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High-precision $^{40}Ar/^{39}Ar$ dating of Australasian tektites associated with bifacial tools in the Bose Basin (Xiaomei and Fengshudao sites), South China and in Vietnam (Go Da and Roc Tung 1 sites).

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ABSTRACT

Bifacial tools discovered at about a hundred Lower Palaeolithic sites in the Bose Basin, southern China, have been previously dated to around 800,000 years ago. This age was obtained by dating four tektites directly associated with the tools at the Nalai site using the $^{40}Ar/^{39}Ar$ method (Michel et al., 2021). Similar ages on tektites from the Bogu and Yangwu sites had been previously published, albeit with limited analytical details, by Hou et al. (2000). In this study, a total of eight tektites, discovered alongside abundant lithic artefacts including bifacial tools, were dated with the $^{40}Ar/^{39}Ar$ technique, using an incremental temperature increase approach. Six of these tektites are from two Lower Palaeolithic sites in the Bose Basin; three from Xiaomei and three others from Fengshudao (China). The remaining two tektites come from two sites in Vietnam, one from Go Da and the other from Roc-Tung 1. With the exception of the site of Go Da, the tektites were buried in lateritic sediments associated with the stone tools. At the Go Da site, the tektites were found in a layer overlying the deposit containing bifacial tools. The tektites display no signs of fluvial abrasion or reworking, making them potentially strong chronological markers. Chemical analyses of major elements and rare earth elements indicate that the tektites belong to the Australasian tektite group. This is further confirmed by new $^{40}Ar/^{39}Ar$ analyses with a weighted mean age of 787.2 ± 8.2 ka (2σ) (MSWD = 0.96, P = 0.45). Therefore, when combined with the available results on Australasian tektites, this suggests a highly precise age of 788.0 ± 2.6 ka (2σ; P = 0.84) for these tektites and consequently, for the bifacial tools in this part of Southeast Asia, located east of the Movius

Line. The presence of bifacial tools attests to either a diffusion of the Acheulean from Africa or a local emergence from previous occupations and traditions in Asia.

Keywords: bifaces, bifacial tools, China, Vietnam, tektite, dating, $^{40}Ar/^{39}Ar$, step-heating, Mid-Pleistocene climate transition

1. Introduction

Understanding the evolution, diffusion, behavioural changes and adaptation of hominins over time, and the impact and role of climate cycles on the distribution of occupations, is intricately linked to defining an accurate chronological framework. Many questions remain unclear, such as the precise dates of the onset of Lower Palaeolithic-type industries, including the Acheulean, in Asia (arrivals of new populations/traditions or local evolution). The most commonly utilized methods for dating events from the earliest phases of hominin occupations and dispersion, i.e., 2.6-0.6 Ma, are based on radioactive decay (such as K-Ar and its improved derivative $^{40}Ar/^{39}Ar$, U-Th, and U-Pb), burial dating by isotopic decay ($^{26}Al/^{10}Be$), cumulative processes (Fission track FT, Electron spin resonance ESR, Luminescence), or on the recording of natural processes (such as magnetostratigraphy), often incorporating biochronological data (Pike and Pettitt, 2003; Scaillet et al., 2008; Grün et al., 2010; Shen et al., 2012; Tribolo et al., 2013; Jourdan et al., 2014; Lebatard et al., 2014; Hellstrom and Pickering, 2015; Tu et al., 2017; Carbonell et al., 2010; de Lombera-Hermida et al., 2015; Carbonell et al., 2016; Harmand et al., 2015; Semaw et al., 2003; Garcia et al., 2010; Toro-Moyano et al., 2013).

In Asia, the earliest evidence, based on current knowledge, was discovered in Central China, and consists of four localities (Xihoudu, Renzidong, Longuppo, Longgudong) potentially indicating the presence of hominins. The ages are between ~2.6 and 1.8 Ma (Shen et al., 2020; Han et al., 2017; Wei et al., 2014; Hou and Zhao, 2010; Li et al., 2017; Bae, 2024, Fig. 1, Fig.

2, Table S1). Several other early sites located in North China date between approximately 2 and 1 Ma ago, such as Shangchen, Gongwangling or sites in the Nihewan Formation (Majuangou, Xiantai, Xiaochangliang, Feiliang, Madigou, Cenjiawan, Donggutuo) (Liu et al., 2014; Zhu et al., 2004; Zhu et al., 2018; Tu et al., 2017; Ao et al., 2010; Ao et al., 2012; Deng et al., 2006; Keates, 2010; Liu et al., 2013; Zhu et al., 2001, 2003; Yang et al., 2016; Ao et al., 2013; Li et al., 2016; Pei et al., 2019; Guan et al., 2016; Liu et al., 2013; Wang et al., 2005; Yang et al., 2017; Yang et al., 2020, see Table S1 for details). All these sites have yielded lithic assemblages, described by some as crudely-made tools. Recent dating studies have improved the chronological framework of early hominin presence in this part of Eurasia, as described in Appendix A (Table S1, Fig. 2).

The emergence and diffusion of the Acheulean (with new technological features including Large Cutting Tools-LCTs) is still enigmatic. The earliest evidence is located in Africa, with sites corresponding to the transition from the Oldowan/Mode 1 (core-and-flake industries) to the Early Acheulean/Mode 2. This occurred diachronically around 1.95-1.0 Ma (Lepre et al., 2011; Beyene et al., 2013; Mussi et al., 2023a). These African industries evolved over time into what is described as the Classical Acheulean from ~1.5 to 0.8 Ma (Mussi et al., 2023b; Galloti and Mussi, 2017). Outside Africa, the Acheulean is younger, with evidence in the Levant of an early "Out of Africa" dispersion for this tradition at ~1.6-1.4 Ma at Ubeidiya (Martinez-Navarro et al., 2012; Sagi, 2005; Rink et al., 2007), possibly followed by a second wave at ~800 ka at Gesher Benot Yakov (Goren-Inbar et al., 2018), suggesting, at the least recurrent phases of diffusion outside Africa.

Moving to Asia, two hypotheses have been put forward regarding the emergence of the Acheulean culture beyond the "Movius Line" in an area where LCTs were considered to be absent (Movius, 1948; Bae, 2024): either this represents the diffusion of the Acheulean from

Africa, as observed in the Near East, or it is a local emergence from previous occupations and traditions in Asia (Bae, 2024).

It is therefore essential to accurately date sites with LCTs (bifaces/bifacial tools/handaxes according to studies and authors) in Eurasia in order to contribute to discussions on the onset of this/these new traditions(s) in Asia, and to better define the possible diffusion of what is described in Africa as the Acheulean. Only we then will gain insights into Pleistocene hominin mobility and behavioural strategies in response to a continually changing climate (Bae et al., 2018, Larick and Ciochon, 2015; Qin and Sun, 2023). For convenience, throughout our paper, we use the generic terminology of LCTs to designate lithic assemblages with bifaces, handaxes and bifacial tools.

In Michel et al. (2021), tektites in close association with LCTs at the Nalai site (Bose Basin, South China) were dated to 809 ± 12 ka from 55 total fusion subsamples. A probability density distribution yielded an age centred at 797 ± 6 ka, tentatively suggesting that they might be part of the Australasian tektite strewnfield recently dated to 788 ± 3 ka (2σ, P = 0.54) by the $^{40}Ar/^{39}Ar$ method (Jourdan et al., 2019). In this new study, our aim is to improve the accuracy of our preliminary dating result of the Bose sites (Michel et al., 2021) and obtain new dates for two sites in Central Vietnam yielding LCTs. We dated tektites *via* $^{40}Ar/^{39}Ar$ analysis by the "step-heating" method in order to circumvent inherited argon present in tektites during the initial steps. Furthermore, with this approach, inverse isochron ages can be calculated, which resolves and takes into account any inherited $^{40}Ar^*$ present in the samples in the calculation, provided that its argon isotopic composition is homogenous, thus leading to more accurate results (Jourdan et al., 2019). $^{40}Ar/^{39}Ar$ dating analyses were conducted on tektites from two archaeological sites located in the Bose Basin in China and from two others sites located in Vietnam (An Khê): Xiaomei, Fengshudao, Go Da and Roc Tung 1, respectively (Fig. 1, Fig.

S1, Fig. S2). Major and trace element geochemistry was applied to tektites to assess whether they were part of the Australasian strewnfield.

2. Australasian tektites: origin, background chronology and chronological markers

Tektites are glasses produced by the melting of the continental crust during the impact of a meteorite. This impact causing the formation of Australasian tektites is supposed to have resulted in the formation of a crater located in Indochina, or more likely, in southern Laos. According to the recent study by Sieh et al. (2020), the crater would be buried under the Bolaven volcanic field, near the northern limit of the strewnfield (Fig. 1), although firm evidence is still lacking. These tektites have been found at varying distances from the impact structure, spanning regions from Southeast Asia to Antarctica, with a chemical composition characteristic of the group of Australasian tektites (Koeberl, 1990; Heide et al., 2001; Glass and Koeberl, 2006; Schwarcz et al., 2016).

Tektites closely associated with artefacts from the Bose Basin in China were initially dated using fission track dating (Guo et al., 1997). The authors obtained an age of 732 ± 39 ka for the tektites of the Bogu site (Fig. S1). Subsequently, the $^{40}Ar/^{39}Ar$ method was applied to two tektites from the Bogu site and one from the Yangwu site, but these results were published without age spectra or detailed analytical data (Hou et al., 2000) (Fig. S1). The authors obtained an overall weighted mean age of 803 ± 6 ka (2σ) from the isochron ages of three samples (Hou et al., 2000; Potts et al., 2000).

This first $^{40}Ar/^{39}Ar$ dating of tektite in Bose Palaeolithic sites, presented by Hou et al. (2000) was questioned by Koeberl and Glass (2000). The latter authors cast doubt on the association of tektites with the artefacts and claimed that tektites are generally found in deposits younger than their isotopic age. They thus called for caution in using them as stratigraphic markers (Koeberl and Glass, 2000; Keates, 2000). Potts et al. (2000) responded clearly, affirming that

the Bose tektites are *in situ* and associated with the stone tools in terrace T4, as described by Hou et al. (2000), in the same way as the stone tools found alongside tektites at the Gaolingpo site (Xie et al., 2021). They attributed the tektite age to the tools as there is no geomorphological and stratigraphical indication of the redeposition of either the tools or tektites (Potts et al., 2000). Later, Wang et al. (2014) presented a detailed morphological study of the Fengshudao site and its bifacial industry. In this site, the first excavated association of tektites, dating to ca. 803 ka, with LCTs (including bifaces), and found *in situ*, was described in one stratigraphic level in terrace T4, indicating that the Bose Basin handaxes most likely date to the Early to Middle Pleistocene transition (Fig. 2). However, according to Langbroek (2015), the age of the earliest bifaces in China and the close association between tektites and bifaces have not yet been demonstrated, although this was clearly established by Wang and Bae (2015), and later confirmed at the Nalai site with Australasian tektites and bifaces found together *in situ* (Michel et al., 2021). It is important to note that two Australasian tektites found *in situ* at the Sangiran area have been successfully used as chronological markers. They are consistent with the magnetic polarity stratigraphy and predate the Matuyama-Brunhes transition (MB) (Hyodo et al., 2011). The data demonstrate the near co-occurrence of the tektite level and the magnetostratigraphic constraint, arguing that the last occurrence of Sangiran hominins dates to ~ 0.79 Ma (Fig. 2).

Later, Jourdan et al. (2019) conducted precise dating on four Australasian tektites from Western Australia, Thailand, Vietnam, and southern China, including a tektite from the Bose Basin previously dated by Hou et al. (2000). The exact origin of the tektite from the Bose Basin was not specified by Jourdan et al. (2019). Age plateau and isochron diagrams yielded concordant data with a weighted-mean age of 788.1 ± 2.8 (P = 0.54) for these Australasian tektites, which aligns closely with the less precise $^{40}Ar/^{39}Ar$ age of 793 ± 14 ka published by Schwarz et al. (2016).

3. Xiaomei and Fengshudao sites in Southern China: Geography, stratigraphy and lithic assemblages

The history of Palaeolithic research in the Bose Basin has been thoroughly documented by Wang et al. (2014). Approximately a hundred sites have been discovered in this basin (de Lumley et al., 2020; Wang et al., 2024). In these three abovementioned studies, the geography/geology of the Bose Basin with its Quaternary terrace stratigraphy (see Fig. S3, Fig. S4), as well as overviews of the site's location and lithic assemblages, are also described in detail.

The Xiaomei site is located in Xiaomei village, Youjiang district, Bose city, Guangxi Zhuang Autonomous Region (23°46'41.5" N, 106°42'21.9" E), on the fourth terrace of the Youjiang River (Fig. S1, Fig. S3, Fig. S4, Fig. S5). It was discovered in the 1980s during an archaeological survey covering an area of 350,000 m^2. Many lithic artefacts and a few tektites were exposed on the ground surface of the laterite deposits at the site. The lithic series were made up of diversified LCTs, including pick and tongue-shaped bifaces typical of the area (Fig. 3, n° 6), on sandstone or quartzite pebbles (Fig. 3, n° 7 and 8), associated with flake-tools (scrapers), and notably a large unifacial core on a massive thick quartzite pebble (Fig. 3, n° 9) with centripetal removals. A test excavation conducted in 1996 unearthed artefacts, associated with tektites. Based on geomorphology and artefacts, the age of this site is assumed to be the same as that of Bogu site.

The Fengshudao site (23°57’39’’N, 106°40’39’’E) is situated along the south bank of the Chengbihe River, a significant tributary of the Youjiang River (Fig. S1, Fig. S3, Fig. S4). The site is located in the fourth terrace, spanning 100 metres from east to west, with a sloping terrain from north to south of approximately 10 to 30 metres. Discovered in 2004, the site was excavated from 2004 to 2005, revealing nearly 100 artefacts and nine tektites *in situ* from an excavated area of 62.6 m^2 (Wang et al., 2014). The lithic assemblage at the Fengshudao site

includes the same diversity as at Xiaomei (Fig. 3, n° 5) with in addition, evidence of the use of bipolar debitage. The main raw materials consist of sandstone, quartzite and quartz collected as pebbles. Both tektites and LCTs are found in exactly the same layer within the laterite (Wang et al., 2024) (Fig. 4).

The bifaces exhibit the characteristic shape of the Bose Basin bifaces (Hou et al., 2000; Xie and Bodin, 2007; Zhang et al., 2010; Huang et al., 2012; Wang et al., 2014; Feng et al. 2018; Wang et al., 2024). They are notably short, broad and stocky, featuring a tongue-shaped extremity (Fig. 3, n° 1, 2 and 3).

4. Go Da and Roc Tung 1 sites in Central Vietnam: Geography, stratigraphy and lithic assemblage

Following the discovery of sites with LCTs near the city of An Khê in Central Vietnam in 2014, by Vietnamese archaeologists, systematic excavations have been conducted since 2015 (Derevianko et al., 2018) (Fig. 1, Fig. S2).

Several other similar Palaeolithic sites were identified at the Roc Tung location, situated on the left bank of the Ba River. Artefacts were collected on the surface or discovered *in situ* during excavations and test pits, with similar stratigraphic contexts. The Roc Tung 1 site (14°02'253" N; 108°40'822" E) is situated on a high and relatively flat area of agricultural land. The stratigraphy is well-documented through excavations and various test pits (Derevianko et al., 2018). Three layers have been identified below the surface debris of an irrigation canal. The cultural layer, situated at the top of the laterite (Layer 3), has yielded several *in situ* artefacts associated with tektites (Fig. S6, Fig. 5).

Go Da (13°58'306" N; 108°39'136" E; 440 m a.s.l.) is located downstream, near An Khê, on a sloping hill, 900 m west of the Ba River (Fig. S2). The stratigraphy established during the excavation is somewhat different on this right bank of the Ba (Derevianko et al. (2018);

237 Kandyba et al. (2021) (Fig. S7). The stratigraphic sequence begins with a substantial weathering
238 crust (layer 1) of the granite bedrock, succeeded by slope wash sediments (layer 2). The cultural
239 horizon at Go Da formed during these erosion and slope wash processes, probably in a cooler
240 climate than the present one. Archaeological materials are specifically situated at the top of the
241 weathering crust and at the base of the slope wash layer (Fig. S7). Tektites found in the upper
242 part of this layer 2 indicate that hominins were present at Go Da before the deposition of
243 Australasian tektites. In other words, it can be asserted that the industries at Go Da predate those
244 at Roc Tung 1, where artefacts are found *in situ* with tektites.
245 The local industry is well described by Derevianko et al. (2018) and Kandyba et al. (2021). The
246 lithic assemblage from the Roc Tung 1 site, collected on the surface but also in stratigraphy
247 context during excavations and test pits, includes over 126 pieces (Derevianko et al. 2018),
248 made on pebbles or boulders. This lithic industry from the left bank of the Ba River is made on
249 local raw materials, most often quartzite cobbles or blocks, but also other raw materials of lesser
250 quality, such as vein quartz. Many tested pebbles have been identified in the assemblage, no
251 doubt corresponding to knappers' efforts to select good-quality blanks (Fig. 6).
252 As in the other An Khê-tradition assemblages (Derevianko et al. 2018), the main features of the
253 industry at Roc Tung 1 are heavy-duty-tools including numerous LCTs (bifaces, picks),
254 choppers, and chopping-tools (Fig. 6, n^{o} 2 and 3) and light-duty tools, such as scrapers and
255 pointed tools, often made on flakes. Finally, flakes and cores attest to simple reduction
256 processes: cores mainly bear a single debitage surface with unipolar or centripetal removals and
257 a limited prepared or cortical striking platform.
258 The lithic assemblage at the Go Da site comprises around a hundred artefacts (Derevianko et
259 al. 2018; Kandyba et al 2021), comparable to those from Roc Tung 1. These consist of
260 numerous split tested pebbles, often large in size, hammerstones on rounded granite pebbles, a
261 heavy-duty tool kit with mainly thick, short and stocky LCTs (including bifaces and picks), on

quartzite pebbles or slabs. Some display a tongue-shaped extremity. Others are choppers on long and massive quartzite pebbles, and pointed tools and scrapers (Fig. 6, n°1). The cores, flakes and small flakes indicate *in situ* reduction processes, mainly unifacial and unipolar removals. This assemblage displays all the characteristics of the An Khê industry, as well as regional traditions.

These two assemblages from Roc Tung 1 and Go Da share many similarities to industries from the Bose Basin in China, notably those from Fengshudao and Xiaomei, discussed in this study.

5. Materials and methods

5.1. Materials.

Our analysed tektites come from the Fengshudao and Xiaomei sites (Bose Basin, China), and Roc Tung 1 and Go Da sites (Central Vietnam). They were discovered *in situ* associated with tools (including LCTs), except for the Go Da site, where the tektites were found in a layer overlying bifacial tool-bearing deposits, providing a minimum age for the artefacts.

Three tektites (F1, F2, F3) collected from the laterite layer of terrace T4 at the Fengshudao site (Fig. 7), display a very thin profile (~0.4-0.6 g) and show no signs of fluvial abrasion. They are very angular and sharp, suggesting that no river re-depositing occurred. Additionally, three tektites, namely B1 (10.2 g), B2 (8.7 g), and B3 (6.5 g), were excavated from the same laterite layer from terrace T4 at the Xiaomei site, with a rounder morphology than the others (Fig. 7).

Two tektites from Central Vietnam; one larger tektite, GD (19.1 g), excavated at the Go Da site, and another, large and very angular tektite, RT1 (10.3 g), with no signs of fluvial abrasion, excavated at the Roc Tung 1 site, complete the sample. The GD tektite is rounder, similar to the Xiaomei tektites studied here, but neither show signs of fluvial abrasion or reworking.

5.2. Method

Before analysis, the eight tektite samples were cleaned in an ultrasonic water bath to remove surface-bonded residues (Fig. 7). The thinner tektites (F1, F2, F3) were reduced to pieces. For the larger ones (B1, B2, B3, GD, and RT1), a piece of each tektite was extracted from the original tektites and reduced to pieces. Some were further crushed in an agate mortar and divided into subsamples for multiple analyses. For $^{40}Ar/^{39}Ar$ dating, subsamples 400-500 µm in size, from F1, F2, B1, B2, B3, GD and RT1 tektites, were cleaned with an HNO_3 2N ultrasonic bath for 15 minutes, in HF 2% for 20 minutes, in H_2O, and then in acetone. Subsamples weighing 30-70 mg were analysed using the "step-heating" method with incremental temperature increases to produce an age spectrum and inverse isochron. The $^{40}Ar/^{39}Ar$ analyses were conducted at the Western Australian Argon Isotope Facility (Australia) using an ARGUS VI multicollection instrument and following the procedure described by Jourdan et al. (2019), used for dating the Australasian tektites. The raw data (Appendix B) were processed using the ArArCALC software (Koppers, 2002) and the ages were calculated using the FCs standards (Jourdan and Renne, 2007), for which an age of 28.294 Ma (± 0.13%) was used (Renne et al., 2011), along with the decay constants recommended by Renne et al. (2011). Our criteria for plateau determination are as follows: plateaus must include at least 70% of ^{39}Ar. The plateau should be distributed over a minimum of three consecutive steps agreeing at 95% confidence level and satisfying a probability of fit (P) of at least 0.05. Plateau ages are given at the 2σ level and are calculated using the mean of all the plateau steps, each weighted by the inverse variance of their individual analytical error. Uncertainties include analytical and J-value errors. Errors with all sources of uncertainties such as the decay constants errors increase the uncertainty by ± 0.2 ka for those samples and are indicated by a square bracket (e.g., [± 3 ka]).

The composition of major and trace elements presented in Tables S2 and S3, was determined for all tektites by Laser Ablation Inductively Coupled Plasma Mass Spectrometry at the Centre Ernest-Babelon of the IRAMAT (CNRS/Orléans University) or by Inductively Coupled Plasma

311 Optical Emission Spectrometry at SARM (Service d'Analyses des Roches et des Minéraux,
312 CRPG Nancy, France (see additional details in SI). The composition of major elements of
313 tektites N411, N425, N862, N959 from Nalai site in the Bose Basin, China, as reported by
314 Michel et al. (2021), was supplemented with the analysis of rare earth elements and is presented
315 in Table S3.
316
317 **6. Results**
318 *6.1 Chemical composition*
319 The major elemental compositions obtained for the tektites B1, B2, B3 (Xiaomei), F1, F2, F3
320 (Fengshudao), GD (Go Da) and RT1 (Roc Tung 1), are presented in Table S2. They comprise
321 the following ranges: 70.05-74.74 % for SiO_2, 11.13-15.44 % for Al_2O_3, 4.17-4.96 % for FeO,
322 1.77-2.67 % for CaO, 2.06-2.42 % for K_2O, 1.92-2.67 % for MgO, 0.93-1.51 % for Na_2O, 0.68-
323 0.78 % for TiO_2, 0.08-0.10 % for MnO, 0.03-0.07 % for P_2O_5. These values are very close to
324 those of the tektites from Nalai (N411, N425, N862, N959) (Michel et al., 2021) (Table S2). In
325 Figure 8, these values are compared with various groups of tektites according to Schwarz et al.
326 (2016) and Wesgate et al. (2021). Figure 8 shows that our tektites belong to the group of
327 Australasian tektites. Tektites from Vietnam (GD and RT1) are very slightly different to those
328 from the Bose Basin. They belong to the subgroup of indochinite showing some regional
329 compositional variation in comparison with the australite subgroup, but ultimately belong to
330 the same Australasian group. In the same way as the Australasian tektites, our tektites exhibit
331 light rare-earth-element-(REE)-enriched compositions with a marked negative EU anomaly, as
332 described by Koeberl (1990), Son and Koeberl (2005), Amare and Koeberl (2006), Wesgate et
333 al. (2021) and Schwarz et al. (2016) (Fig. 9).
334
335 *6.2 $^{40}Ar/^{39}Ar$ dating*

We obtained seven plateau ages ranging from 779 ± 19 ka (MSWD = 0.53; P=0.93) to 827 ± 57 ka (MSWD = 0.09; P = 1.00) and including between 91 and 100 % of the total released ^{39}Ar (Fig. 10, Appendix B). Inverse isochrons yielded similar ages ranging from 774 ± 24 to 842 ± 67 and with trapped $^{40}Ar/^{36}Ar$ ratios in error of the atmospheric value of 298.6 ± 0.3 and ranging from 293.3 ± 4.9 to 300.8 ± 6.0 (Appendix C). The K/Ca ratio (derived from $^{39}Ar_K/^{37}Ar_{Ca}$) shows homogenous values across a given tektite but varies among samples with average values ranging from 0.32 ± 0.18 to 1.29 ± 0.11. The seven plateau ages (P = 0.84) and inverse isochron ages (P = 0.25) are all indistinguishable from each other, indicating the dating of a single event, as expected for tektites originating from a single impact. Furthermore, all intercept $^{40}Ar/^{36}Ar$ values define a single population (P = 0.57) with a weighted mean of 296 ± 3, suggesting that no inherited $^{40}Ar^*$ is present in the samples analysed in this study. Therefore, we calculated a single weighted mean age of 787.2 ± 8.2 ka (2σ; MSWD = 0.96; P = 0.45) as the best estimate for the impact event that produced these tektites. This age is indistinguishable from the previous age of 788.1 ± 2.8 (Jourdan et al., 2019), indicating that the tektites are part of the Australasian strewnfield, as also evidenced by their chemical composition. When combined with our new age, we obtained a conclusive best age estimate of 788.0 ± 2.6 [2.8] ka (2σ; P = 0.84) for the Australasian tektites that will be used in the rest of this study.

7. Discussion on the new results of the Chinese and Vietnamese sites regarding the emergence and diffusion of the Acheulean in Eurasia

7.1 Emergence of the Acheulean in Africa and its initial diffusion

The emergence of the Acheulean in Africa is dated to around 1.75 to < 1.0 Ma (i.e., in southern Ethiopia, Beyene et al., 2013) and around 1.76 Ma years ago at Kokiselei 4 in Kenya (Lepre et al., 2011) but may have occurred earlier, around 1.95 Ma years ago at Garba IV (Upper Awash, Ethiopia, Mussi et al., 2023a). This shift was characterized among others (flaking methods,

land-use patterns) by hominin capability to produce large flakes and LCTs, including for example, handaxes, picks and sometimes cleavers. The earliest LCTs (including bifaces), outside Africa are reported at ~1.4-1.2 Ma ago in Ubeidiya in the Levant (Martinez-Navarro et al., 2012; Sagi, 2005; Rink et al., 2007), and are also dated to ~1.5 Ma in Attirampakkam, India, indicating a rapid diffusion throughout Eurasia, if we consider that these industries are related to the African Acheulean. These types of LCTs are not present, earlier than 0.9-0.7 Ma in Western Europe (Pappu et al., 2011; Vallverdu et al., 2014; Voinchet et al., 2015; Antoine et al., 2019; Moncel et al., 2020a; Moncel et al., 2020b). In Asia, the core-and-flake series (Mode 1) persist when Lower Palaeolithic/Acheulean (Mode 2) industries with LCTs (bifaces/bifacial tools/handaxes) appear in some areas around 1.5-0.8 Ma ago. The number of discovered sites increase during the Mid-Pleistocene climate transition (MPT) (1.0-0.6 Ma) suggesting that this period played a crucial role in the diffusion of hominins in Eurasia (Fig. 2, Table S1).

7.2. New insights from Chinese and Vietnamese sites

These new assemblages with LCTs in Asia are currently found in four main Chinese areas (specifically Dingcun, Bose Basin, Luonan Basin, and the Danjiangkou Reservoir Region DRR) (Li et al., 2018, Li et al., 2014). Unfortunately, dating details are limited, except for the site of Yunxian (open-air site of Xuetangliangzi, DRR region, Central China), where two *Homo erectus* crania were discovered with one handaxe and 13 LCTs collected from the surface (Li et al., 2018). This site is approximatively dated between ~1.1-0.85 Ma using both paleomagnetism, biochronology and ESR dating on teeth and quartz (de Lumley and Li, 2008; Echassoux et al., 2008; Tissoux et al., 2008; Feng, 2008) (Fig.1, Fig.2, Table S1). Many other sites with LCTs, up to 200 LCTs, were discovered in this area but further chronological research is required. They are regarded as the most significant persistence of LCTs for a long period, from the late Early Pleistocene to the early part of the Late Pleistocene (Li et al., 2018).

Our results on four Chinese and Vietnamese sites provide strong and accurate data on Asian human occupations with LCTs dated to ~ 788 ka. Through these new data, we contribute to understanding of the chronology and diffusion of the earliest populations in Asia.

Early human populations thrived and expanded across mainland East Asia, from low latitudes whatever their technology (e.g., the Bose Basin) to high northern latitudes (e.g., the Nihewan Basin, Zhoukoudian). The associated industry is often roughly dated using paleomagnetism, as seen in Maliang (Nihewan Formation, North China), Wutaicun (Central China), Longgangsi-2 and 3 (Central China). The determined ages are approximately ~0.78 Ma (Wang et al., 2005), ~0.9 Ma and ~1.2-0.7 Ma (Sun et al., 2017) respectively. Despite approximate dating, an overview of paleoenvironmental and archaeological data in the Nihewan Basin reveals changes in hominin presence and indicates that sustained occupation in high latitudes characterized by strong seasonality was not possible until the Late Pleistocene, as evidenced by chronological gaps (Yang et al., 2020). Mode1/Oldowan industries persisted in Asia at Bailong Cave with human teeth in Central China, dated between ~0.78 Ma and ~0.51 Ma, and also using multi-dating methods such as paleomagnetism, $^{26}Al/^{10}Be$ burial on quartz and ESR/U-series on teeth (Liu et al., 2015; Han et al., 2018; Kong et al., 2018).

Moving outside China, this lithic industry is also evidenced at the site of Kalinga between around 1.05 and 0.63 Ma, in the Philippines (Ingicco et al., 2018), and between around 1.01 and 0.7 Ma at Mata Menge and Wolo Sege in Indonesia (Brumm et al., 2016). During the same period, an Acheulean-type industry is present at Shuigou-Huixinggou, in Central China, but approximatively dated to ~0.9 Ma by paleomagnetism (Li et al., 2017). Other Mode 1/Mode 2 sites dated by alternative radioisotopic methods provide more precise dating (Fig.2, Table S1). This is the case for Zhoukoudian Locality 1, in North China, where human remains and industries with bifacial tools and flake-tools (Derevianko, 2008) are well dated to ~0.78-0.4 Ma

using multi-dating methods, such as paleomagnetism, $^{26}Al/^{10}Be$ burial and U-Th (Shen et al., 2009, Shen et al., 2016).

Li et al. (2018) propose that the technological transmission hypothesis could be a suitable explanation for the emergence of Chinese LCTs technology and suggest a diffusion of the Acheulean-type tradition by hominins from west to east to China and other Asia aeras as Vietnam. Other authors propose a local onset derived from previous Mode 1/core-and-flake assemblages (convergence), giving rise to the An Khê tradition observed at the Go Da and Roc Tung Lower Palaeolithic sites in Vietnam (Derevianko et al., 2018) and the Acheulean in the Bose Lower Palaeolithic sites (Wang et al., 2014; Wang and Bae, 2015; Wang et al., 2024; Bae, 2024) (Fig.1, Fig.2, Table S1).

Our results highlight that the industries at the Bose and An Khê sites are now well dated to 788.0 ± 2.6 ka (2σ) by dating *in situ* Australasian tektites associated with the bifaces. This significant chronological marker accurately positions the industries at the Bose and An Khê sites within the chronological sequence of industries in Asia and also indicates a well-established presence of LCTs and possibly the Acheulean-type tradition in this region of Asia.

8. Conclusion

Our dating of Australasian tektites discovered *in situ* alongside artefacts at the Bose sites in southern China and An Khê in Central Vietnam using $^{40}Ar/^{39}Ar$ gives an age of 788.0 ± 2.6 [2.8] ka. This age indicates that LCTs (including bifaces), and thus what can be described as the Acheulean, developed in this part of Asia around 788 ka during the Mid-Pleistocene climate transition, regardless of the hypothesis regarding the onset of the Acheulean (Fig. 2, Table S1). Our result can be compared to the age of the Acheulean industry also found at around 1.1-0.8 Ma at DRR sites, Yunxian and Shuigou-Huixinggou in Central China. This new LCT-making tradition is penecontemporaneous with persistent core-and-flake series (Mode 1) at Nihewan in

435 northern China, at Bailong, as well as Longgangsi in Central China. This persistence of
436 assemblages without LCTs extends to the Philippines at Kalinga and Indonesia at Mata Menge
437 and Wolo Sege, with for some, the presence of *Homo erectus* while the Acheulean-type
438 assemblages persist at Zhoukoudian (~0.8-0.6 Ma) in North China. The Bose and An Khê sites
439 can be considered as the earliest well-dated evidence of Acheulean-type tradition beyond the
440 Movius Line in eastern Asia, showing that hominins in these areas were capable of making
441 LCTs, including bifaces at ~788 ka.
442

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448

449 **Figure captions**

450 **Figure 1.** Portion of the Australasian tektite strewnfield (modified from Wesgate et al., 2021)
451 with a potential crater impact in southern Laos (Sieh et al., 2020). The Movius Line is
452 represented by the red dashed line, separating Western Asia, where LCTs were discovered from
453 Eastern Asia, where LCTs, were considered absent (Movius, 1948). However, since then,
454 Acheulean assemblages with LCTs have been discovered east of the line (Bae, 2024). The
455 archaeological sites are located south of the 45°N parallel and are classified in chronological
456 order**.** The sites are dated using methods such as radiometric dating and/or relative dating,
457 including biochronology and paleomagnetism, based on current knowledge (Table S1). The
458 distribution indicates sites with Mode 1 (core-and-flake assemblages) (marked with stars), those

459 with *Homo* remains (marked with circles), and those associated with Acheulean/Mode 2
460 (marked with triangles). Red symbols represent the studied sites, while black symbols denote
461 other key sites (see details in Tab S1): (**1**) Masol, India, (**2**) Riwat, Pakistan, (**3**) Attirampakkam,
462 India, (**4**) Renzidong, Central China, (**5**) Xihoudu, northern China (**6**) Longgupo, Central China,
463 (**7**) Longgudong, Central China, (**8**) Shangchen, Central China, (**9**) Gongwangling (Lantian
464 man), North China, (**10**) Niujianbao, Southwest China, (**11**) Many sites in the Nihewan Basin,
465 northern China: e.g. Donggutuo, Maliang, Feilang Xiaochangliang, Xiantai, Majuangou,
466 Madigou, Cenjiawan Xiaochangliang, (**12**) Sangiran, Bapang, Lower Lahar unit, Central Java,
467 Indonesia, (**13**) Longgangsi 3-2, (**14**) Soa Basin, Ola Bula Formation, Mata Menge, Wolo Sege,
468 Central Flores, eastern Indonesia (**15**) Yunxian, DRR sites, Central China, (**16**) Wutaicun,
469 Central China, (**17**) Shuigou-Huiximggou, Central China, (**18**) Meipu, Central China, (**19**)
470 Trinil, Java, Indonesia, (**20**) Many sites in the Bose Basin, Bogu, Yangwu; Nalai, Fengshudao,
471 Xiaomei (this study), (**21**) Roc Tung 1 and Go Da, Central Vietnam (this study), (**22**) Kalinga,
472 Philippines, (**23**) Bailong, Central China, (**24**) Zhoukoudian Locality 1, northern China, (**25**)
473 Yiyuan, northern China.

474

475 **Figure 2**. Chronological sequence of Palaeolithic sites with hominin fossils and/or lithic
476 assemblages according to geographical location and correlation with marine isotope stages and
477 $\delta^{18}O$ stacks (Lisiecki and Raymo, 2005). The horizontal grey band denotes the Mid-Pleistocene
478 climate transition MPT (1.0-0.6 Ma).

479

480 **Figure 3.** Lithic artefacts from Fengshudao site (1 to 5) and from Xiaomei site (6 to 9). 1 to 3-
481 tongue-shaped bifaces (N007612; N007622; N007623); 4- chopper (N007775); 5- large flake
482 (N007566); 6-tongue-shaped biface (N73 H05); 7 & 8- picks (N94 5.6; N193 G2); 9- large core
483 (N59).

Figure 4. Fengshudao site excavation. Photographs showing the *in situ* discovery of biface No. Z007773 (2) in the laterite layer, in close association with tektite No. FSD-059 (1).

Figure 5. Roc Tung 1 excavation. Photograph showing an *in situ* discovery of a pebble core No 16.RT1.ST79 (2) in the laterite layer (Layer 3), in close association with a tektite No 14 (1). Bifaces were excavated in the same layer.

Figure 6. Lithic artefacts from Go Da site (1) and from Roc Tung 1 site (2 and 3). 1- scraper; 2- chopper; 3- biface.

Figure 7. Photograph of tektites analysed in this study: F1, F2, F3 (~0.4-0.6 g) are three thin tektites excavated from Fengshudao site, Bose Basin, China; B1 (10.2 g), B2 (8.7 g), B3 (6.5 g) are three tektites excavated from Xiaomei site, Bose Basin, China ; GD (19.1 g) is a tektite excavated from Go Da site and RT1 (10.3 g) is a tektite excavated from Roc Tung 1 site, Vietnam. GD and RT1 were cleaned with a H_20 ultrasonic bath.

Figure 8. Chemical composition of various tektite groups, based on the original figure by Schwarz et al. (2016) with modifications. This figure includes a comparison of compositions with cited references by Schwarcz et al. (2016) (Taylor, 1962; Chapman and Schreiber, 1969; O'Reilly et al., 1983; Koeberl et al., 1997; Meisel et al., 1997; Albin et al., 2000; Son and Koeberl, 2005; Amare and Koeberl, 2006), including Belize (BZ1) (Central America, with impact glasses formed at 804 ± 9 ka, Rochette et al., 2021), Ivory Coast tektite (Ivorite), and

507 Australasian tektites such as Indochinite B (Muong-Nong), Western Canada (WC1) with
508 impact glasses formed at 785 ± 7 ka ($^{40}Ar/^{39}Ar$ age, Schwarcz et al., 2016), and those with a
509 weighted FT age of 822 ± 20 ka from Malaysia, Java, Australia (group A) (Wesgate et al.,
510 2021). Additionally, we present the chemical compositions of tektites from Nalai, Xiaomei,
511 Fengshudao, Roc Tung 1 and Go Da sites, demonstrating similarities to the Australasian tektite
512 group.
513
514 **Figure 9.** Rare earth element abundances for tektites N411, N425, N862, N959 (Nalai site); F1,
515 F2, F3: tektites (Fengshudao site); B1, B2, B3 (Xiaomei site); GD (Go Da site); RT1 (Roc Tung
516 1 site). They are chondrite-normalized rare-earth-element (REE) abundance curves (chondrite
517 concentrations are from McDonough and Sun, 1995). The abundances are compared with
518 various tektites, including Belize (BZ1), Ivory Coast tektite 1, and Australasian tektites, such
519 as Indochinite B (Muong-Nong), Western Canada (WC1) (Schwarcz et al., 2016), and those
520 from Malaysia (UT1389), Java (UT2336), Australia (UT2330, UT2334, UT1392, UT2402)
521 (Wesgate et al., 2021). The patterns of our tektites are similar to Australasian tektites (Schwarcz
522 et al., 2016; Wesgate et al., 2021), but distinct to the Belize and the Ivory coast tektites with
523 their lower concentrations and different impact events (Schwarcz et al., 2016).
524
525 **Figure 10**. $^{40}Ar/^{39}Ar$ age spectra of tektites. Plateau age given at the 2σ level. B1, B2, B3:
526 tektites from Xioamei site; F1, F2: tektites from Fengshudao site; RT1: tektite from Roc Tung
527 1; GD: tektite from Go Da.
528
529 **Appendix A.** Supplementary information.
530 **MC2**. Ar isotopic data corrected for blank.
531 **MC3**. $^{39}Ar/^{40}Ar$ vs. $^{36}Ar/^{40}Ar$ inverse isochron plots.

MC4. Tables S2 and S3

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Figure 1

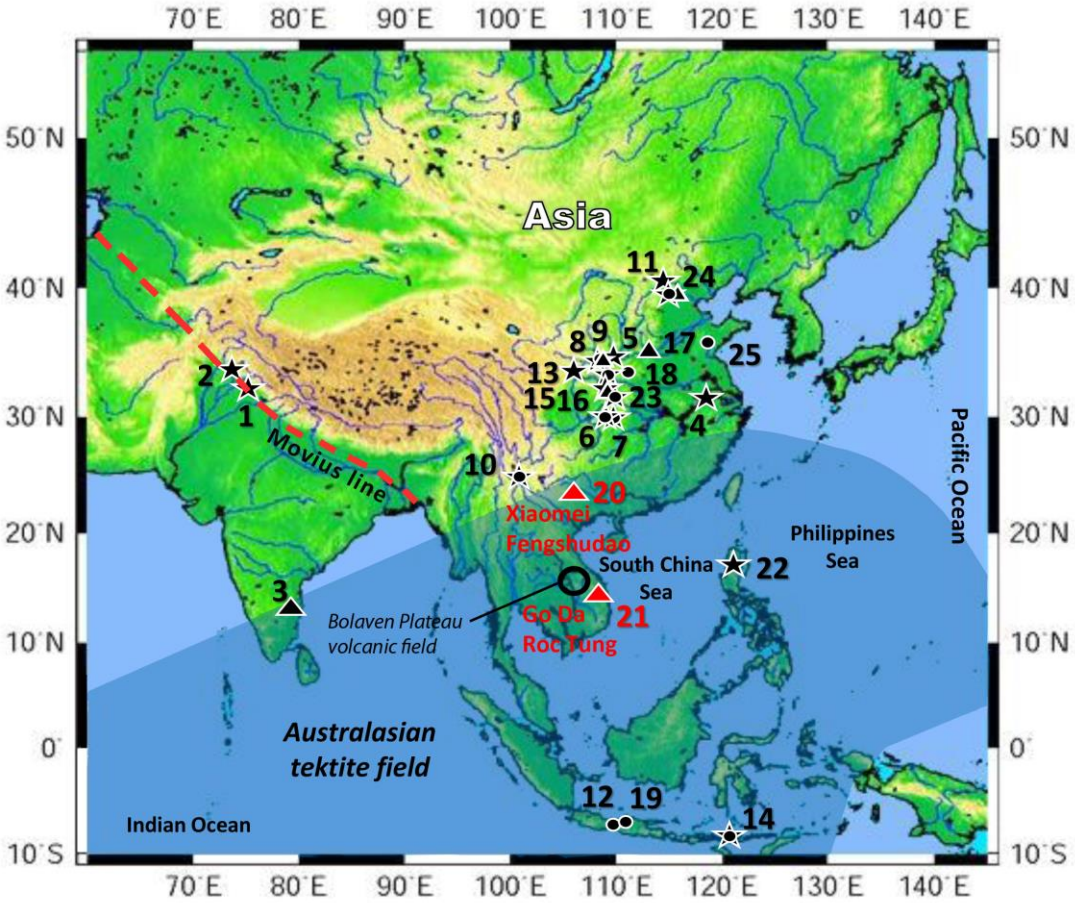


Figure 2

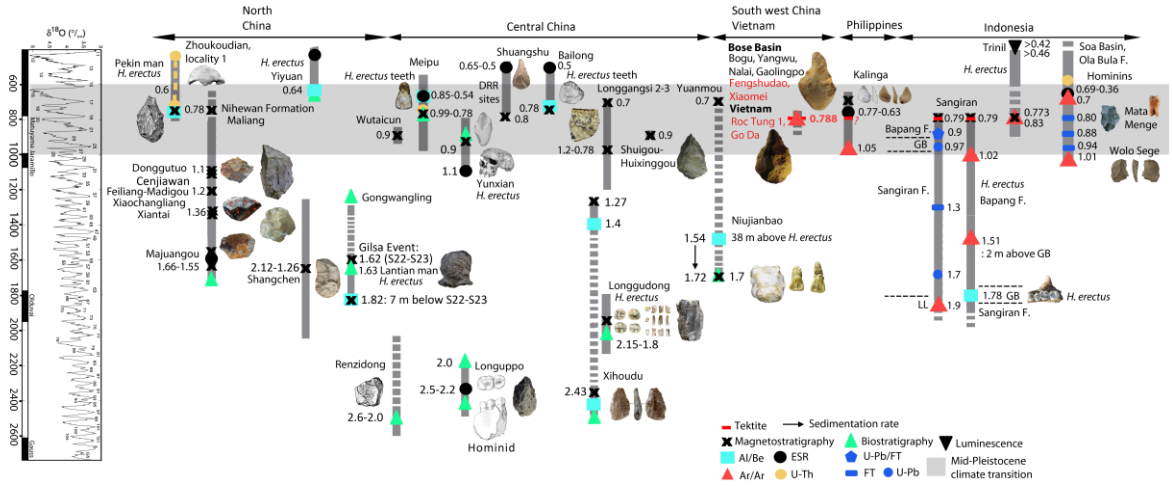


Figure 3

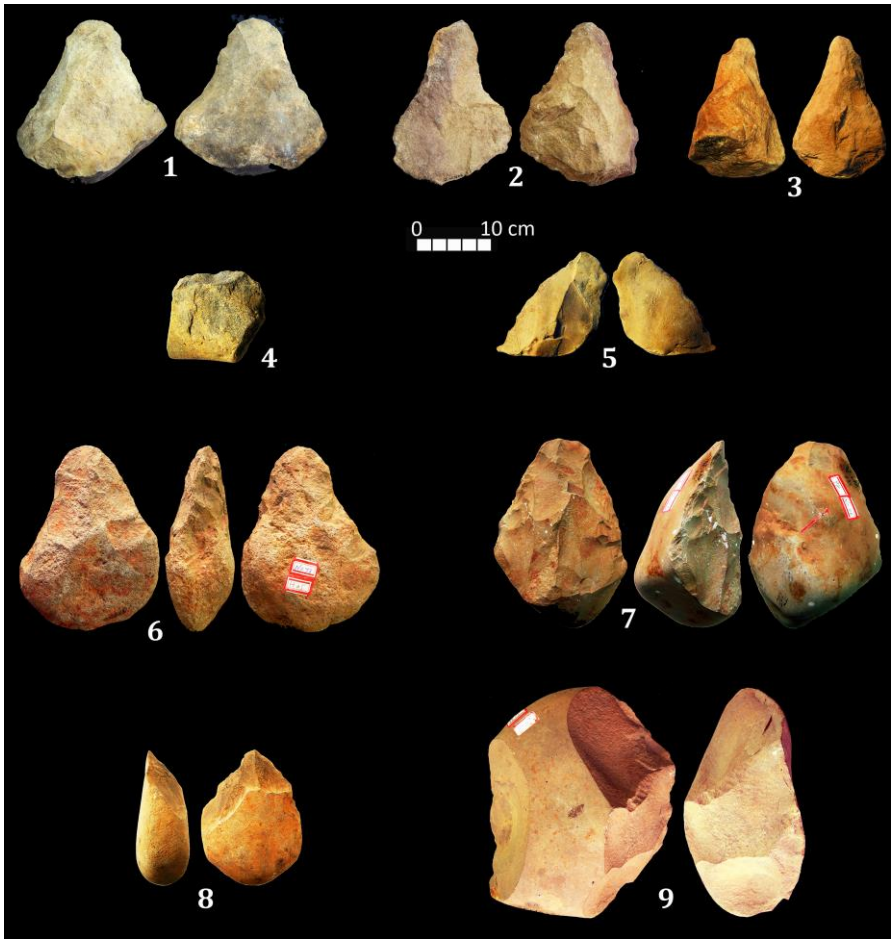


Figure 4

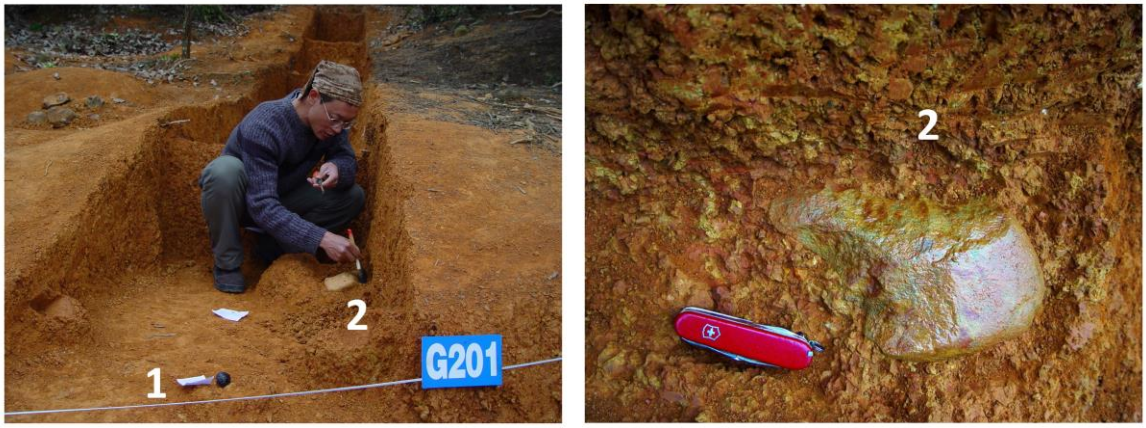


Figure 5

Figure 6

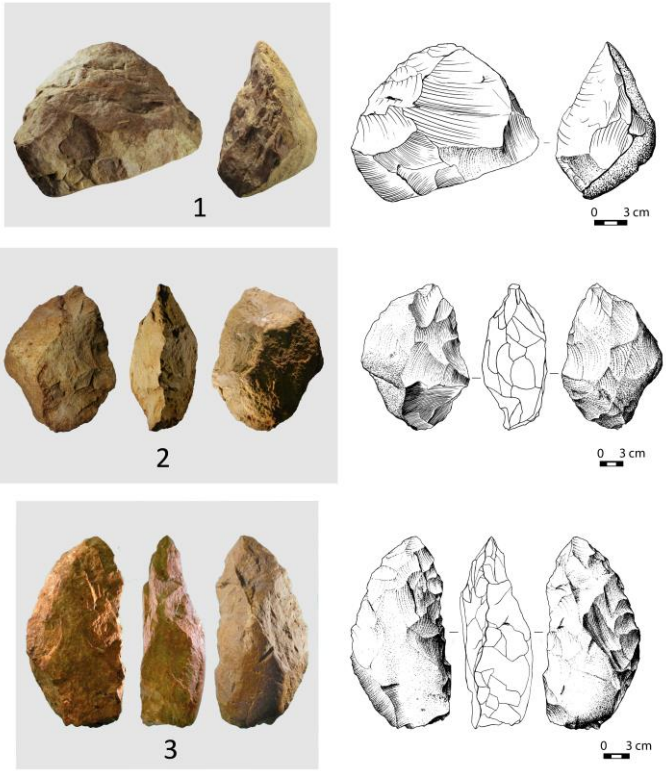


Figure 7

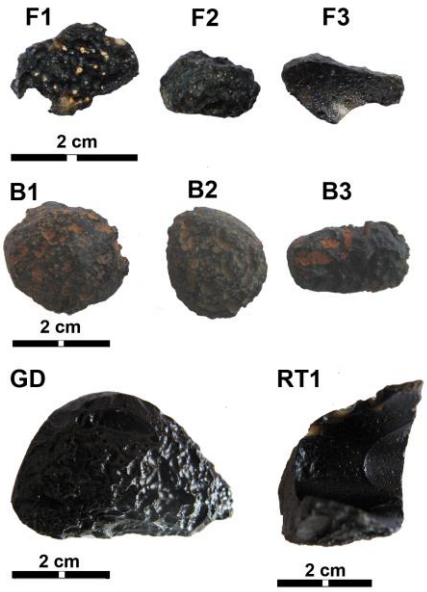


Figure 8

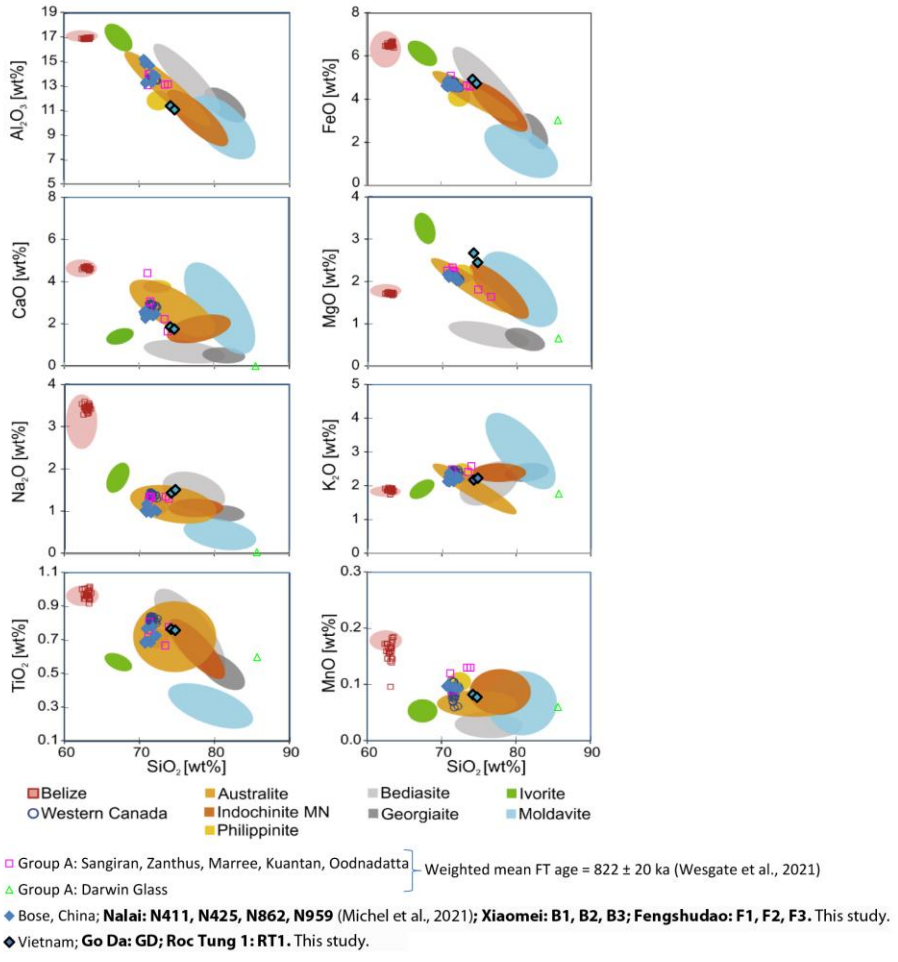
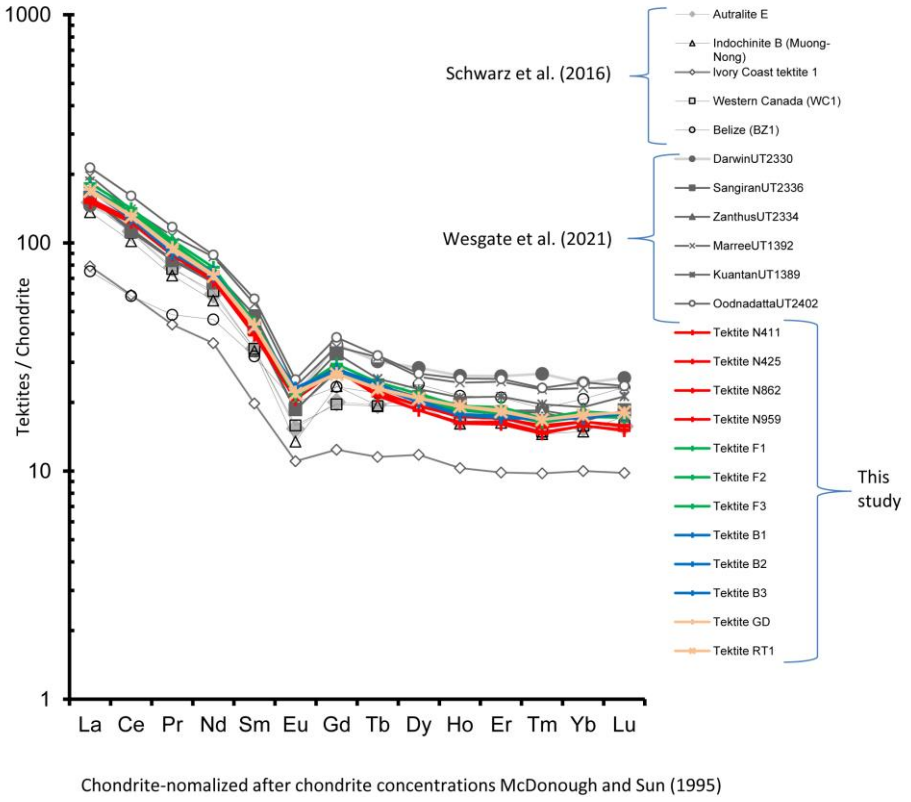


Figure 9



Chondrite-nomalized after chondrite concentrations McDonough and Sun (1995)

Figure 10