et al., 2023; Proffitt et al., 2023a, 2023b; Stout et al., 2010; Toth and Schick, 2009). Consequently, the emergence of the Oldowan can still (cf. Leakey, 1971) be argued to reflect a behavioral and evolutionary shift within the hominin lineage, although the nature and species-associations of any changes have become less clear in recent years (Bobe and Wood, 2021; Braun et al., 2019; Hovers, 2012; Lewis and Harmand, 2016; Plummer et al., 2023).

Nyayanga, located in the Homa Peninsula of Kenya, has recently emerged as an important archaeological and paleontological site yielding evidence of Oldowan stone tools and butchered fauna dating to between 2.595 and 3.032 Ma (Plummer et al., 2023). These findings not only represent the earliest currently known occurrences of the Oldowan but also greatly expand our understanding of its early geographic distribution. Further, some lithics at Nyayanga were found alongside *Paranthropus* molars, challenging prevailing assumptions regarding Oldowan species-associations and providing a rare instance of Early Stone Age (ESA) hominin fossil and lithic remains in close association. The co-occurrence of cut marked fauna and flakes, including those excavated in direct contact with hippopotamid remains, further distinguishes Nyayanga as an exceptional ESA occurrence extending hominin dietary and technological behaviors “similar to other Oldowan assemblages” into the Pliocene (Plummer et al., 2023: 563).

Of equal importance, Nyayanga highlights the temporal and spatial porosity of the ESA archaeological record (Isaac, 1972, 1977; Schick and Toth, 2006). Remarkably, Nyayanga potentially extends artefactually confirmed evidence of Oldowan flake production and megafauna exploitation back in time by ca. 400,000 and 600,000 years (respectively). While it is conceivable that the locality may have a younger age of 2.595 Ma, helium dating (U–Th/He) indicates a best-fit age of 2.90 ± 0.70 Ma and magnetostratigraphy results place several of the most important sites at, or shortly after, 3.032 Ma (Plummer et al., 2023). Furthermore, Nyayanga is the first documented occurrence of Oldowan tools predating 2.4 Ma outside of Ethiopia, thereby expanding the spatial range of early expedient flake tool production by over 1300 km (Plummer et al., 2023).

Due to the fragmentary nature of the ESA archaeological record (Key

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et al., 2021a; Kuhn, 2021; Shea, 2017), it is likely that Nyayanga represents the earliest currently-known occurrence of the Oldowan and not necessarily the origination age for this technology. An inferred incremental ability to produce, and reliance upon, flaked lithic technology through the early ESA (Kuhn, 2021; Shea, 2017; Stout et al., 2019) further supports an increased temporal range for Oldowan occurrences beyond know archaeological sites, potentially at low—or even archaeologically undetectable—densities. In other words, Nyayanga is unlikely to represent the earliest instance of Oldowan flake tool production. Alternatively, it can be argued that by establishing the presence of the Oldowan between 2.595 and 3.032 Ma, Nyayanga actually pushes the emergence of the Oldowan to a much earlier phase in prehistory.

Here we use optimal linear estimation (OLE) to model when Oldowan-like flake technologies may have been first produced by hominins. Optimal linear estimation is a frequentist technique capable of estimating how much earlier an archaeological phenomenon may have existed prior to the earliest known artefactual evidence (Key et al., 2021a). Essentially, OLE reconstructs the missing 'long tail' of an archaeological phenomenon's temporal distribution. The technique accounts for the reduced prevalence of artefacts when a phenomenon is first adopted and was created to provide more accurate inferences regarding the temporal range of sparse and fragmentary records (Rivadeneira et al., 2009; Roberts and Solow, 2003; Solow, 2005).

2. Material and methods

OLE has been applied in diverse prehistoric contexts (e.g., Bebber and Key, 2022; Djakovic et al., 2022; Vidal-Cordasco et al., 2022), and forms part of a growing movement to more accurately reconstruct the temporal resolution of human origins research (e.g., Miller-Atkins and Premo, 2018; Du et al., 2020; Rezek et al., 2020; Faith et al., 2021; Bobe and Wood, 2021; Roberts et al., 2023). The present investigation provides a revised chronology relative to Oldowan estimates published by Key et al. (2021b).

When OLE is applied to archaeological phenomena several important assumptions must be met. Firstly, the data used in the model should exhibit a joint distribution that roughly follows a Weibull form. Secondly, the investigated phenomenon is presumed to have existed prior to its earliest known occurrence. Thirdly, all occurrences, or sites in this case, included in the model can be considered discrete (i.e., independent from one another). It is also assumed that taphonomic factors are not disproportionately affecting different portions of the early Oldowan record (Surovell and Brantingham, 2007). Key et al. (2021a) provided a detailed outline of these and other assumptions, and as previously discussed, early Oldowan sites generally satisfy the requirements of the model (Key et al., 2021b). Additionally, we assume that all occurrences currently assigned to the Oldowan were produced by hominins (Proffitt, et al., 2023b). Optimal linear estimation can be applied to the Oldowan irrespective of whether it represents a single cultural tradition or multiple instances of cultural convergence (Hovers, 2012; Stout et al., 2019; Tennie et al., 2017); although the latter's modeled phenomenon is the ability to produce Oldowan-level technologies, not the Oldowan as a single lithic tradition (O'Brien et al., 2018). Finally, OLE produces a theoretically grounded *estimate* for when a phenomenon originated or ended, and as with any modeling endeavor, it is impacted by the accuracy of the data used.

As is generally recommended for OLE, the 10 (k) earliest currently-known Oldowan occurrences provide the chronology (spacing) data entered into the model (Table 1; Fig. 1). Sites and date range data were taken from Key et al. (2021b) and references within, with the addition of Nyayanga and the newly described Omo 79 occurrence (Delagnes et al., 2023). Given the addition of one new independent site (Table 1), the 2.0 Ma Western Olduvai Basin occurrence (Stollhofen et al., 2021) was removed to keep k constant. For each site, a central date and date range were identified following site dating information outlined in relevant research articles (Table 1). 'Central dates' either refer to the central point of the radiometrically dated range, or were centrality dates informed by other geochronological information as outlined in each respective study (Key et al., 2021b, Table 1). It is important to note that debate persists for some occurrences (e.g., Braun et al., 2019; Sahle and Gossa, 2019). Additional analyses using alternative site selection scenarios can be found in the Supplementary Online Material (SOM) S1 and S2.

Table 1
The 10 earliest Oldowan sites and their associated central value and date range data. Central values are often the midpoint of a site's assigned date range, but can also reflect the referenced author's preferences given sediment accumulation rates and the weighting assigned to different dating methods. See Key et al. (2021b) for more information.

Rank	Site	Preferred central date	Date range	Reference
1	Nyayanga (Upper)	3,032,000	3,032,000–2,595,000	Plummer et al. (2023)
	Nyayanga (U–Th/He)	2,900,000	3,032,000–2,595,000	
	Nyayanga (Midpoint)	2,813,500	3,032,000–2,595,000	
	Nyayanga (Lower)	2,595,000	3,032,000–2,595,000	
2	Ledi-Geraru	2,581,000	2,610,000–2580,000	Braun et al. (2019)
3	OGS-7, Gona	2,580,000	2,580,000–2,530,000	Semaw et al. (2003)
4	AB-Lw, Ain Boucherit	2,440,000	2,580,000–2,300,000	Sahnouni et al. (2018)
5	AL 666, Hadar	2,345,000	2,360,000–2,330,000	Kimbel et al. (1996); Goldman-Neuman and Hovers (2012)
6	Lokalalei 1	2,330,000	2,390,000–2,290,000	Kibunjia (1994); Tiercelin et al. (2010)
7	Omo 57, 123, 79	2,295,000	2,320,000–2,270,000	Delagnes et al. (2011, 2023); McDougall et al. (2012)
8	Lokalalei 2C[a]	2,266,000	–	Delagnes and Roche (2005); Tiercelin et al. (2010)
9	Member 5, Sterkfontein	2,180,000	2,390,000–1,970,000	Granger et al. (2015)
10	Kanjera South	2,000,000	2,300,000–1,920,000	Ditchfield et al., (2019)

[a] Additional information concerning the dates assigned to Lokalalei 2C can be viewed in Key et al. (2021b). The age of some sites are subject to continuing debate and the values presented here represent those widely cited within the literature. Therefore, these data represent the state of current understanding within the field. We do not consider sites where the reliability of the artefacts themselves is questioned.

Our analyses included four dates for Nyayanga (Fig. 1). As the earliest Oldowan occurrence, it has a comparatively high weighting within the model relative to other sites. We independently investigate the upper 3.032 Ma and lower 2.595 Ma thresholds of Nyayanga's date range, which are argued to be robustly determined (Plummer et al., 2023). In addition, we also examine the 2.813 Ma central value (midpoint) of this range. This date is not derived from Plummer et al. (2023) and instead reflects the middle of the site's published date-range. Further, U–Th/He and magnetostratigraphy techniques indicate that an age close to 3.032 Ma could be preferred, thus, we also use the U–Th/He best fit date of 2.900 Ma U–Th/He (Plummer et al., 2023).

We apply OLE in the reverse temporal direction following Key et al. (2021b) and Solow (2005). Optimal linear estimation produces two important dates pertaining to the origin of the Oldowan. The first (T_O) is an estimated date of origination, which represents the inferred point in time when the Oldowan emerged, measured in years before present. The

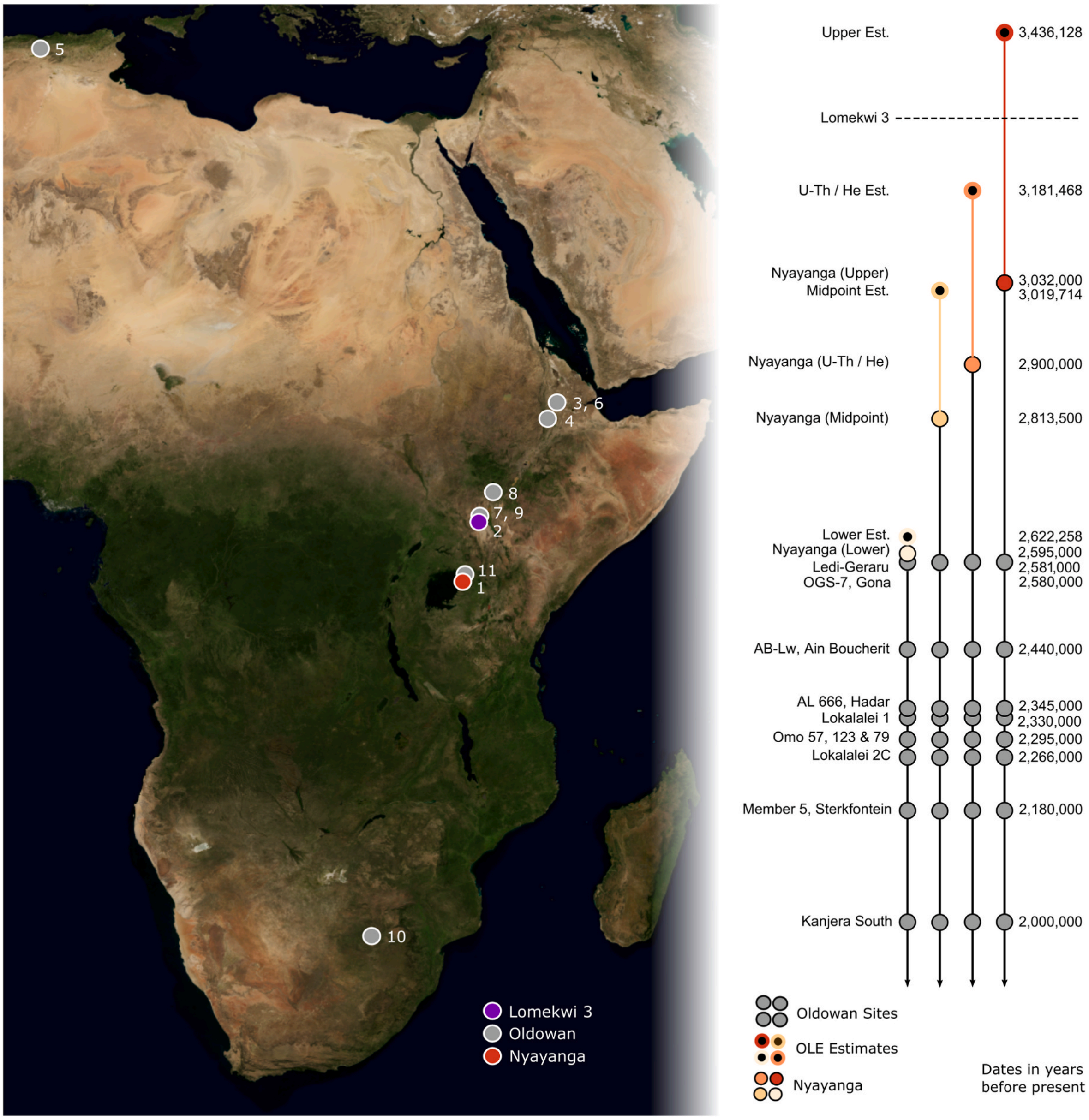

Fig. 1. Timelines illustrating how Nyayanga impacts current understanding concerning the emergence of the Oldowan. The peach through red dots with black outlines highlight the four dates used for Nyayanga in the analyses, while the same colors with a solid black center illustrate how much further back in time Nyayanga pushes the Oldowan after optimal linear estimation (OLE) modeling. Also noted are the location of the archaeological sites present in the timeline: 1 = Nyayanga, 2 = Lomekwi 3, 3 = Ledi-Geraru, 4 = OGS-7 Gona, 5 = AB-Lw Ain Boucherit, 6 = AL 666 Hadar, 7 = Lokalalei 1, 8 = Omo 57,123 and 79, 9 = Lokalalei 2C, 10 = Member 5 Sterkfontein, 11 = Kanjera South. Note that the model returns results expressed as single units (i.e., individual years) but the dating methods used for the input data, and therefore our temporal understanding of the Early Stone Age, is not this precise. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Modeled origin dates for the Oldowan following the discovery of flake tools and butchered fauna at the 2.595 to 3.032 Ma locality of Nyayanga, Kenya. Note that the model provides results expressed as single units (i.e., individual years) but the dating methods used for the input data, and therefore our temporal understanding of the Early Stone Age, is not as precise and often has a resolution of tens or hundreds of thousands of years. The optimal linear estimation results presented here should be interpreted with similar resolution.

Estimate	T_O (years BP)			T_{CI} (years BP)		
	Preferred central date	Resampling (normal)	Resampling (uniform)	Preferred central date	Resampling (normal)	Resampling (uniform)
Nyayanga (3.032 ma)	3,436,128	3,291,734	3,051,591	4,572,920	4,288,607	3,733,217
Nyayanga (U–Th/He)	3,181,468	3,136,037	3,046,336	3,940,537	3,890,642	3,721,294
Nyayanga (Midpoint)	3,019,714	3,029,999	3,044,650	3,570,749	3,638,497	3,715,727
Nyayanga (2.595 ma)	2,622,258	2,783,574	3,046,028	2,741,973	3,096,187	3,720,910

second date is the upper bound of each model's 1 – α confidence interval (T_{CI}). In this context T_{CI} represents the date beyond which the probability of the Oldowan occurring prior to that point is below 5% (when α = 0.05). Further details regarding the OLE technique, including its formulaic expression, can be found in open access formats elsewhere (Key et al., 2021b; Pimiento and Clements, 2014; Roberts et al., 2021).

In this study, OLE was first applied to the author-preferred central date associated with each occurrence. Subsequently, to account for the date ranges associated with each site, we replicated the resampling procedure outlined by Key et al. (2021b) where dates were randomly drawn from the temporal range of each site and these newly sampled date-sets were investigated. This procedure was repeated 10,000 times using both normal and uniform sampling distributions. The mean values derived from all iterations are presented in Table 2. Each analysis was independently conducted for the four investigated Nyayanga dates under investigation. All analyses were run in R v. 4.1.2 (R Core Team, 2022) using the code available in the SOM Files S1 and S2, and the 'sExtinct' package v. 1.1 (Clements et al., 2012). Additional post-hoc analyses under hypothetical future site-discovery scenarios are presented in the following section. We do not describe them here to keep the distinction between data-led and hypothetical models clear.

3. Results

Nyayanga adds uncertainty to our understanding of when the Oldowan first emerged, but in most modeled scenarios, it extends its origin beyond three million years ago (Fig. 2). Previous models based on prior discoveries suggested the technology to first appear around 2.617 to 2.644 Ma (Key et al., 2021b). With the inclusion of Nyayanga, the estimated timeframe for the emergence of the Oldowan extends between 2.622 and 3.436 Ma, with the upper and lower thresholds determined using the site ages of 2.595 and 3.032 Ma, respectively (Table 2). Our preference is to use the midpoint and U–Th/He best fit dates for Nyayanga (see below). Both are broadly consistent and suggest the Oldowan to have emerged at 3.020 or 3.181 Ma. More conservative model estimates place the Oldowan's emergence at 2.622 Ma.

Optimal linear estimation models produce results with precision consistent to the discrete units of time observed in the input data; in this instance, individual years before present (Key et al., 2021a). Temporal resolution in the ESA is, however, substantially lower, often working at scale of tens or hundreds of thousands of years. The results in Table 2 and the SOM S1 and S2 should, therefore, be interpreted with similar resolution. Estimate differences between the four Nyayanga data conditions are underpinned by the model's assumed Weibull-form distribution of site occurrences. This explains why a larger gap between Nyayanga and Ledi-Geraru results in an even greater distance between Nyayanga and the estimated origination age (i.e., the model pushes the Oldowan's origin further back; Fig. 2). Simply, the model expects a gradual fall-off in the Oldowan's distribution 'tail'. In turn, despite Nyayanga's lower date threshold scenario (2.595 ma) occasionally returning early (>3.0 ma) estimates during the resampling procedure, these instances are less frequent than other scenarios, and the median and 25–75 percent quartiles are substantially younger.

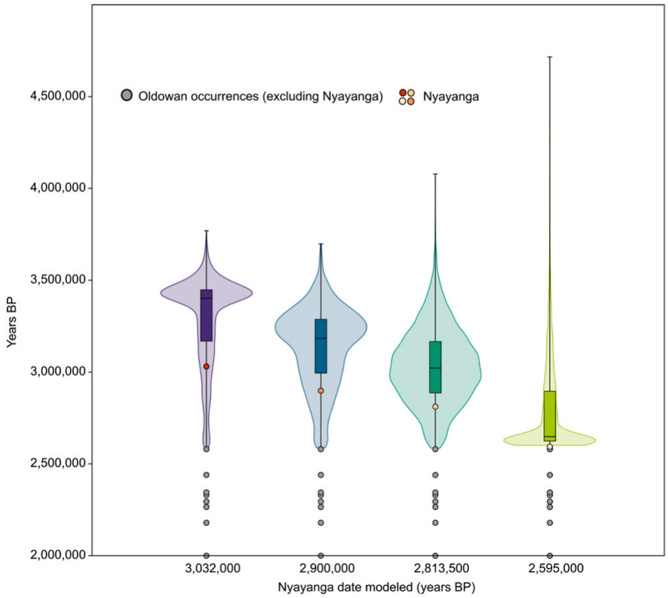

Fig. 2. Violin boxplots detailing predicted origin dates for the Oldowan under the four Nyayanga date scenarios (upper threshold, U–Th/He, central, lower threshold), derived from 10,000 iterations of the random sampling method using a normal distribution.

4. Discussion and conclusions

Our preferred origination date-range takes into account the uncertainty surrounding Nyayanga's age, while also acknowledging Plummer et al.'s (2023) preference for the locality to fall within the upper end of its 2.595 to 3.032 Ma temporal boundaries. The 3.020 or 3.181 Ma dates encompass estimates derived from six of the eight resampling procedures (Table 2). The midpoint and U–Th/He best fit ages are also methodologically consistent with the central dates used for other sites in the analysis (Table 1).

The emergence of the Oldowan at 3.020 or 3.181 Ma alters existing evolutionary models for the technology's appearance (Braun et al., 2019; Gallotti, 2018; Hovers, 2012; Stout et al., 2019). It increases the likelihood that *Australopithecus* was involved in its initial production (Asfaw et al., 1999; Bobe and Wood, 2021). In turn, it reinforces the proposition that the systematic production of sharp-edged flakes for extractive foraging (cf. Braun et al., 2019) was carried out by a genus other than *Homo* (Gallotti, 2018; Hovers, 2012; Plummer and Finestone, 2018), and provides additional temporal evidence for the need to re-evaluate the ecological factors driving this important technological threshold in our evolutionary history (Faith et al., 2021). Simultaneously, new possibilities are raised concerning the potential of lithic-focused cultural transmission between *Australopithecus*, *Paranthropus*, and early *Homo*. Additionally, it potentially strengthens the case for cultural links with the Lomekwi 3 occurrence by reducing the temporal gap needing to be bridged by social learning mechanisms (Flicker and Key, 2023; Stout et al., 2019).

If, however, subsequent evidence confirms the accuracy of Nyayanga's lower date limit (2.595 Ma), then this locality has minimal impact on our understanding of when the Oldowan emerged. An origin of 2.622 Ma falls within existing modeled origination ranges and suggests an emergence shortly before the earliest currently evidenced Oldowan sites (Braun et al., 2019; Key et al., 2021b; Plummer and Finestone, 2018; Semaw et al., 2003). In this scenario, such a short 'long tail' of the early Oldowan would be a result of the tight temporal constraint on the three earliest occurrences, partly due to their dating being based on magnetostratigraphy techniques. Nevertheless, Plummer et al.'s (2023) discoveries at Nyayanga would still be exceptional for extending the spatial distribution of the early Oldowan and for the close association of *Paranthropus* fossils, butchered fauna, and flaked stone tools. However, they would align with previous expectations regarding temporal aspects of the Oldowan's emergence.

If the upper limit of Nyayanga's date range (3.032 Ma) is later verified, then OLE suggests the Oldowan to have a long trajectory deep into the Pliocene, potentially originating earlier than the Lomekwi 3 stone tool and Dikika cut mark occurrences (McPherron et al., 2010; Harmand et al., 2015; Dominguez-Rodrigo et al., 2011; Archer et al., 2020, Fig. 1). Indeed, a 3.436 Ma origin would suggest either the co-occurrence of two culturally and technologically distinct lithic traditions—the Oldowan and Lomekwian—or that Lomekwi 3 is part of a broader, as-yet undefined, earlier Oldowan behavioral repertoire. These findings therefore underscore the importance of additional early Oldowan/Lomekwian site discoveries to provide further support for existing technological distinctions (Braun et al., 2019; Harmand et al., 2015).

The T_{CI} dates ranged widely, spanning from 2.742 to 4.573 Ma (Table 2), which is to be expected considering the four Nyayanga scenarios investigated. When using the midpoint and U–Th/He best fit dates, the estimated threshold beyond which the likelihood of the Oldowan existing drops to 5% or lower, ranges from 3.571 to 3.941 Ma. These dates provide an upper limit with a low probability, but they do raise the possibility of Oldowan-like flaked lithic technologies predating 3.5 Ma, although current temporal evidence suggests this to be unlikely. Such a scenario would have considerable implications for our understanding of the biological and ecological factors driving the development of expediently produced small (relative to Harmand et al., 2015) core and flake technologies.

To assess the robustness of our estimates, we investigated the impact of additional hypothetical site discoveries. We employed uniform and Weibull-form site discovery distributions, simulating the ‘discovery’ of four and six new sites (respectively) between 2.0 and 3.0 Ma (SOM S1). This analysis was repeated for all four Nyayanga scenarios. In both discovery distributions, the estimate ranges were reduced by approximately 50%, substantially reducing the temporal uncertainty introduced by Nyayanga (SOM Tables S1 and S2). Estimates broadly converged on the current midpoint estimates and the lower end of the present preferred estimates, indicating an emergence around 3.0 Ma (±100,000). The upper estimates were approximately 3.38 Ma. While hypothetical in nature, these results suggest that future site discoveries (within existing ranges) may not substantially alter OLE estimates.

Additionally, we explored two other scenarios: one incorporating Omo 79 as an independent site, and another excluding Kanjera South from the analyses. These are outlined in SOM S1 and S2. Neither substantially altered the lower, midpoint and U–Th/He estimates. However, they both increased the upper estimate by approximately 120,000 years (SOM Tables S3 and S4). It is important to note that the present estimates may be subject to revision through future site discoveries outside of current discovery patterns, although these will likely remain within the T_{CI} dates.

In summary, we agree with Plummer et al. (2023), that the Nyayanga site substantially impacts our understanding of the Oldowan’s emergence. By applying OLE modeling to the range of dates presented for this site, however, it becomes clear that the Oldowan may possibly have originated shortly after the Lomekwi 3 stone tool occurrence, somewhere between 3.020 and 3.181 Ma. Yet, it is crucial to acknowledge that without further resolution regarding the age of Nyayanga, or additional site discoveries, OLE suggests the emergence of the Oldowan to be within the range of 2.622–3.436 Ma. Consequently, the findings by Plummer et al. (2023) enhance the likelihood of *Australopithecus* being responsible for the earliest Oldowan occurrences, although additional data are required before this can be confirmed.

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Supplementary Online Material

Supplementary Online Material to this article can be found online at https://doi.org/10.1016/j.jhevol.2023.103468.

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