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High-precision $^{40}\text{Ar}/^{39}\text{Ar}$ 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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3 **High-precision $^{40}\text{Ar}/^{39}\text{Ar}$ dating of Australasian tektites associated with**
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5 **and in Vietnam (Go Da and Roc Tung 1 sites).**

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44 **ABSTRACT**

45 Bifacial tools discovered at about a hundred Lower Palaeolithic sites in the Bose Basin,
46 southern China, have been previously dated to around 800,000 years ago. This age was obtained
47 by dating four tektites directly associated with the tools at the Nalai site using the $^{40}\text{Ar}/^{39}\text{Ar}$
48 method (Michel et al., 2021). Similar ages on tektites from the Bogu and Yangwu sites had
49 been previously published, albeit with limited analytical details, by Hou et al. (2000). In this
50 study, a total of eight tektites, discovered alongside abundant lithic artefacts including bifacial
51 tools, were dated with the $^{40}\text{Ar}/^{39}\text{Ar}$ technique, using an incremental temperature increase
52 approach. Six of these tektites are from two Lower Palaeolithic sites in the Bose Basin; three
53 from Xiaomei and three others from Fengshudao (China). The remaining two tektites come
54 from two sites in Vietnam, one from Go Da and the other from Roc-Tung 1. With the exception
55 of the site of Go Da, the tektites were buried in lateritic sediments associated with the stone
56 tools. At the Go Da site, the tektites were found in a layer overlying the deposit containing
57 bifacial tools. The tektites display no signs of fluvial abrasion or reworking, making them
58 potentially strong chronological markers. Chemical analyses of major elements and rare earth
59 elements indicate that the tektites belong to the Australasian tektite group. This is further
60 confirmed by new $^{40}\text{Ar}/^{39}\text{Ar}$ analyses with a weighted mean age of 787.2 ± 8.2 ka (2σ) (MSWD
61 = 0.96, P = 0.45). Therefore, when combined with the available results on Australasian tektites,
62 this suggests a highly precise age of 788.0 ± 2.6 ka (2σ ; P = 0.84) for these tektites and
63 consequently, for the bifacial tools in this part of Southeast Asia, located east of the Movius

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

66

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

69

70 **1. Introduction**

71 Understanding the evolution, diffusion, behavioural changes and adaptation of hominins over
72 time, and the impact and role of climate cycles on the distribution of occupations, is intricately
73 linked to defining an accurate chronological framework. Many questions remain unclear, such
74 as the precise dates of the onset of Lower Palaeolithic-type industries, including the Acheulean,
75 in Asia (arrivals of new populations/traditions or local evolution). The most commonly utilized
76 methods for dating events from the earliest phases of hominin occupations and dispersion, i.e.,
77 2.6-0.6 Ma, are based on radioactive decay (such as K-Ar and its improved derivative $^{40}\text{Ar}/^{39}\text{Ar}$,
78 U-Th, and U-Pb), burial dating by isotopic decay ($^{26}\text{Al}/^{10}\text{Be}$), cumulative processes (Fission
79 track FT, Electron spin resonance ESR, Luminescence), or on the recording of natural processes
80 (such as magnetostratigraphy), often incorporating biochronological data (Pike and Pettitt,
81 2003; Scaillet et al., 2008; Grün et al., 2010; Shen et al., 2012; Tribolo et al., 2013; Jourdan et
82 al., 2014; Lebatard et al., 2014; Hellstrom and Pickering, 2015; Tu et al., 2017; Carbonell et al.,
83 2010; de Lombera-Hermida et al., 2015; Carbonell et al., 2016; Harmand et al., 2015; Semaw
84 et al., 2003; Garcia et al., 2010; Toro-Moyano et al., 2013).

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

89 [2, Table S1](#)). Several other early sites located in North China date between approximately 2 and
90 1 Ma ago, such as Shangchen, Gongwangling or sites in the Nihewan Formation (Majuangou,
91 Xiantai, Xiaochangliang, Feiliang, Madigou, Cenjiawan, Donggutuo) ([Liu et al., 2014](#); [Zhu et](#)
92 [al., 2004](#); [Zhu et al., 2018](#); [Tu et al., 2017](#); [Ao et al., 2010](#); [Ao et al., 2012](#); [Deng et al., 2006](#);
93 [Keates, 2010](#); [Liu et al., 2013](#); [Zhu et al., 2001, 2003](#); [Yang et al., 2016](#); [Ao et al., 2013](#); [Li et](#)
94 [al., 2016](#); [Pei et al., 2019](#); [Guan et al., 2016](#); [Liu et al., 2013](#); [Wang et al., 2005](#); [Yang et al.,](#)
95 [2017](#); [Yang et al., 2020](#), see [Table S1 for details](#)). All these sites have yielded lithic
96 assemblages, described by some as crudely-made tools. Recent dating studies have improved
97 the chronological framework of early hominin presence in this part of Eurasia, as described in
98 [Appendix A \(Table S1, Fig. 2\)](#).

99 The emergence and diffusion of the Acheulean (with new technological features including
100 Large Cutting Tools-LCTs) is still enigmatic. The earliest evidence is located in Africa, with
101 sites corresponding to the transition from the Oldowan/Mode 1 (core-and-flake industries) to
102 the Early Acheulean/Mode 2. This occurred diachronically around 1.95-1.0 Ma ([Lepre et al.,](#)
103 [2011](#); [Beyene et al., 2013](#); [Mussi et al., 2023a](#)). These African industries evolved over time into
104 what is described as the Classical Acheulean from ~1.5 to 0.8 Ma ([Mussi et al., 2023b](#); [Galloti](#)
105 [and Mussi, 2017](#)). Outside Africa, the Acheulean is younger, with evidence in the Levant of an
106 early “Out of Africa” dispersion for this tradition at ~1.6-1.4 Ma at Ubeidiya ([Martinez-Navarro](#)
107 [et al., 2012](#); [Sagi, 2005](#); [Rink et al., 2007](#)), possibly followed by a second wave at ~800 ka at
108 Gesher Benot Yakov ([Goren-Inbar et al., 2018](#)), suggesting, at the least recurrent phases of
109 diffusion outside Africa.

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

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

115 It is therefore essential to accurately date sites with LCTs (bifaces/bifacial tools/handaxes
116 according to studies and authors) in Eurasia in order to contribute to discussions on the onset
117 of this/these new traditions(s) in Asia, and to better define the possible diffusion of what is
118 described in Africa as the Acheulean. Only we then will gain insights into Pleistocene hominin
119 mobility and behavioural strategies in response to a continually changing climate (Bae et al.,
120 2018, Larick and Ciochon, 2015; Qin and Sun, 2023). For convenience, throughout our paper,
121 we use the generic terminology of LCTs to designate lithic assemblages with bifaces, handaxes
122 and bifacial tools.

123 In Michel et al. (2021), tektites in close association with LCTs at the Nalai site (Bose Basin,
124 South China) were dated to 809 ± 12 ka from 55 total fusion subsamples. A probability density
125 distribution yielded an age centred at 797 ± 6 ka, tentatively suggesting that they might be part
126 of the Australasian tektite strewnfield recently dated to 788 ± 3 ka (2σ , $P = 0.54$) by the
127 $^{40}\text{Ar}/^{39}\text{Ar}$ method (Jourdan et al., 2019). In this new study, our aim is to improve the accuracy
128 of our preliminary dating result of the Bose sites (Michel et al., 2021) and obtain new dates for
129 two sites in Central Vietnam yielding LCTs. We dated tektites *via* $^{40}\text{Ar}/^{39}\text{Ar}$ analysis by the
130 “step-heating” method in order to circumvent inherited argon present in tektites during the
131 initial steps. Furthermore, with this approach, inverse isochron ages can be calculated, which
132 resolves and takes into account any inherited $^{40}\text{Ar}^*$ present in the samples in the calculation,
133 provided that its argon isotopic composition is homogenous, thus leading to more accurate
134 results (Jourdan et al., 2019). $^{40}\text{Ar}/^{39}\text{Ar}$ dating analyses were conducted on tektites from two
135 archaeological sites located in the Bose Basin in China and from two others sites located in
136 Vietnam (An Khê): Xiaomei, Fengshudao, Go Da and Roc Tung 1, respectively (Fig. 1, Fig.

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

139

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

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

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

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

162 the Bose tektites are *in situ* and associated with the stone tools in terrace T4, as described by
163 [Hou et al. \(2000\)](#), in the same way as the stone tools found alongside tektites at the Gaolingpo
164 site ([Xie et al., 2021](#)). They attributed the tektite age to the tools as there is no geomorphological
165 and stratigraphical indication of the redeposition of either the tools or tektites ([Potts et al.,](#)
166 [2000](#)). Later, [Wang et al. \(2014\)](#) presented a detailed morphological study of the Fengshudao
167 site and its bifacial industry. In this site, the first excavated association of tektites, dating to ca.
168 803 ka, with LCTs (including bifaces), and found *in situ*, was described in one stratigraphic
169 level in terrace T4, indicating that the Bose Basin handaxes most likely date to the Early to
170 Middle Pleistocene transition ([Fig. 2](#)). However, according to [Langbroek \(2015\)](#), the age of the
171 earliest bifaces in China and the close association between tektites and bifaces have not yet
172 been demonstrated, although this was clearly established by [Wang and Bae \(2015\)](#), and later
173 confirmed at the Nalai site with Australasian tektites and bifaces found together *in situ* ([Michel](#)
174 [et al., 2021](#)). It is important to note that two Australasian tektites found *in situ* at the Sangiran
175 area have been successfully used as chronological markers. They are consistent with the
176 magnetic polarity stratigraphy and predate the Matuyama-Brunhes transition (MB) ([Hyodo et](#)
177 [al., 2011](#)). The data demonstrate the near co-occurrence of the tektite level and the
178 magnetostratigraphic constraint, arguing that the last occurrence of Sangiran hominins dates to
179 ~ 0.79 Ma ([Fig. 2](#)).

180 Later, [Jourdan et al. \(2019\)](#) conducted precise dating on four Australasian tektites from Western
181 Australia, Thailand, Vietnam, and southern China, including a tektite from the Bose Basin
182 previously dated by [Hou et al. \(2000\)](#). The exact origin of the tektite from the Bose Basin was
183 not specified by [Jourdan et al. \(2019\)](#). Age plateau and isochron diagrams yielded concordant
184 data with a weighted-mean age of 788.1 ± 2.8 (P = 0.54) for these Australasian tektites, which
185 aligns closely with the less precise $^{40}\text{Ar}/^{39}\text{Ar}$ age of 793 ± 14 ka published by [Schwarz et al.](#)
186 [\(2016\)](#).

187 3. Xiaomei and Fengshudao sites in Southern China: Geography, stratigraphy and lithic 188 assemblages

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

195 The Xiaomei site is located in Xiaomei village, Youjiang district, Bose city, Guangxi Zhuang
196 Autonomous Region (23°46'41.5" N, 106°42'21.9" E), on the fourth terrace of the Youjiang
197 River (Fig. S1, Fig. S3, Fig. S4, Fig. S5). It was discovered in the 1980s during an
198 archaeological survey covering an area of 350,000 m². Many lithic artefacts and a few tektites
199 were exposed on the ground surface of the laterite deposits at the site. The lithic series were
200 made up of diversified LCTs, including pick and tongue-shaped bifaces typical of the area (Fig.
201 3, n° 6), on sandstone or quartzite pebbles (Fig. 3, n° 7 and 8), associated with flake-tools
202 (scrapers), and notably a large unifacial core on a massive thick quartzite pebble (Fig. 3, n° 9)
203 with centripetal removals. A test excavation conducted in 1996 unearthed artefacts, associated
204 with tektites. Based on geomorphology and artefacts, the age of this site is assumed to be the
205 same as that of Bogu site.

206 The Fengshudao site (23°57'39''N, 106°40'39''E) is situated along the south bank of the
207 Chengbihe River, a significant tributary of the Youjiang River (Fig. S1, Fig. S3, Fig. S4). The
208 site is located in the fourth terrace, spanning 100 metres from east to west, with a sloping terrain
209 from north to south of approximately 10 to 30 metres. Discovered in 2004, the site was
210 excavated from 2004 to 2005, revealing nearly 100 artefacts and nine tektites *in situ* from an
211 excavated area of 62.6 m² (Wang et al., 2014). The lithic assemblage at the Fengshudao site

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

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

220

221 **4. Go Da and Roc Tung 1 sites in Central Vietnam: Geography, stratigraphy and lithic** 222 **assemblage**

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

226 Several other similar Palaeolithic sites were identified at the Roc Tung location, situated on the
227 left bank of the Ba River. Artefacts were collected on the surface or discovered *in situ* during
228 excavations and test pits, with similar stratigraphic contexts. The Roc Tung 1 site (14°02'253"
229 N; 108°40'822" E) is situated on a high and relatively flat area of agricultural land. The
230 stratigraphy is well-documented through excavations and various test pits (Derevianko et al.,
231 2018). Three layers have been identified below the surface debris of an irrigation canal. The
232 cultural layer, situated at the top of the laterite (Layer 3), has yielded several *in situ* artefacts
233 associated with tektites (Fig. S6, Fig. 5).

234 Go Da (13°58'306" N; 108°39'136" E; 440 m a.s.l.) is located downstream, near An Khê, on a
235 sloping hill, 900 m west of the Ba River (Fig. S2). The stratigraphy established during the
236 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° 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

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

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

269

270 **5. Materials and methods**

271 5.1. Materials.

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

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

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

285 5.2. Method

286 Before analysis, the eight tektite samples were cleaned in an ultrasonic water bath to remove
287 surface-bonded residues (Fig. 7). The thinner tektites (F1, F2, F3) were reduced to pieces. For
288 the larger ones (B1, B2, B3, GD, and RT1), a piece of each tektite was extracted from the
289 original tektites and reduced to pieces. Some were further crushed in an agate mortar and
290 divided into subsamples for multiple analyses. For $^{40}\text{Ar}/^{39}\text{Ar}$ dating, subsamples 400-500 μm
291 in size, from F1, F2, B1, B2, B3, GD and RT1 tektites, were cleaned with an HNO_3 2N
292 ultrasonic bath for 15 minutes, in HF 2% for 20 minutes, in H_2O , and then in acetone.
293 Subsamples weighing 30-70 mg were analysed using the "step-heating" method with
294 incremental temperature increases to produce an age spectrum and inverse isochron. The
295 $^{40}\text{Ar}/^{39}\text{Ar}$ analyses were conducted at the Western Australian Argon Isotope Facility (Australia)
296 using an ARGUS VI multicollection instrument and following the procedure described by
297 Jourdan et al. (2019), used for dating the Australasian tektites. The raw data (Appendix B) were
298 processed using the ArArCALC software (Koppers, 2002) and the ages were calculated using
299 the FCs standards (Jourdan and Renne, 2007), for which an age of 28.294 Ma ($\pm 0.13\%$) was
300 used (Renne et al., 2011), along with the decay constants recommended by Renne et al. (2011).
301 Our criteria for plateau determination are as follows: plateaus must include at least 70% of ^{39}Ar .
302 The plateau should be distributed over a minimum of three consecutive steps agreeing at 95%
303 confidence level and satisfying a probability of fit (P) of at least 0.05. Plateau ages are given at
304 the 2σ level and are calculated using the mean of all the plateau steps, each weighted by the
305 inverse variance of their individual analytical error. Uncertainties include analytical and J-value
306 errors. Errors with all sources of uncertainties such as the decay constants errors increase the
307 uncertainty by ± 0.2 ka for those samples and are indicated by a square bracket (e.g., [± 3 ka]).
308 The composition of major and trace elements presented in Tables S2 and S3, was determined
309 for all tektites by Laser Ablation Inductively Coupled Plasma Mass Spectrometry at the Centre
310 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 SiO₂, 11.13-15.44 % for Al₂O₃, 4.17-4.96 % for FeO,
322 1.77-2.67 % for CaO, 2.06-2.42 % for K₂O, 1.92-2.67 % for MgO, 0.93-1.51 % for Na₂O, 0.68-
323 0.78 % for TiO₂, 0.08-0.10 % for MnO, 0.03-0.07 % for P₂O₅. 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 ⁴⁰Ar/³⁹Ar dating

336 We obtained seven plateau ages ranging from 779 ± 19 ka (MSWD = 0.53; P=0.93) to $827 \pm$
337 57 ka (MSWD = 0.09; P = 1.00) and including between 91 and 100 % of the total released ^{39}Ar
338 (Fig. 10, Appendix B). Inverse isochrons yielded similar ages ranging from 774 ± 24 to $842 \pm$
339 67 and with trapped $^{40}\text{Ar}/^{36}\text{Ar}$ ratios in error of the atmospheric value of 298.6 ± 0.3 and ranging
340 from 293.3 ± 4.9 to 300.8 ± 6.0 (Appendix C). The K/Ca ratio (derived from $^{39}\text{Ar}_K/^{37}\text{Ar}_{Ca}$)
341 shows homogenous values across a given tektite but varies among samples with average values
342 ranging from 0.32 ± 0.18 to 1.29 ± 0.11 . The seven plateau ages (P = 0.84) and inverse isochron
343 ages (P = 0.25) are all indistinguishable from each other, indicating the dating of a single event,
344 as expected for tektites originating from a single impact. Furthermore, all intercept $^{40}\text{Ar}/^{36}\text{Ar}$
345 values define a single population (P = 0.57) with a weighted mean of 296 ± 3 , suggesting that
346 no inherited $^{40}\text{Ar}^*$ is present in the samples analysed in this study. Therefore, we calculated a
347 single weighted mean age of 787.2 ± 8.2 ka (2σ ; MSWD = 0.96; P = 0.45) as the best estimate
348 for the impact event that produced these tektites. This age is indistinguishable from the previous
349 age of 788.1 ± 2.8 (Jourdan et al., 2019), indicating that the tektites are part of the Australasian
350 strewnfield, as also evidenced by their chemical composition. When combined with our new
351 age, we obtained a conclusive best age estimate of 788.0 ± 2.6 [2.8] ka (2σ ; P = 0.84) for the
352 Australasian tektites that will be used in the rest of this study.

353

354 **7. Discussion on the new results of the Chinese and Vietnamese sites regarding the** 355 **emergence and diffusion of the Acheulean in Eurasia**

356 *7.1 Emergence of the Acheulean in Africa and its initial diffusion*

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

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

373

374 7.2. New insights from Chinese and Vietnamese sites

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

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

389 Early human populations thrived and expanded across mainland East Asia, from low latitudes
390 whatever their technology (e.g., the Bose Basin) to high northern latitudes (e.g., the Nihewan
391 Basin, Zhoukoudian). The associated industry is often roughly dated using paleomagnetism, as
392 seen in Maliang (Nihewan Formation, North China), Wutaicun (Central China), Longgangsi-2
393 and 3 (Central China). The determined ages are approximately ~0.78 Ma (Wang et al., 2005),
394 ~0.9 Ma and ~1.2-0.7 Ma (Sun et al., 2017) respectively. Despite approximate dating, an
395 overview of paleoenvironmental and archaeological data in the Nihewan Basin reveals changes
396 in hominin presence and indicates that sustained occupation in high latitudes characterized by
397 strong seasonality was not possible until the Late Pleistocene, as evidenced by chronological
398 gaps (Yang et al., 2020). Mode1/Oldowan industries persisted in Asia at Bailong Cave with
399 human teeth in Central China, dated between ~0.78 Ma and ~0.51 Ma, and also using multi-
400 dating methods such as paleomagnetism, $^{26}\text{Al}/^{10}\text{Be}$ burial on quartz and ESR/U-series on teeth
401 (Liu et al., 2015; Han et al., 2018; Kong et al., 2018).

402 Moving outside China, this lithic industry is also evidenced at the site of Kalinga between
403 around 1.05 and 0.63 Ma, in the Philippines (Ingicco et al., 2018), and between around 1.01
404 and 0.7 Ma at Mata Menge and Wolo Sege in Indonesia (Brumm et al., 2016). During the same
405 period, an Acheulean-type industry is present at Shuigou-Huixinggou, in Central China, but
406 approximatively dated to ~0.9 Ma by paleomagnetism (Li et al., 2017). Other Mode 1/Mode 2
407 sites dated by alternative radioisotopic methods provide more precise dating (Fig.2, Table S1).

408 This is the case for Zhoukoudian Locality 1, in North China, where human remains and
409 industries with bifacial tools and flake-tools (Derevianko, 2008) are well dated to ~0.78-0.4 Ma

410 using multi-dating methods, such as paleomagnetism, $^{26}\text{Al}/^{10}\text{Be}$ burial and U-Th (Shen et al.,
411 2009, Shen et al., 2016).

412 Li et al. (2018) propose that the technological transmission hypothesis could be a suitable
413 explanation for the emergence of Chinese LCTs technology and suggest a diffusion of the
414 Acheulean-type tradition by hominins from west to east to China and other Asia areas as
415 Vietnam. Other authors propose a local onset derived from previous Mode 1/core-and-flake
416 assemblages (convergence), giving rise to the An Khê tradition observed at the Go Da and Roc
417 Tung Lower Palaeolithic sites in Vietnam (Derevianko et al., 2018) and the Acheulean in the
418 Bose Lower Palaeolithic sites (Wang et al., 2014; Wang and Bae, 2015; Wang et al., 2024; Bae,
419 2024) (Fig.1, Fig.2, Table S1).

420 Our results highlight that the industries at the Bose and An Khê sites are now well dated to
421 788.0 ± 2.6 ka (2σ) by dating *in situ* Australasian tektites associated with the bifaces. This
422 significant chronological marker accurately positions the industries at the Bose and An Khê
423 sites within the chronological sequence of industries in Asia and also indicates a well-
424 established presence of LCTs and possibly the Acheulean-type tradition in this region of Asia.

425

426 **8. Conclusion**

427 Our dating of Australasian tektites discovered *in situ* alongside artefacts at the Bose sites in
428 southern China and An Khê in Central Vietnam using $^{40}\text{Ar}/^{39}\text{Ar}$ gives an age of 788.0 ± 2.6
429 [2.8] ka. This age indicates that LCTs (including bifaces), and thus what can be described as
430 the Acheulean, developed in this part of Asia around 788 ka during the Mid-Pleistocene climate
431 transition, regardless of the hypothesis regarding the onset of the Acheulean (Fig. 2, Table S1).

432 Our result can be compared to the age of the Acheulean industry also found at around 1.1-0.8
433 Ma at DRR sites, Yunxian and Shuigou-Huixinggou in Central China. This new LCT-making
434 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) Niujuanbao, 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 $\delta^{18}\text{O}$ 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).

484

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

487

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

491

492 **Figure 6.** Lithic artefacts from Go Da site (1) and from Roc Tung 1 site (2 and 3). 1- scraper;
493 2- chopper; 3- biface.

494

495 **Figure 7.** Photograph of tektites analysed in this study: F1, F2, F3 (~0.4-0.6 g) are three thin
496 tektites excavated from Fengshudao site, Bose Basin, China; B1 (10.2 g), B2 (8.7 g), B3 (6.5
497 g) are three tektites excavated from Xiaomei site, Bose Basin, China ; GD (19.1 g) is a tektite
498 excavated from Go Da site and RT1 (10.3 g) is a tektite excavated from Roc Tung 1 site,
499 Vietnam. GD and RT1 were cleaned with a H₂O ultrasonic bath.

500

501 **Figure 8.** Chemical composition of various tektite groups, based on the original figure by
502 [Schwarz et al. \(2016\)](#) with modifications. This figure includes a comparison of compositions
503 with cited references by [Schwarcz et al. \(2016\)](#) ([Taylor, 1962](#); [Chapman and Schreiber, 1969](#);
504 [O'Reilly et al., 1983](#); [Koeberl et al., 1997](#); [Meisel et al., 1997](#); [Albin et al., 2000](#); [Son and](#)
505 [Koeberl, 2005](#); [Amare and Koeberl, 2006](#)), including Belize (BZ1) (Central America, with
506 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 ($^{40}\text{Ar}/^{39}\text{Ar}$ 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.** $^{40}\text{Ar}/^{39}\text{Ar}$ 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.** $^{39}\text{Ar}/^{40}\text{Ar}$ vs. $^{36}\text{Ar}/^{40}\text{Ar}$ inverse isochron plots.

532 **MC4. Tables S2 and S3**

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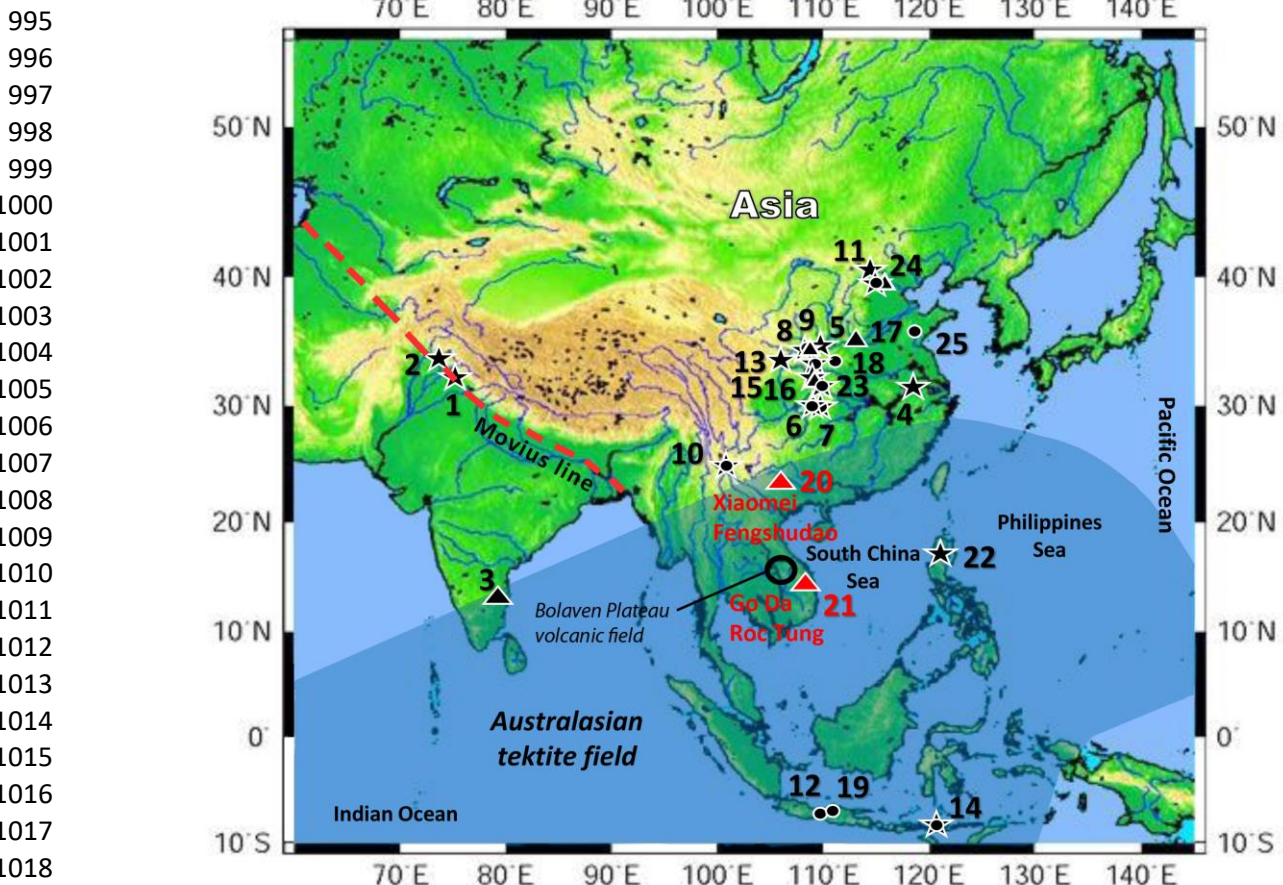
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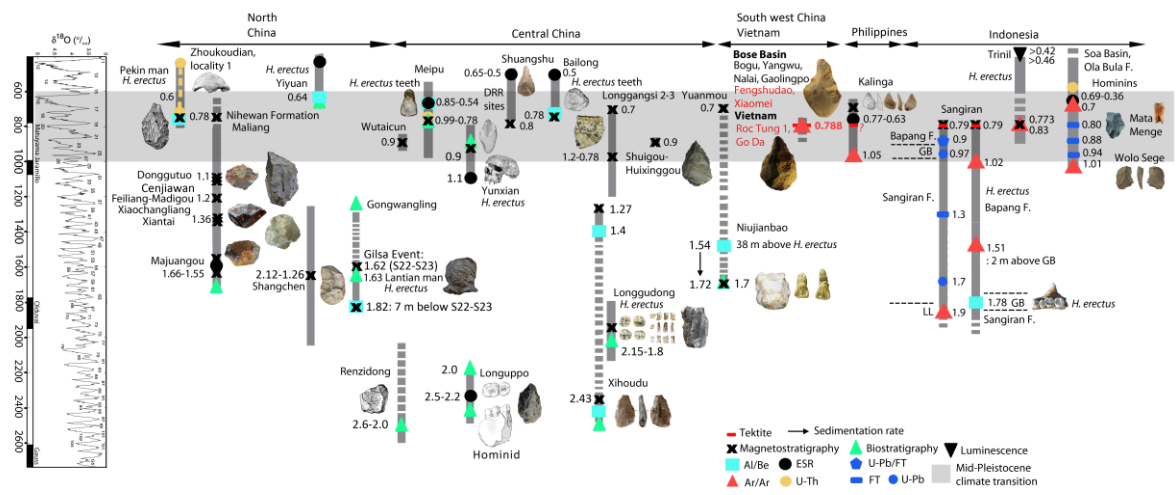
993 Figure 1

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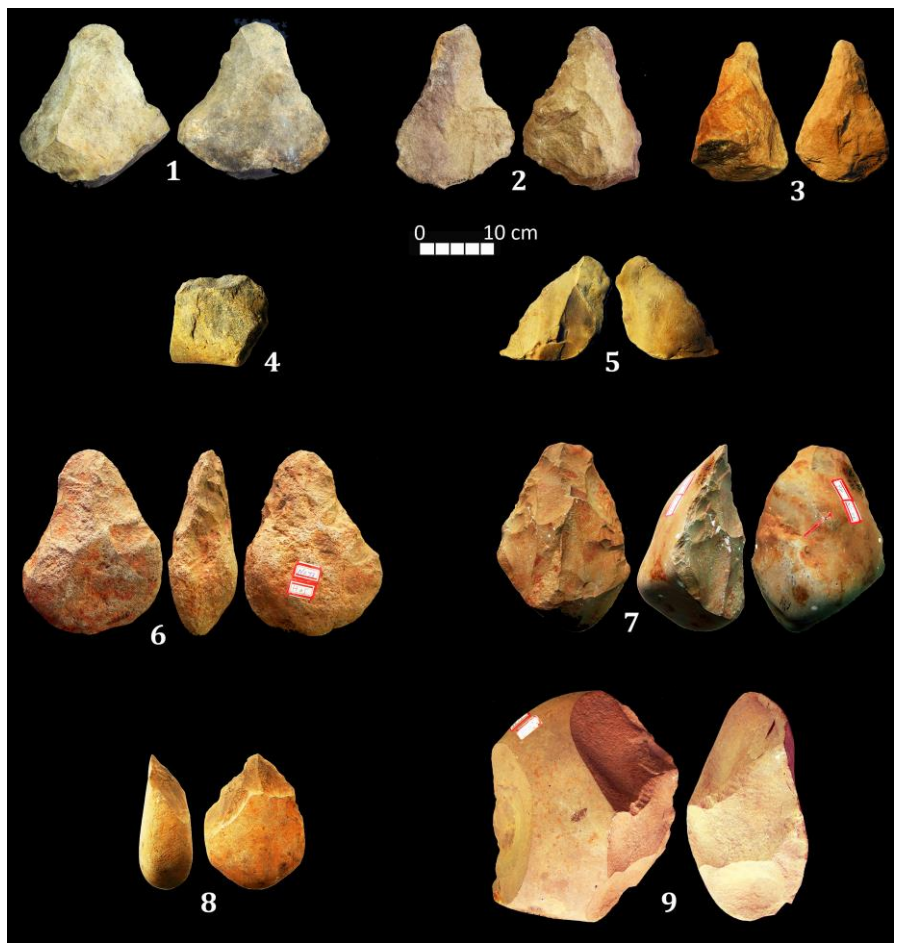


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1020 Figure 2



1038 Figure 3



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1070 Figure 4



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1073 Figure 5

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1091 Figure 6

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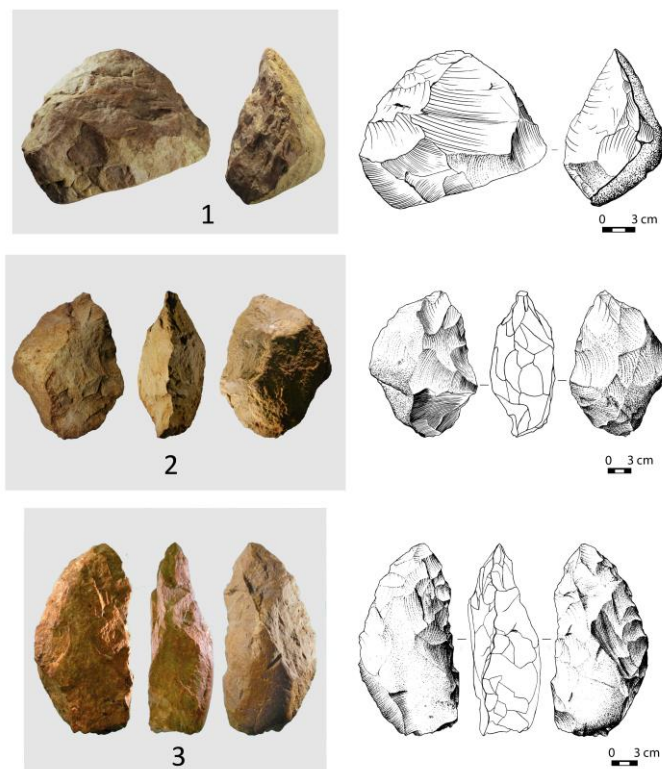
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Figure 7

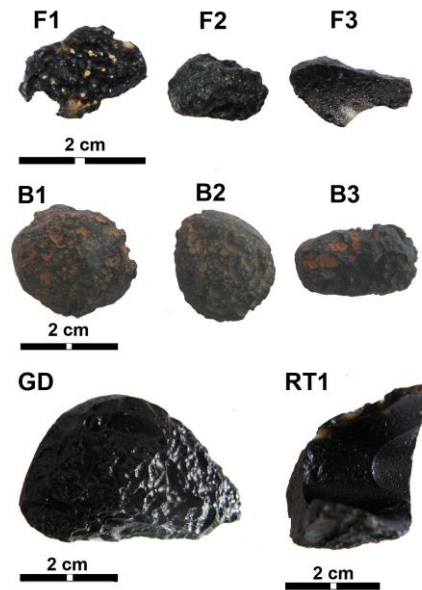
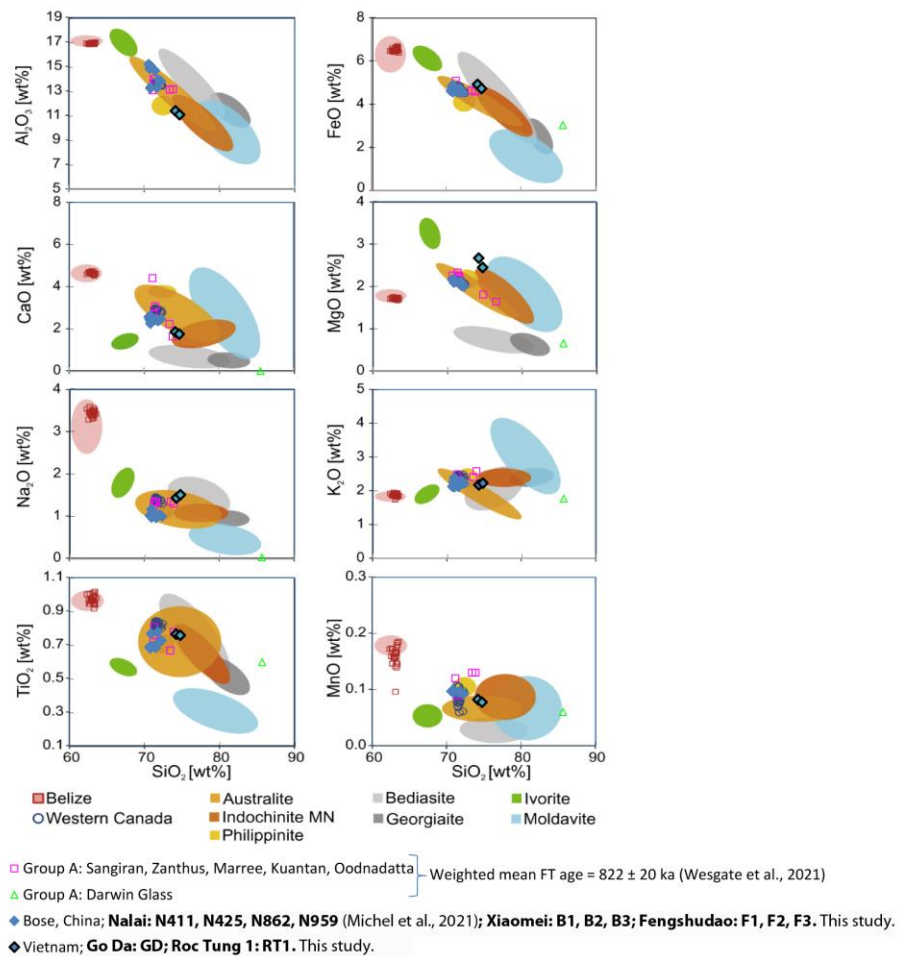
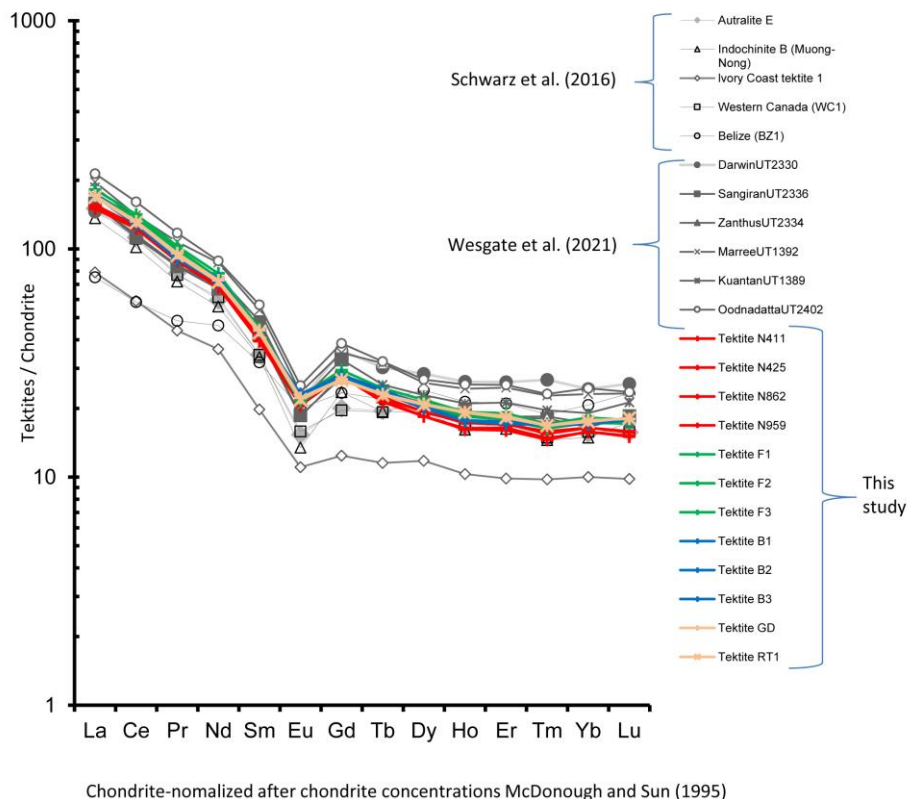


Figure 8



1157
1158 Figure 9



1183
1184 Figure 10

