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4 **Drainage and erosion of Cambodia's Great Lake in the middle-late**
5 **Holocene: the combined role of climatic drying, base-level fall and**
6 **river capture**
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RAPID DRAINAGE OF THE TONLE SAP LAKE

38 **ABSTRACT**

39

40 We provide evidence for a large-scale geomorphic event in Cambodia's great lake, the Tonlé Sap,
41 during the middle Holocene. The present-day hydrology of the basin is dominated by an annual flood
42 pulse where water from the Mekong River raises the lake level by *c.* 8m during the monsoon season.
43 We present new subsurface geophysical data, allied to new and past core studies, which unequivocally
44 show a period of major mid-Holocene erosion across the entire Tonlé Sap basin that is coincident
45 with establishment of the lake's flood pulse. We argue that this widespread erosion, which removed
46 at least 1.2 m of sediment across the lake's extent, was triggered by up to three, likely interacting,
47 processes: (1) base-level lowering due to mid-Holocene sea-level fall, leading to (2) capture of the
48 Tonlé Sap drainage by the Mekong River, and (3) a drying climate that also reduced lake level.
49 Longer-term landscape evolution was thus punctuated by a rapid, river capture- and base-level fall-
50 induced, lake drainage that established the ecosystem that flourishes today. The scale of change
51 induced by this mid-Holocene river capture event demonstrates the susceptibility of the Tonlé Sap to
52 ongoing changes in local base-level and hydrology induced by anthropogenic activity, such as
53 damming and sand mining, within the Mekong River Basin.

54

55 **Keywords:** Tonlé Sap, Holocene; Paleogeography; Paleolimnology; Southeastern Asia

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57

58 **1. INTRODUCTION**

59 Draining the Tibetan Plateau and the Annamite Mountains bordering Laos and Vietnam, the Mekong
60 River is an iconic but threatened river system. Not only is the Mekong one of the world's largest
61 rivers, generating large fluxes of water ($450 \text{ km}^3 \text{ yr}^{-1}$; MRC, 2005) and sediment ($\sim 87 \text{ Mt yr}^{-1}$; Darby
62 *et al.*, 2016), it is (after the Amazon) the second most biodiverse river on the planet (Ziv *et al.*, 2012).

63 Critical in supporting and sustaining the Mekong's rich ecosystem is Cambodia's great lake,
64 the Tonlé Sap. The Tonlé Sap Lake lies within a sub-catchment (drainage area of $85,790 \text{ km}^2$, around
65 11% of the total area) of the Mekong and forms the largest freshwater body in southeast Asia
66 (measuring *c.* $2,400 \text{ km}^2$ during the dry season but expanding to *c.* $10,800 \text{ km}^2$ during the rainy
67 season; Kummu and Sarkkula, 2008). The defining feature of the lake is its remarkable hydrology,
68 whereby the Tonlé Sap River exhibits a seasonal reversal of its flow direction. In the dry season
69 (November to April), the Tonlé Sap drains under gravity to the Mekong River at the Chaktomuk
70 confluence at Phnom Penh (Figure 1). In the wet season, from May to October, the Mekong's water
71 levels rise higher than those in the Tonlé Sap, inducing a pressure gradient that causes the Tonlé Sap
72 River to reverse direction and flow back towards the Tonlé Sap Lake. Similar to other seasonally
73 flooded systems (Junk *et al.*, 1989; Junk *et al.*, 1997a, b), this annual flood pulse drives exceptionally
74 high ecological productivity (Rainboth, 1996; Sverdrup-Jensen, 2002; Junk *et al.*, 2006; Lamberts,
75 2006; Arias *et al.*, 2012). For example, the lake's fishery and associated aquaculture provide up to
76 80% of the protein consumption for the whole of Cambodia (Ahmed *et al.*, 1998; Hortle, 2007). The
77 ingress of Mekong flood waters during the monsoon season means that the volume of fresh water
78 stored in the lake varies on average from 1.8 km^3 during the driest month to 58.3 km^3 during the peak
79 flow (Kummu and Sarkkula, 2008). The Tonlé Sap lake therefore acts as a natural flood storage
80 capacitor, storing very large volumes of flood water in the wet season, thereby significantly
81 attenuating flood levels in the Mekong delta downstream (Kite, 2001; Hung *et al.*, 2012; Piman *et al.*;
82 2013). Conversely, the stored floodwater is released back to the Mekong River during the dry season,

RAPID DRAINAGE OF THE TONLE SAP LAKE

83 a key stage of the agricultural growing season, at which time approximately half of the river discharge
84 to the Mekong Delta in Vietnam originates from the lake (Fuji *et al.*, 2003; Kummu *et al.*, 2014).

85 It is evident that the connection of the Mekong and Tonlé Sap rivers at the Chaktomuk Junction
86 represents a critical node in the drainage network of the Mekong Basin. In recent years, knowledge
87 of the hydrology of the Tonlé Sap system and its hydrodynamic relationship with the Mekong River
88 mainstem has increased substantially (Fuji *et al.*, 2003; Inomata and Fukami, 2008; Kummu and
89 Sarkkula, 2008). Nevertheless, significant gaps remain, most particularly in terms of understanding
90 the extent to which the connection, and its hydrological functioning, may be vulnerable to system
91 responses induced by climate change and the ongoing, rapid, socio-economic development of the
92 Mekong Basin (e.g. Arias *et al.*, 2013, 2014; Kummu *et al.*, 2010; Lamberts, 2008; Lamberts and
93 Koponen, 2008; ICEM, 2010; MRC, 2018).

94 In part, a clear understanding of the vulnerability of the Chaktomuk connection has remained
95 elusive because hitherto there has been no clear consensus from prior palaeo-environmental analyses
96 regarding the timing at, and hydro-geomorphic conditions under, which the connection between the
97 Mekong and Tonlé Sap rivers was established initially. On the one hand, distinctive changes in
98 lithological characteristics of the two main sediment facies deposited within the lake are interpreted
99 as representing a transition from a non-pulsing to a flood-pulsed system. Specifically, sediments
100 below the transition only contain kaolinite and smectite clay minerals, whereas illite and chlorite are
101 also present above the transition, which was dated in two cores to $5,081 \pm 86$ ^{14}C years BP (5,615-
102 5,992 cal. years BP) and $5,620 \pm 120$ ^{14}C years BP (6,184-6,715 cal. years BP) (Okawara and
103 Tsukawaki, 2002). Since illite and chlorite minerals are not sourced within the Tonlé Sap catchment,
104 but rather are products of weathering in the Mekong River basin upstream, their presence is a signal
105 of the onset of a connection between the Tonlé Sap lake and Mekong River (Okawara and Tsukawaki,
106 2002; Day *et al.*, 2011). A more recent study (Day *et al.*, 2011) has independently identified the
107 transition from a non-connected to Mekong-connected system as being marked by shifts (dated
108 between 4,450 and 3,910-4,450 cal. years BP) in Sr, Nd and Pb isotopes and elemental concentrations

RAPID DRAINAGE OF THE TONLE SAP LAKE

109 to values characteristic of modern Mekong River sediments (Day *et al.*, 2011). A subsequent study
110 by Fukumoto (2014) also argues for a Mekong connection dated to around 3,900 cal. years BP, based
111 on evidence from a lake sediment core that shows a rise in magnetic susceptibility and some elements
112 (notably K) around this time. Conversely, a lake sediment core collected by Penny (2006), in which
113 mangrove pollen and diatoms tolerant of brackish conditions were found to be present in the early
114 Holocene, was interpreted as indicating that a connection between the Tonlé Sap lake and South
115 China Sea, via the Mekong River, has existed throughout the Holocene (Penny, 2006). These
116 divergences in interpretations of timing, when combined with the point that the previous cores have
117 been interpreted in isolation, without understanding their spatial context, make it challenging to
118 clearly identify the environmental conditions during the onset and early evolution of the (postulated)
119 connection between the Tonlé Sap Lake and the main Mekong River system.

120 The present paper aims to use a combination of detailed geophysical surveys and analysis
121 of proxy records preserved in lake sediment cores, to provide new insight into the Holocene evolution
122 of the Tonlé Sap Lake and thereby cast new light on the issues discussed above. Our findings show
123 that the connection between the lake and the Mekong River, caused by the Mekong capturing the
124 Tonlé Sap River, induced catastrophic (lake-wide) changes in lake drainage, causing erosion of *c.* 10
125 km³ of sediment. We interpret the period of the capture (postdating ~6,200 cal. years BP) to be
126 contemporaneous with a period of drying and declining sea-level, which would have enabled a
127 lowering of base level and wave reworking that led to this large pulse of erosion. Our work highlights
128 the vulnerability of the Chaktomuk connection to changes in hydro-climatic conditions, underscoring
129 the importance of maintaining natural river flow dynamics at the Chaktomuk connection to support
130 the Tonlé Sap Lake's unique and highly valuable ecosystem function.

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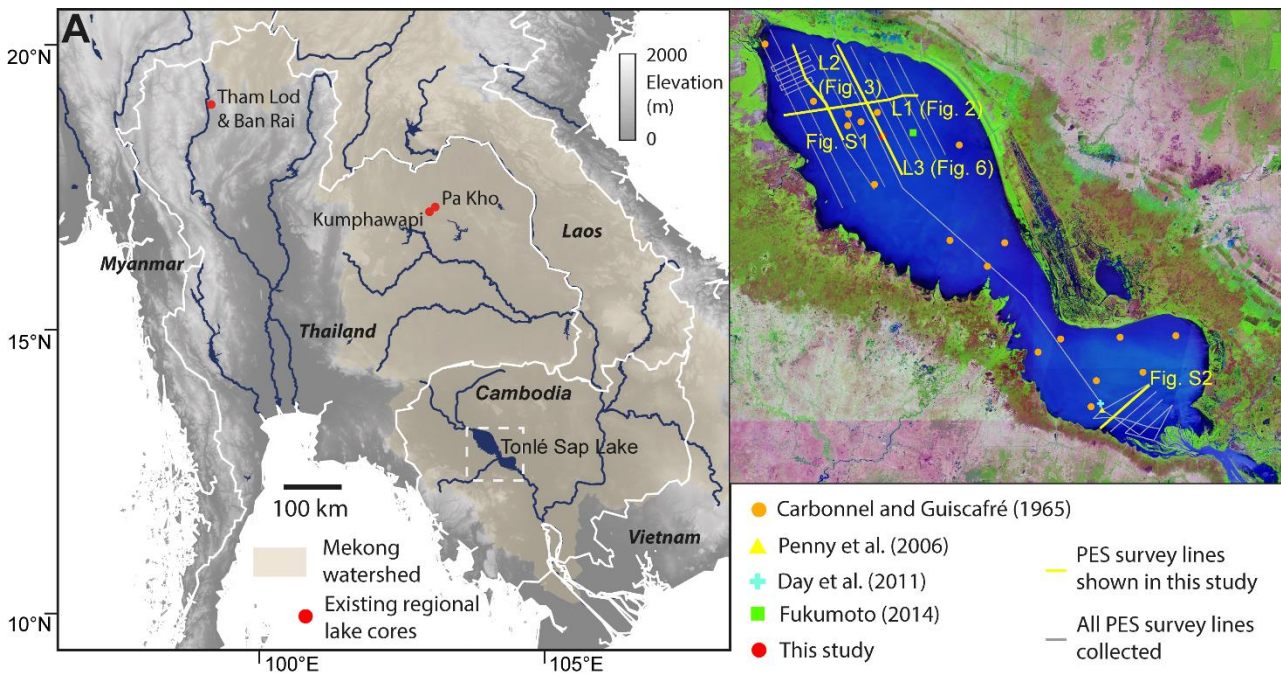
132 **2. METHODS**

133 We undertook geophysical surveys and analysis of lake sediment records to provide a new perspective
134 on the palaeo-environmental history of the Tonlé Sap Lake. Specifically, we collected a new sediment

RAPID DRAINAGE OF THE TONLE SAP LAKE

135 core, from which geochemical and other proxy records were determined and analysed (see below for
136 discussion of core collection and analysis, including the establishment of a chronology via
137 radiocarbon dating and age-depth modelling) to reconstruct changing environmental conditions. As
138 discussed fully below, we also collected over 500 km of new geophysical data (Parametric Echo
139 Sounding; PES) survey lines, including targeting the site of our new core record as well as the sites
140 of existing core records from prior studies (Figure 1). These PES lines provide a clear picture of the
141 sub-bottom sediments from across the lake and hence link the new and existing published core records
142 into a common stratigraphic framework. These new geophysical data not only provide a longer-term
143 perspective on landscape change, but also afford the opportunity to reappraise our new and prior core
144 sediment records within a broader stratigraphic spatial context. The clear stratigraphic correlation
145 delivered by the geophysical data also allows for much stronger chronological control due to the
146 ability to pool the radiocarbon dates obtained from the multiple, previously isolated, core records.

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149 **Figure 1:** Location of the Tonlé Sap Lake in central Cambodia. (A) Regional context showing the
150 Mekong catchment and locations of other regional studies of lake sediment records discussed herein
151 (see Figure 7 in Section 4 for details), at lakes Pa Kho, Kumphawapi, Tham Lod and Ban Ra in
152 Thailand. (B) Locations of Parametric Echo Sounding (PES) survey lines (grey lines show all PES
153 lines collected, yellow lines identify lines shown in other diagrams; ; note that Fig. S1 and Fig. S2
154 are in the Supplementary Data) and new sediment core record (red circle) used in this study. The
155 locations of previous sediment core records from the Tonlé Sap Lake and discussed in the text are
156 also indicated.

157 **2.1 Parametric Echo-Sounding (PES)**

158 The sub-bottom profiling data were obtained using an Innomar SES-2000 Light Parametric Echo
159 Sounder (PES) on October 23rd - 29th 2014, deployed from a wooden boat, providing a total of *c.* 530
160 km of PES transects (Figure 1). The PES was linked to an EdgeTech motion reference unit to remove
161 any effects of vessel heave, pitch and roll, although weather conditions during the surveys were
162 excellent, with position being given by a Leica System 1230 GPS. The PES operates by transmitting
163 two signals of different frequency (100 kHz and a selectable lower frequency between 4 kHz and 15
164 kHz) that, due to the non-linearities in sound propagation at high pressures, interact and produce new
165 acoustic frequencies (Sambrook Smith *et al.*, 2013). The high-frequency signal and narrow beam
166 footprint provide an accurate estimate of water depth, whilst the lower frequencies penetrate the bed
167 and produce reflections from differences in sedimentary bedding/structures in the subsurface. In this
168 manner, PES can produce high-resolution imaging of the bed topography and subsurface structure
169 simultaneously, and its performance is particularly good in finer-grained sediments such as silts and
170 clays. Further details of the PES are given in Sambrook Smith *et al.* (2013, 2016).

171 During the survey set-up, initial optimisation tests showed that a secondary frequency of 8 kHz
172 provided the best results in terms of resolution and depth of penetration into the subsurface. The depth
173 of water within the Tonlé Sap lake at the time of the survey was *c.* 7m, and it was found that the
174 combination of the sediment size (median grain size *c.* 6 microns), soft lakebed sediments (that
175 minimised a hard surface acoustic return) and the PES input power and frequencies used, often
176 enabled imaging of reflections below the first return multiple. Thus in many, but not all, places the
177 PES imaged strong reflections at depths up to 15 m below the lake-bed. Poor acoustic penetration
178 was present in some areas due to subaqueous vegetation growing on the lake-bed near the shore,
179 vegetation debris accumulated on the PES transducer, and occasional cavitation around the transducer
180 head at higher boat speeds. However, despite these restrictions, the PES provided imaging of the
181 subsurface with a vertical resolution of *c.* 0.15 m.

RAPID DRAINAGE OF THE TONLE SAP LAKE

182 As shown in Figure 1, the PES surveys focused on ten NW-SE lines in the north of the lake,
183 linked by one W-E line (Line 1, indicated as L1 in Figure 1), together with a smaller grid of lines at
184 the NW of the lake. One long line was run down the centre of the entire lake, and a small grid of
185 survey lines was collected near the delta at the southern end of the lake. Lines were also run to
186 intersect the location of the core taken as part of this research (Core LC2; see Section 2.2), as well as
187 a previous core taken by Day *et al.* (2011; Core TS-18-XII-03), for which detailed geochemical data
188 are available. The co-location of the PES and core records is advantageous because it enables further
189 ground-truthing of the PES reflections from the core records, as well as further contextualisation of
190 the palaeo-environmental interpretations derived from the prior work. In this regard, it may also be
191 noted that two PES lines also ran either side of, and within *c.* 1.3 km of the CT10 core site reported
192 by Fukumoto (2014) and several of the PES lines were located close to some of the cores described
193 by Carbonnel and Guiscafré (1965). Although the Carbonnel and Guiscafré (1965) cores are
194 described in less detail than the more recent studies, they still provide useful further context for the
195 PES data. A PES survey line was also run over the locality of core S2C1 from Penny (2006), although
196 later examination of this data showed that the core location was likely in error to the level of accuracy
197 required to geo-locate the PES results with the core characteristics. The PES-core correlation with
198 the S2C1 core of Penny (2006) could thus not be undertaken.

199 The data were collected using Innomar PES software, whilst boat tracks and navigation were
200 recorded on a separate PC running Global Mapper software. PES processing was accomplished using
201 Innomar ISE post-processing software (Innomar, 2016) and involved accumulation of track points at
202 a 0.2 m spacing to yield a consistently scaled horizontal distance, filtering to enhance reflections and
203 reduce water column noise, application of a moderate time-varying gain and a smoothing using
204 between 2 and 3 ensembles. This processing methodology yielded PES panels for all lines, and these
205 were then used within Innomar ISE software to manually trace key surfaces that could be exported
206 and used to estimate water depths and thicknesses of sediment packages.

207

208 **2.2 Sediment Core Retrieval and Analysis**

209 A sequence of overlapping cores was obtained from a part of the lake from which test sampling
210 revealed to be a relatively deep infill. Coring took place in March 2013 when lake water depth was
211 relatively low, *c.* 1.5m. A 0.6 m long core tube was used in a UWITEC gravity-type corer with core
212 catcher to sample the upper (most recent) sediments, including the undisturbed sediment-water
213 interface. Zorbitrol™ was used to solidify the overlying 0.05 m of water to maintain the integrity of
214 the sediment surface, and the core was extruded and subsampled in 0.01 m sections. A 1 m-long 7
215 cm diameter Livingstone Piston corer was deployed to retrieve overlapping cores to a total sediment
216 depth of 4.58 m. Upon extrusion in the field, all cores were carefully wrapped in cling film and kept
217 in cool storage (+4 °C) until they could be sub-sampled.

218 The core sequences were extruded in the field and cleaned. A 0.01 m deep U-channel was taken
219 from each core sequence and carefully wrapped. Following the U-channel sampling, the remainder
220 of the cores were sub-sampled in the field and chopped into 0.01 m resolution contiguous slices. The
221 individual sub-samples were analysed at the University of Southampton for loss-on-ignition (LOI)
222 and particle size, the latter using a Micromeritics® Saturn DigiSizer® II particle size analyser. The
223 overlapping cores were correlated using the LOI and Itrax (see below) data, with core depths then re-
224 mapped onto a single depth model that was used for subsequent age/depth modelling. Geochemical
225 analysis was undertaken on the U-channels using an Itrax core scanner (Cox Analytical Systems,
226 Gothenburg, Sweden) at the National Oceanography Centre, University of Southampton. Both a
227 photographic and X-radiographic image were obtained at high resolution prior to each core's XRF
228 scan. The chosen resolution of the XRF scans was determined by visual inspection of the core
229 stratigraphy for fine laminae. A Molybdenum tube (30kV, 30mA) was used to scan each core at 500
230 µm resolution and at 200 µm for the surface gravity core. Exposure time was set at 30 seconds.

231 For the organic matter geochemistry, undertaken at contiguous 0.01 m samples, ¹³C/¹²C
232 analyses were performed by combustion in a Costech ECS4010 Elemental Analyser (EA) on-line to
233 a VG TripleTrap and Optima dual-inlet mass spectrometer, with δ¹³C values calculated to the VPDB

RAPID DRAINAGE OF THE TONLE SAP LAKE

234 scale using a within-run laboratory standards calibrated against NBS18, NBS-19 and NBS-22.
235 Replicate analysis of well-mixed samples indicated a precision of $\pm <0.1\%$ (1 SD). C/N ratios
236 (including %C measurements) were calibrated against a Broccoli standard (BROC2). Replicate
237 analysis of well-mixed samples indicated a precision of $\pm <0.1$.

238

239 **2.3 Radiocarbon dating and age-depth modelling**

240 We used ^{14}C dating to establish a chronology for our Tonlé Sap lake core sequence. No terrestrial
241 macrofossils were found in the sequence, only some wood fragments, requiring that most ^{14}C
242 measurements were sourced from bulk sediment. Eleven samples were sent to Beta Analytic and
243 prepared for ^{14}C dating using their standard methods. All eleven radiocarbon dates were used in the
244 BACON 2.2 Bayesian modelling software (Blaauw and Christen, 2011) to create an age/depth model.

245

246 **3. RESULTS AND INTERPRETATION**

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248 **3.1 Overview of PES Facies**

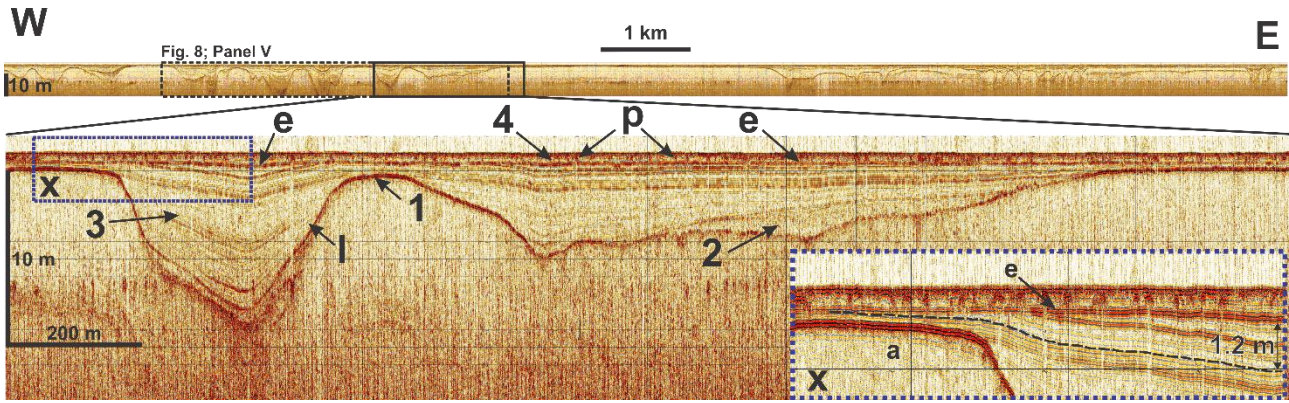
249 The PES imaging revealed a complex, but nevertheless consistent, series of reflectors (Table 1;
250 Figures 2 and 3) that were classified into facies according to their principal reflection characteristics.
251 Note that these detailed classifications provide the basis for interpretations of depositional processes
252 and stratigraphy across the Tonlé Sap Lake and comparison (Section 3.4) with previous research. The
253 PES profiles show four major facies based on the reflection characteristics (Table 1), revealing the
254 presence of a palaeo-valley network across the entire Tonlé Sap lake that has been infilled by
255 Holocene sediments (Table 1; Figures 2 and 3; also see Supplementary Data Figures S1 and S2). A
256 strong undular basal reflector (Facies 1; Table 1; labelled '1' in Figures 2 and 3; also see
257 Supplementary Data Figures S1 and S2) is interpreted as representing the erosive surface of a likely
258 Pleistocene valley network, with valleys up to *c.* 15 m deep, likely eroded during the sea-level low
259 stand that accompanied the Last Glacial Maximum (Tjallingii *et al.*, 2010; Fukumoto, 2014). This

RAPID DRAINAGE OF THE TONLE SAP LAKE

260 valley surface is overlain by sediments that have infilled the valley network and represent: i) a series
261 of minor fluvial or valley-slope deposits (Facies 2; Table 1; labelled '2' in Figures 2 and 3; as well
262 as Figures S1 and S2) that drape against the underlying valley sides in places, and ii) parallel-bedded
263 lacustrine deposits that comprise the majority of the infill (Table 1; Facies 3 and 4; labelled '3a-c'
264 and '4' in Figure 3B). The lacustrine deposits of Facies 3 are characterised by parallel, reflectors that
265 mirror any underlying basal topography but with no internal truncations, that attest to the spatially
266 continuous sedimentation that gradually infilled the pre-existing topography. The presence of a clear
267 disconformity between Facies 3 and 4 (Figures 2 and 3; labelled 'e'; see also Figures S1 and S2) is
268 indicative of an erosion surface (indicated also by radiocarbon dating, as discussed further in Section
269 3.3) that is present between the lacustrine Facies 3 and 4. Indeed, the disconformity can be traced
270 across the entire Tonlé Sap lake, with the facies above this surface characterised by parallel-bedded
271 sediments that contain individual point reflectors (Table 1; labelled 'p' in Figures 2 and 3B). These
272 point reflectors likely represent siderite concretions (Pottier *et al.*, 2012) or accumulations of the
273 Asiatic clam *Corbicula fluminaea* (Penny, 2006) that are commonly found in the upper layer of the
274 Tonlé Sap lake sediments. If the thickness of the parallel reflectors in Facies 3 that are truncated by
275 the erosion surface are examined (Figure 2, inset X), it is evident that erosion of *c.* 1.2 m of lacustrine
276 sediment must have taken place before the resumption of lacustrine sedimentation in Facies 4, a key
277 point that is returned to below. However, the amplitude of relief along this erosional surface is small,
278 with one N-S transect line in the north of the Tonlé Sap lake (location marked L3 on Figure 1)
279 showing an erosional relief of 0.85 m along a transect length of 10 km. Overall, the new PES data
280 thus show the occurrence of a major episode of lake-bed erosion that very likely extends across the
281 entire lake (the disconformity being expressed across the entire 530 km extent of our PES survey),
282 producing the disconformity between Facies 3 and 4.

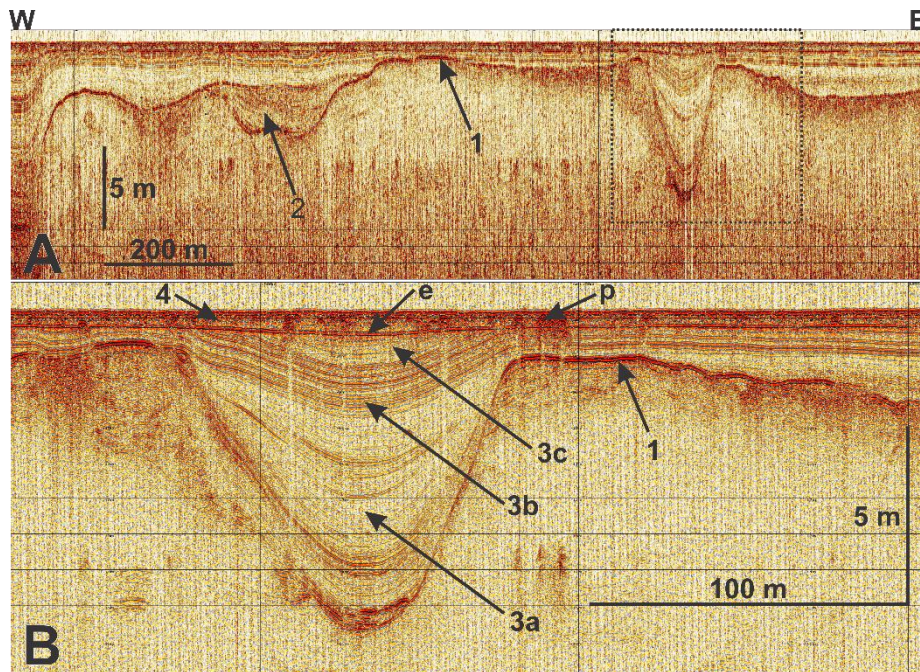
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RAPID DRAINAGE OF THE TONLÉ SAP LAKE



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285 **Figure 2:** PES profiles of Line 1 (see L1 on Figure 1 for location) running W-E across the Tonlé Sap
286 Lake, illustrating the principal palaeo-valleys and PES Facies 1-4, with the labels being detailed in
287 the text and Table 1. Top profile is 14.25 km wide, with area in black rectangle shown in detail below.
288 Inset X illustrates the truncation of reflectors used to estimate the amount of erosion at c. 1.2m.
289



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292 **Figure 3:** PES profile of W-E Line 2 at north of Tonlé Sap Lake (see L2 on Figure 1 for location),
293 illustrating: A) several examples of palaeo-valleys, and B) detail of the infill of the palaeo-valley
294 outlined in rectangle in A). PES Facies 1-4, labels and features are detailed in the text and Table 1.
295

296 3.2 Chronology and Sedimentation Rates

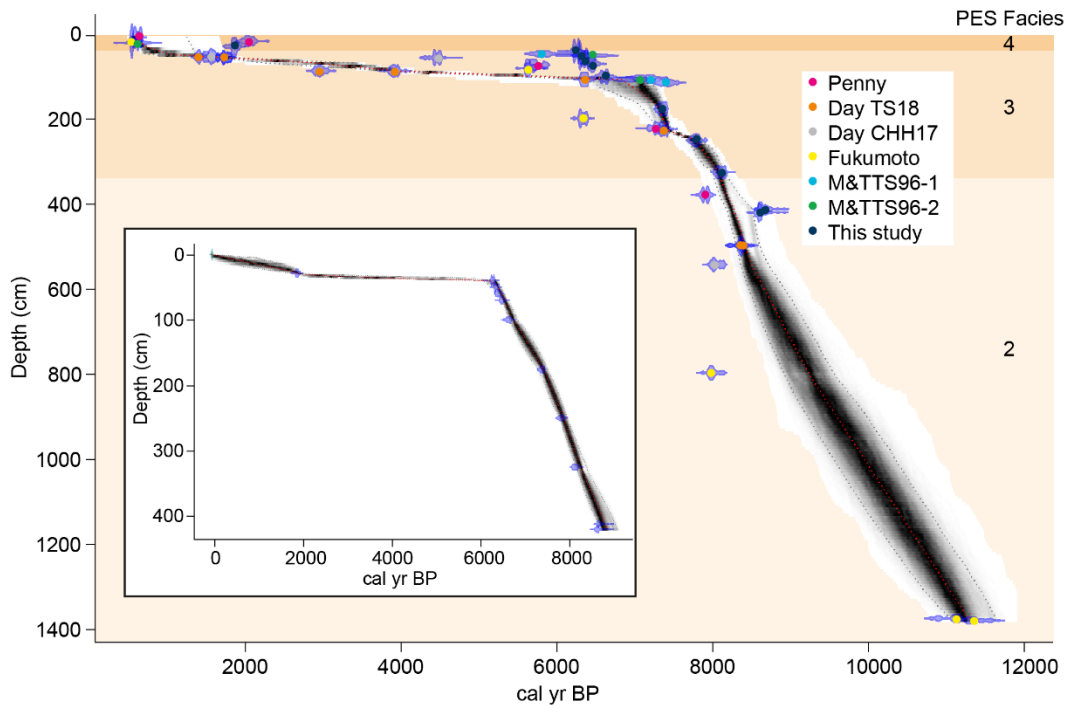
297 We used 11 new radiocarbon dates derived from the bulk sediment samples from our core LC2 to
298 develop a bespoke age-depth model for that core (Figure 4a). In addition, our core and PES facies
299 compare excellently, both with each other and with the previous studies of Day *et al.* (2011; Core TS-
300 18-XII-03) and Fukumoto (2014; core CT10). The tight stratigraphic correlation between these cores,
301 which can now confidently be made due to the availability of the PES data, thus makes it possible to

RAPID DRAINAGE OF THE TONLE SAP LAKE

302 undertake a meta-analysis of all the radiocarbon dates obtained from this study and the previously
303 published core records. We thereby employed a total of 40 ^{14}C dates (Table 2) to create a new master
304 chronology for the lake (Figure 4b). Consistent with prior studies, the age-depth models in both
305 Figure 4a and Figure 4b reveal a distinct discontinuity in the rates of sedimentation above and below
306 Facies 3 and 4. The sedimentation rates below 0.50 m (Facies 3) are relatively rapid, averaging *c.* 1.5
307 mm/year, as the basin accumulated *c.* 3.75 m sediment depth in just over 2,500 years (from 420 – 45
308 cm since *c.* 8,800 – 6,300 cal. yr BP). The onset of sedimentation above the discontinuity is somewhat
309 older (*c.* 6.2k; Figure 4b) when compared to the value of between 4,450 and 3,910 cal. years BP
310 estimated by Day *et al.* (2011), which could represent a N-S gradient of sedimentation rates. However,
311 the key point is that the new PES data reveal that the discontinuity in fact represents an erosion
312 surface, such that it is now clear that at least ~1.2 m of sediment accumulated in Facies 4 but was
313 then lost due to widespread erosion. This missing sediment must have been eroded at some point in
314 the interval between *c.* 6,200 - 2,000 cal. years BP. When accounting for this ~1.2 m of eroded
315 sediment, the time-averaged sedimentation rate for Facies 4 decreases to *c.* 0.3 mm/year. Finally, it
316 can be noted that dates gained within the top metre of sediments (Figure 4) show a consistent
317 younging of dates upwards, suggesting that mixing within this layer has unlikely occurred to a major
318 degree.

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RAPID DRAINAGE OF THE TONLE SAP LAKE



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323 **Figure 4.** Age-depth model for the Tonlé Sap lake sediment sequences based on calibrated ^{14}C ages
324 from (inset) the core sequence LC2 collected in this study and (main panel) a compilation of ^{14}C ages
325 including those from sequence LC2 as well as prior studies (see Table 2). The calibrated ages were
326 determined using the Calib 7.0 program and IntCal13 (Reimer *et al.*, 2013). Note that the symbol
327 shapes indicate the calibrated ^{14}C dates with two standard deviations, the grey shading indicates the
328 likely age model and the dotted lines show the 95% confidence ranges of the age model. The age
329 modelling was undertaken using the BACON package in R (Blaauw & Christen, 2011) with the
330 following parameters: acc.mean=5; acc.shape=1.5; mem.mean=0.7; mem.strength=4. The
331 boundaries between the different lithographic units (PES Facies 1 to 4) discussed in the text and Table
332 3 are also indicated.

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3.3 Palaeo-environmental Reconstruction

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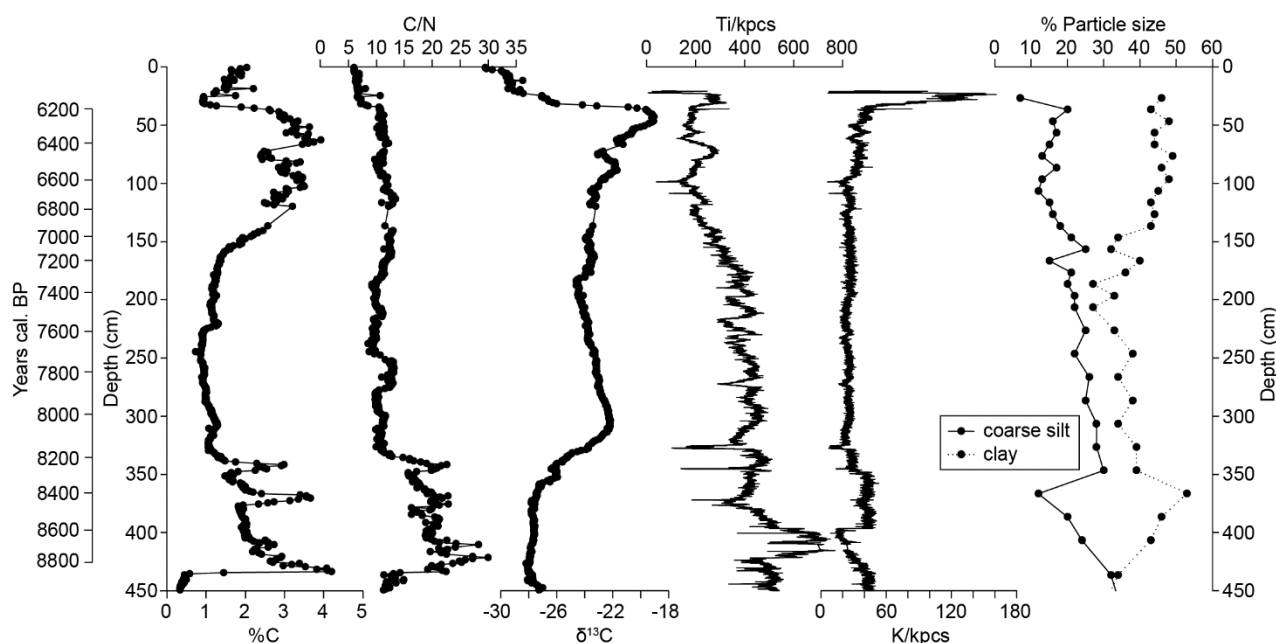
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The palaeo-environmental data show a number of marked changes throughout the core LC2 sequence (Figure 5), and we have chosen two elements from the Itrax data set to illustrate the key geochemical changes. The titanium plot (Figure 5) shows an oscillating, but long-term, decline from the earliest part of the sequence where organic sediments are preserved, around 420 cm, dated to *c.* 8,600 cal. yr BP, to around 120 cm (dated to *c.* 6,900 cal. yr BP). Titanium is often used as an inwash indicator, having a detrital origin, and as such can often be used to reflect relative changes in precipitation (e.g., Metcalfe *et al.*, 2010; Swierczynski *et al.*, 2012). The record shows enhanced Ti towards the base, with declining values thereafter, which could relate to a wetter early part of the record followed by relative drying. Nonetheless, the size of the basin and regional inflows means this could be an overly

RAPID DRAINAGE OF THE TONLE SAP LAKE

345 simplistic interpretation. The potassium record shows relatively little change throughout much of the
 346 record, but shows a marked change around 36 cm. Here we use K as a representative of the
 347 alkali/alkali earth elements that Day *et al.* (2011) used (Factor 2 elements, Fig 6), and our geochemical
 348 data are very similar to that from Day *et al.* (2011). This period in the sequence is difficult to date
 349 precisely, as the age/depth model suggests a coherent sequence exists until *c.* 36 cm (6,200 cal. yr
 350 BP), whereas by *c.* 30 cm, the sequence is dated to around 2,000 cal. yr BP. The change in K at around
 351 36 cm is also reflected in a change in particle size and a relative decline in organic content from
 352 previously relatively high values. These changes are all indicative of a change in sediment coming
 353 into the lake at around 36 cm in the sequence.



354

355 **Figure 5.** Palaeo-environmental proxies from the LC2 core taken in this study. Vertical axes show
 356 both depth, and calibrated ages (cal. yr BP) as calculated from our age model up to 36 cm depth
 357 (6,200 cal. yr BP). From left to right, the plots show %C, C/N ratios, $\delta^{13}\text{C}$, Itrax XRF Ti normalised
 358 against counts per second (kpcs), Itrax XRF K normalised against counts per second, and percentage
 359 particle size for the coarse silt (62-31 microns) and clay (<3.9 microns) size fractions.
 360

361 While the geochemical changes may reflect catchment precipitation and changes in sediment
 362 sources, organic matter (%C, C/N and $\delta^{13}\text{C}$) can indicate sediment sources, productivity, and whether
 363 the lake is a closed or open basin. The basal part of the sequence contains low %C, C/N and $\delta^{13}\text{C}$,
 364 most probably indicating an open freshwater system with the organic matter predominantly algal

RAPID DRAINAGE OF THE TONLE SAP LAKE

365 derived. From 430 to 330 cm (8,840-8,180 cal. yr BP), the C/N rises and is consistently >10, and
366 mainly >20, and when coupled with low $\delta^{13}\text{C}$ (-28 to -25‰) suggests incorporation of terrestrial C3
367 plants from the catchment, which could relate to an expansion of C3 vegetation in the floodplain.
368 There follows an interesting transition between 330 to 300 cm (8,180-8,010 cal. yr BP), where C/N
369 falls, suggesting increased algal dominance, and increased $\delta^{13}\text{C}$ may reflect increased algal
370 productivity, and the system remains relatively stable until 170 cm (7,250 cal. yr BP). After 170 cm,
371 %C increases, C/N remains relatively low, indicative of an algal dominated system, and the high $\delta^{13}\text{C}$
372 is most likely aquatic productivity. The increase in %C, suggesting high productivity, coupled with a
373 relative decline in Ti, may suggest a relatively drier system, perhaps moving towards a closed basin
374 evaporative system. Above 50 cm (6,310 cal. yr BP), the low $\delta^{13}\text{C}$ and C/N are interpreted as a result
375 of a change in algal communities but productivity is likely low, which, coupled with the geochemical
376 data, may represent a change in sediment source.

377

378 **3.4 Correlation of PES Facies with Core Records**

379 The PES survey line that intersects our new core LC2 (Figure 6a) shows an excellent correspondence
380 with the core description. The PES data (Figure 6a) show that the core was taken at the edge of a
381 palaeo-valley, and displays the same four PES facies as summarised for the rest of the Tonlé Sap
382 Lake (Table 1). It should be noted that core LC2 and the PES data were not taken at the same time
383 (March 2013 and October 2014 respectively) and thus although the data match well, and geographic
384 co-location is good, the resolution of the 2013 GPS data (*c.* 10-15 m) may result in a small error in
385 their co-location. As shown by the PES data above, such small errors in co-location can potentially
386 introduce some mismatch due to possible rapid changes in sediment thicknesses and facies types.

387 It is likely that our 4.58 m long core was unable to penetrate the hardened surface of the
388 Pleistocene valley fill and thus this surface, and the sediments beneath (PES Facies 1) were not
389 sampled. The basal 1.26 m of the core (458 to 332 cm) likely correlates to the lowest, rather
390 structureless, PES reflections, which lay beneath the first very strong sets of reflections within the
391 valley fill sediments at this locality. These lower sediments are interpreted to represent PES Facies 2

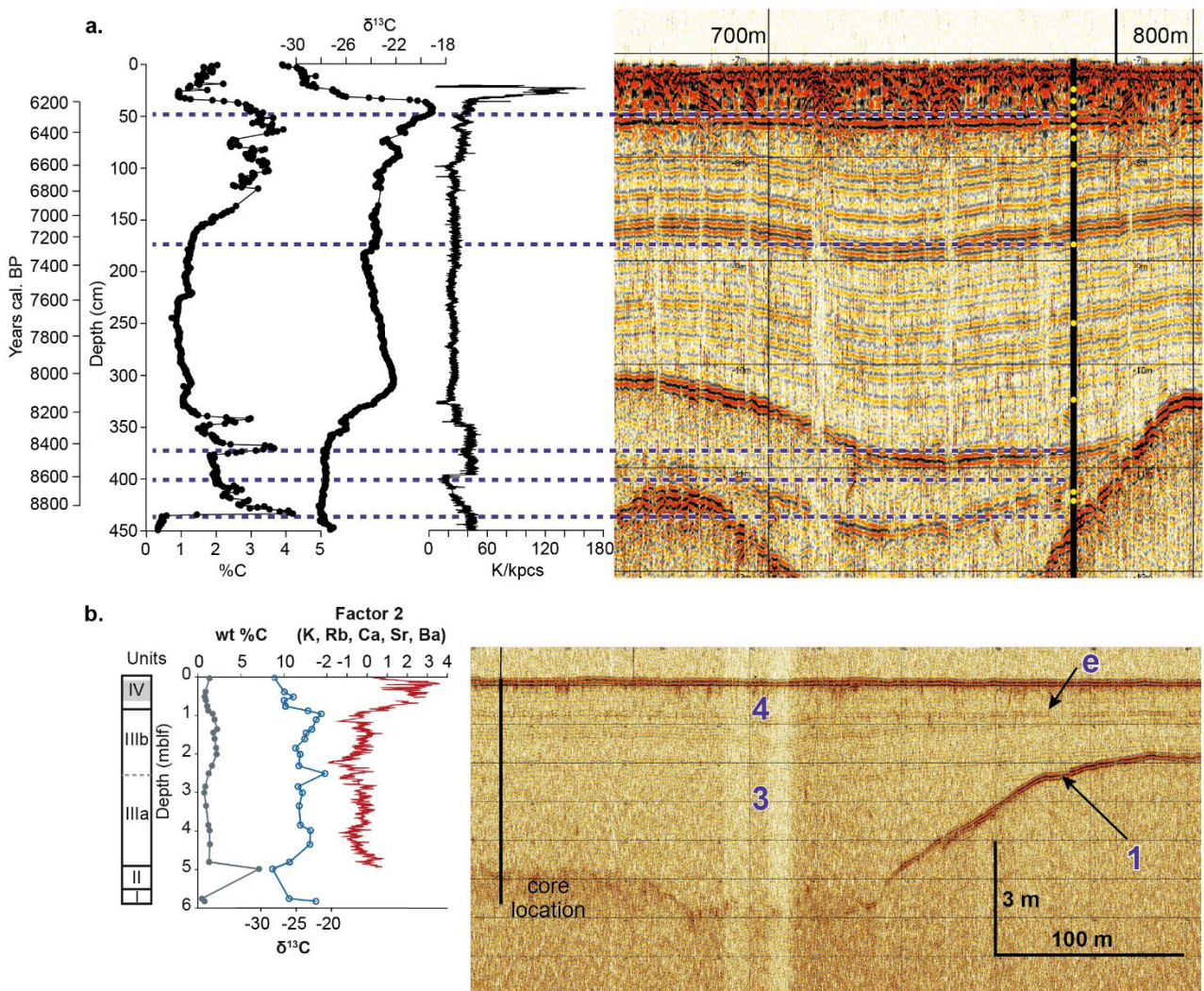
RAPID DRAINAGE OF THE TONLE SAP LAKE

392 (fluvial or subaerial slope deposits) and indicate an open freshwater system with a large inwash of
393 terrestrial C3 plants. Above this series of strong reflections, the next 3 m of sediment represents
394 lacustrine sedimentation, with PES Facies 3 demonstrating a series of parallel reflections that drape
395 the underlying topography. The lower part of this unit represents an algally-dominated freshwater
396 lake (Facies 3a, b) but above *c.* 170 cm, and noticeably above the strong reflections that mark the
397 base of PES Facies 3c (Figure 6a), the palaeo-environmental interpretation indicates a potentially
398 drying climate and more evaporative lake conditions. The top *c.* 32 cm of Core LC2 correlates with
399 PES Facies 4 and lies above the distinct erosion surface that can be correlated across the entire Tonlé
400 Sap lake. These lacustrine sediments display a marked change in their geochemistry, and past work
401 (Penny, 2006; Day *et al.*, 2011; Fukumoto, 2014) shows a consensus that it is in these sediments, and
402 during this time period, that the Mekong River became connected with the Tonlé Sap Lake. The
403 characteristics of PES Facies 4 at the site of Core LC2 show faint parallel reflections and the presence
404 of abundant point reflections, interpreted herein as being generated either by siderite concretions or
405 shelly materials within this upper sediment.

406 The PES profile through the site of the Day *et al.* (2011) TS18-XII-03 core matches the
407 corresponding core log very well (Figure 6b). Significantly, the distinct upper one metre (recall that
408 this layer has isotopic signatures characteristic of sediments deposited within a flood-pulsing lake
409 connected to the Mekong) corresponds closely to reflections that clearly delimit PES Facies 4 and
410 which lie above the strong erosional base of this facies that can be traced across the entire lake. The
411 section of the Day *et al.* (2011) TS18-XII-03 core below 1 m to 5 m depth appears linked to lacustrine
412 PES Facies 3, with no evidence for Facies 2 at this site. The reflections here are rather weak, but
413 parallel laminated sediment is clearly evident, terminating at 5 m depth against the strong reflection
414 interpreted to represent the Pleistocene palaeo-valley surface of PES Facies 1. The core CT10 detailed
415 by Fukumoto (2014) and a nearby PES section likewise match excellently despite being located
416 approximately 1.3 km apart, but the PES provides a far higher level of resolution and lateral
417 correlation. PES Facies 4 correlates well with Unit 7 of Fukumoto (2014), whilst the rather

RAPID DRAINAGE OF THE TONLE SAP LAKE

418 structureless Unit 6 of Fukumoto (2014), with weak reflections, matches PES Facies 3c. Unit 5 of
 419 Fukumoto (2014) shows a marked increase in the total diatom assemblage and it is noticeable how
 420 this correlates with a series of far stronger reflections in Facies 3b. Units 2, 3 and 4 of Fukumoto
 421 (2014) map onto Facies 3a, although it is noticeable that the core shows a region of higher diatom
 422 abundance within this region that again appears linked to a zone of stronger parallel reflections within
 423 Facies 3a. However, the spatial disparity between the CT10 core and PES panel do not allow closer
 424 correlation, and nor do the PES profiles here penetrate to the maximum depth of core CT10.



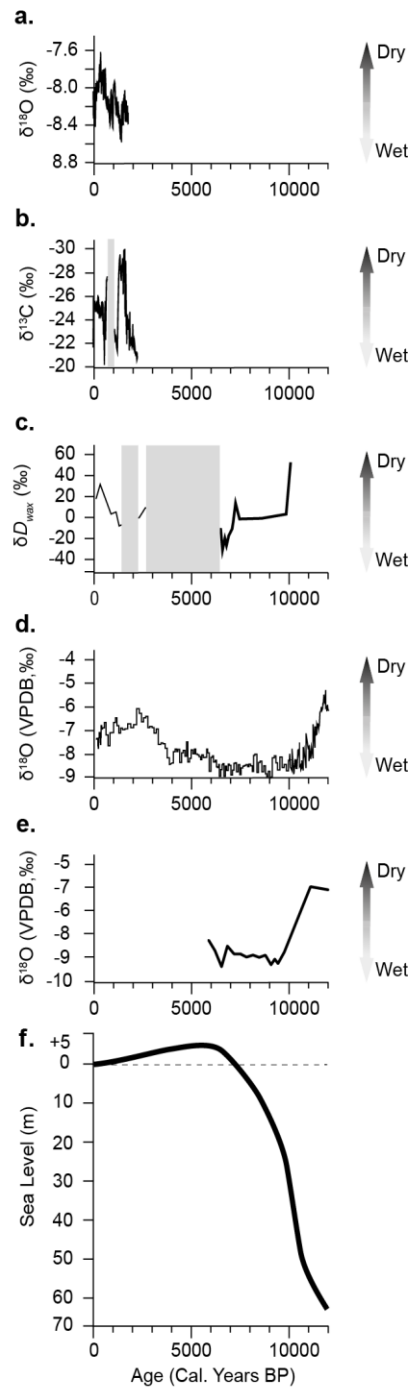
425
 426 **Figure 6.** Examples of PES data showing the relationships between the Tonlé Sap Lake sediment
 427 PES facies determined from the geophysical surveys (right hand side) and selected palaeo-
 428 environmental datasets (left hand side). (a) Comparison of PES versus LC2 core (this study) data and
 429 (b) PES versus core from the study by Day (2011). Labels are detailed in the text and Table 1.
 430

432 **4. SYNTHESIS**

433 The new data presented herein, together with the synthesis of previous research on the Tonlé Sap
434 Lake and its Holocene history (Table 3), permit a unified synthesis of the palaeo-environmental
435 changes that have led to its infill and changing rates of sedimentation. The background environmental
436 and climate context to the development of the Tonlé Sap Lake, as inferred from a range of regional
437 palaeo-records (Figure 7), is one of rapidly rising sea level of around 60 m from *c.* 11, 000 - 6,000
438 cal yr BP (Ta *et al.*, 2002; Figure 7f). After the highstand of around 5 m above present day mean sea-
439 level at *c.* 5,000 cal. yr BP, sea level starts to fall, through to the present day. During this period, the
440 climate has oscillated considerably, and interpretation of the records is not straightforward. Yang *et*
441 *al.* (2014) compare cave-based speleothem records from China (East Asian Summer Monsoon
442 (EASM) region) with those from the Indian Summer Monsoon (ISM) region and argue that the
443 coherence of the records, and modern source area of precipitation originating from the SW, implies
444 the signature of these records is dominated by rainfall variability of the ISM region. Nonetheless, the
445 trajectory of change is markedly similar, and likely implies a relatively stable (and likely wetter) early
446 Holocene, with a clear change at around 6,000 cal. years BP to potentially drier conditions. Other
447 records from the region, such as the Yulin loess-palaeosol record, show peaks in precipitation
448 between *c.* 7,000 to 4,000 cal. yr BP, again with notable drying thereafter (Lu *et al.* 2013). This broad
449 drying trend, from between *c.* 6,000 to 4,000 cal. yr BP, and into the later Holocene, can be compared
450 with similar drying events identified from Lake Kumphawapi in Thailand (Figure 1) from between
451 *c.* 6,500 to 1,400 cal. yr BP where multiple hiatuses are present, and that have been explained by
452 periodic desiccation events of the wetland and erosion due to subsequent lake-level rise (Chawchai
453 *et al.*, 2015b; Figure 7c). The broad change in lake level, rising from *c.* 2,000 cal. yr BP, and reaching
454 shallower parts around 1,400 cal. yr BP, is linked to a relative increase in effective precipitation, and
455 compares well with a change in directional trend in the Chinese speleothem data, notably from
456 Dongge Cave (Yang *et al.*, 2014).

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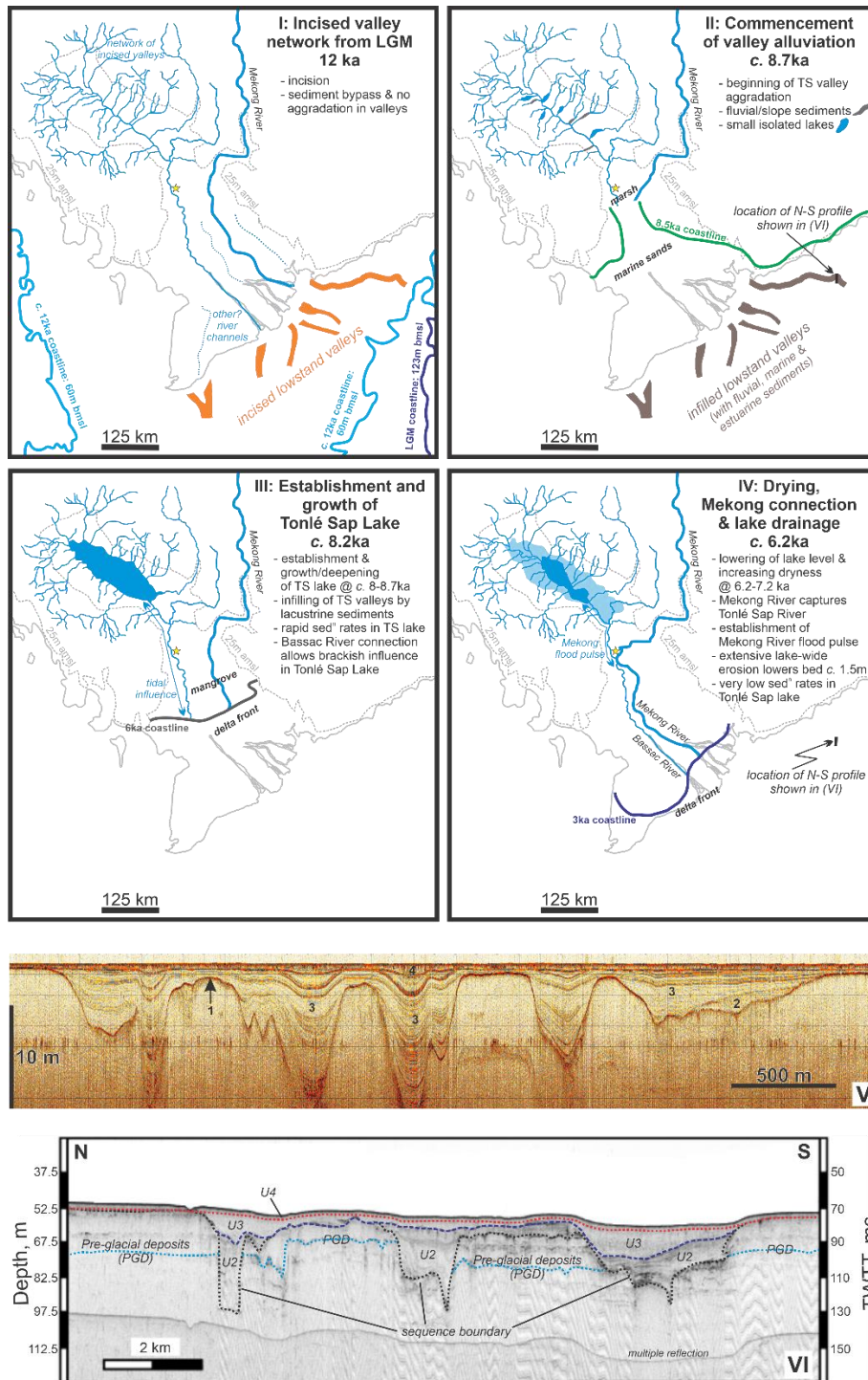
RAPID DRAINAGE OF THE TONLE SAP LAKE



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459 **Figure 7.** Synthesis of regional proxy records of climate change and sea-level rise from the present
 460 day to 15,000 cal. years BP based on: (a) $\delta^{18}\text{O}$ data from Wanxiang Cave (33°N, 105°E) speleothems
 461 (Zhang *et al.*, 2008); (b) $\delta^{13}\text{C}$ data from the Lake Pa Kho (17°N, 102°E) sediment record (Chawchai
 462 *et al.*, 2015a); (c) δD_{wax} (i.e., a hydrogen isotope proxy being the average value of C_{29} *n*-alkane and
 463 C_{31} *n*-alkane δD values) data from the Lake Kumphawapi (17°N, 103°E) sediment record (Chawchai
 464 *et al.*, 2015b); (d) $\delta^{18}\text{O}$ data from the Dongge Cave (25°N, 108°E) speleothem (Yuan *et al.*, 2004); (e)
 465 $\delta^{18}\text{O}$ data from the Tham Lod and Ban Rai (19°N, 99°E) freshwater bivalve records (Marwick and
 466 Gagan, 2011), and; (f) Regional sea-level reconstruction for the Mekong delta region (Ta *et al.*, 2002).
 467 Note that the grey shaded areas in panels (b) and (c) highlight areas with missing data due to an
 468 erosional hiatuses in the sediment records. The locations of the sites used in panels (a) through (e)
 469 are also illustrated on Figure 1.
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RAPID DRAINAGE OF THE TONLE SAP LAKE



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473 **Figure 8.** I-IV: Schematic palaeo-geographic reconstructions of the Holocene evolution of the Tonlé Sap Lake and Mekong delta. See text for explanation. Palaeo-shoreline positions and location of offshore incised palaeo-valleys after Nguyen *et al.* (2000), Tjallingii *et al.* (2010, 2014) and Zoccarato *et al.* (2018); V: Parametric Echo Sounder panel from the present study (this is part of L1 on Figure 1; see Figure 2 also for precise location), illustrating the palaeo-valleys and their infill. PES facies numbered as detailed in the text and Table 1; VI: Sub-bottom profile data from the Mekong coast (see location in Panel II) adapted from fig. 5 of Dung *et al.* (2013). See text for explanation. Sequence boundary is the LGM erosion surface and incised valleys. U2 and U3 are sediments that infill valleys and show the transition from fluvial to marine deposits. U2 is located at the base of the valley and represents possible fluvial lowstand to transgressive deposits. U3 is interpreted as transgressive estuarine to shallow marine deposits, whilst U4 is interpreted as a condensed section formed due to sediment starvation in the distal part of the highstand deposits (ages ranging from 0.3-8 ka).

RAPID DRAINAGE OF THE TONLE SAP LAKE

485 The preceding synthesis presents an overall picture of rising and then falling (from *c.* 5,000 cal.
486 yr BP) sea level, coupled with a mid-Holocene (*c.* 6,000 cal. yr BP) change in precipitation regime,
487 that sets for the context for the Holocene evolution of the Tonlé Sap Lake through the stages that are
488 described as follows and summarised in Figure 8:

489

490 1. Estimates of climate around the LGM in Southeast Asia are variable, but typically point to
491 cooler temperatures (*e.g.*, Zhang *et al.*, 2019), with a reduced EASM, and precipitation from
492 this period until *c.* 8ka may have been relatively reduced (Lu *et al.*, 2013). Nevertheless, it is
493 clear that erosion was taking place in the Tonlé Sap, creating a valley network that likely
494 connected with the valleys that have also been detected and quantified (see Figure 8; Panel I)
495 in the offshore surveys of Tjallingii *et al.* (2010, 2014), Dung *et al.* (2013) and Liu *et al.*
496 (2017). In the Tonlé Sap region, the PES data reveal these valleys were a maximum of *c.* 15
497 m deep. These channels developed a complex network that likely fed into a main channel that
498 flowed to the south (Figure 8; Panels I - V), perhaps connecting with the present day Bassac
499 River and flowing to the present day coast, where subsurface data reveal Pleistocene valleys
500 *c.* 20-30 m deep and defining a sequence boundary (Figure 8, Panel VI; Dung *et al.*, 2013).
501 These valleys thus fed sediment out to the Mekong delta through an incised lowstand valley
502 network, with sediment bypass negating any significant valley aggradation. During this
503 period, we speculate the principal Mekong River adopted a different course and thus had no
504 influence on the Tonlé Sap River. Significant lowstand valleys detected in the present day
505 coastal region (Figure 8; Panel I) bear witness to the multiple channels, or multiple positions
506 of the main channel, through time.

507 2. Alluviation within the Pleistocene valley network of the Tonlé Sap region began at *c.* 8.7 ka
508 at our core site (Figure 8; Panel II), as freshwater sediments with a high organic content and
509 showing strong terrestrial characteristics, as evidenced through the C/N ratio and carbon
510 isotopes data. We interpret our PES data as indicating fluvial or slope sedimentation, perhaps

RAPID DRAINAGE OF THE TONLE SAP LAKE

511 with small isolated lakes in the valley network. This is supported by the interpretation of
512 wetland environments during this time by Day *et al.* (2011). In the coastal region, Dung *et al.*
513 (2013) interpret initial sedimentation as only occurring within the Pleistocene valleys, and as
514 demonstrating an estuarine or fluvial nature (their Unit 2, Figure 8; Panel VI) as the valley
515 network began to infill during sea-level rise. At this time, marine sands began to accumulate
516 along a coastline where the Mekong delta was prograding to the south (Figure 8; Panel II).

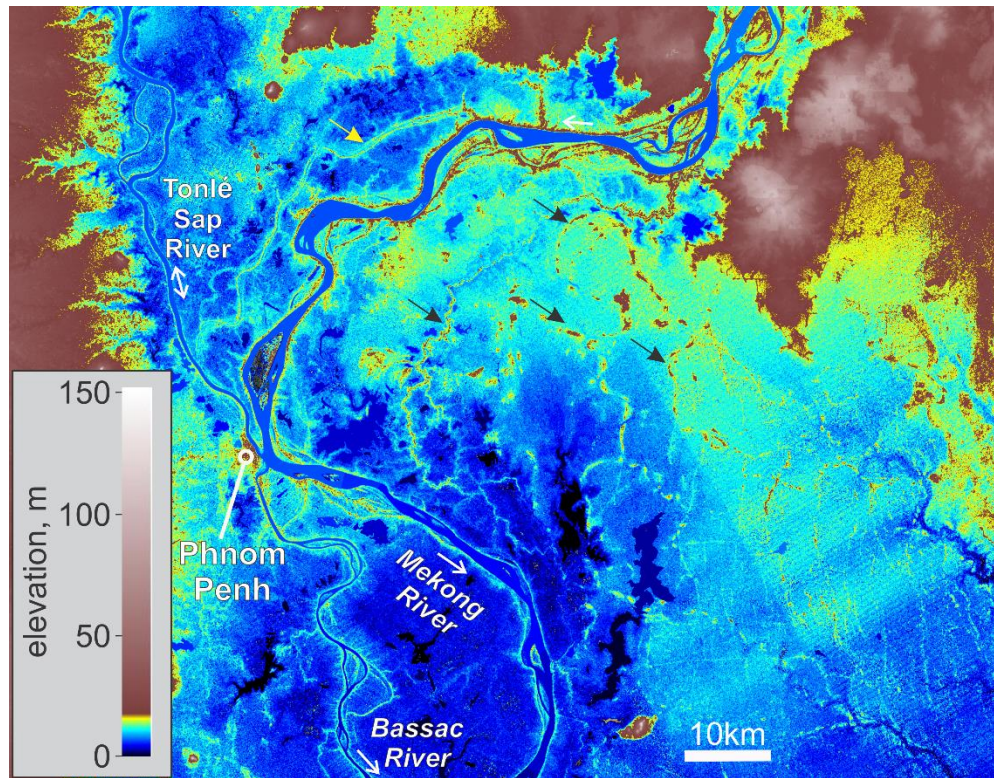
- 517 3. Establishment of the Tonlé Sap Lake and major lacustrine sedimentation within these valleys
518 (Figure 8; Panel III) began at *c.* 8.2 ka, and produced sedimentation that mantled the entire
519 alluvial landscape, signifying growth and establishment of a lake that was eventually deep
520 enough to drown the underlying topography. Flooding of the valley network, and
521 establishment of the lake, must have occurred due to input from the river network, as well as
522 possible incursions from the coast through the Bassac channel. This period marked the time
523 of maximum sedimentation rates within the lake (*c.* 15 mm/year). Such lacustrine
524 sedimentation characterises the majority of the infill of the valley network, with geochemical
525 data indicating a likely climatic drying after *c.* 7,250 cal. yr BP, whose onset is shown by
526 distinct strong reflections in the PES data, and also matches well with regional climate indices
527 (Figure 7). Although our data do not reveal a marine or brackish water influence on
528 sedimentation during deposition of Facies 3, Penny (2006) argued for a tidal and/or saline
529 influence in the lake during the early to middle Holocene. We speculate that any connection
530 of the Tonlé Sap Lake to the coast during this time was likely solely via the smaller Bassac
531 River channel that would have permitted such a possibility, but without the need for a
532 connection to the principal Mekong River. Saline intrusion, or backwater tidal effects, within
533 the lake would be more likely in connections with a smaller channel, which would also not
534 produce any change in sediment geochemistry as occurs after the connection to the Mekong
535 River was established (see below). However, in the period after *c.* 7,250 cal. yr BP, the lake
536 likely shrunk in volume and area due to this drying climate.

RAPID DRAINAGE OF THE TONLE SAP LAKE

537 4. A period of widespread erosion occurred over the entire lake sometime after *c.* 6.2 ka (PES
538 Facies 4) and produced the marked disconformity between PES Facies 3 and 4. This erosion
539 event removed around *c.* 1.2 m of sediment across the entire lake, and sedimentation after this
540 period was very different in both its much slower rate (*c.* 0.3 mm/year) and its marked
541 compositional difference that shows a connection with the Mekong River (Table 3; Figure 8;
542 Panel IV). Widespread erosion across the Tonlé Sap Lake was thus coincident with
543 establishment of the flood pulse hydrology, generating the distinctive environment that is
544 present today. We speculate this lake level lowering and erosion was linked to: (i) falling sea-
545 level after the mid-Holocene highstand at *c.* 5,500 ka (Figure 7f) that would have increased
546 river gradients; (ii) a period of enhanced climatic dryness that may also have lowered lake
547 levels, potentially permitting enhanced wave erosion of the lakebed, and; (iii) avulsion of the
548 Mekong River that allowed connection with the Tonlé Sap River and Lake, and potentially
549 generated higher water surface slopes from the Tonlé Sap Lake during the dry season, as well
550 as providing a larger conduit and water volume for the export of this sediment. From the depth
551 of erosion of *c.* 1.2 m, and assuming a maximum lake area of 10,000 km², we estimate a
552 volume of *c.* 12 km³ of sediment was eroded during this period. The Mekong River delta was
553 prograding to the south and by *c.* 3 ka had reached a location near its present-day position
554 (Figure 8, Panel IV). Avulsion of alluvial channels is an omnipresent feature of deltas, and
555 the Mekong River delta has undoubtedly experienced several such events in its Holocene
556 advance. Although we have no data for the dating of such avulsions, topographic data for the
557 current deltaic floodplain (Figure 9) reveal a series of abandoned channels, of approximately
558 the same size as the present-day Mekong River, which likely bear witness to such events. We
559 speculate herein that connection of the Mekong River to the Tonlé Sap drainage system, at
560 some time after *c.* 6.2 ka, was through such an avulsion that enhanced and aided lake-wide
561 erosion and export of this sediment to the delta.

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574 **Figure 9.** Topography of the Mekong River floodplain derived from SRTM data, illustrating the
575 current Mekong, Bassac and Tonlé Sap rivers, together with the topographic signature of older
576 palaeo-channels (labelled with black and yellow arrows) on the Mekong River floodplain. The
577 sinuosity and width of these topographically elevated channels is of the same order as the current
578 Mekong River, and may indicate the past positions of the Mekong main channel.
579

580

581 **5. CONCLUSIONS**

582 An annual flood pulse, whereby water from the Mekong River raises the lake level by *c.* 8m during
583 the monsoon season, dominates the present-day hydrology of Cambodia's great lake, the Tonlé Sap.
584 This flood-pulse is instrumental in bringing sediment and nutrients to the lake and its floodplain and
585 provides a pathway for fish migration, establishing one of the richest fish habitats in Southeast Asia
586 that is responsible for providing up to 80% of protein to Cambodia's growing population. In this
587 study, we have presented new subsurface geophysical data, that when allied to new and past sediment
588 core studies, unequivocally shows a period of major mid-Holocene erosion across the entire Tonlé
589 Sap Lake that is coincident with establishment of the lake's critically important flood pulse. We argue
590 that this widespread erosion, which removed at least 1 m of sediment across the entire lake, was
591 triggered by base-level lowering due to capture of the Tonlé Sap drainage by the Mekong River, an

RAPID DRAINAGE OF THE TONLE SAP LAKE

592 event that would have significantly altered lake levels. This river capture also occurred during a
593 period of falling sea-level after the mid-Holocene highstand, and after a period of climatic dryness,
594 which would both have aided avulsion of the Mekong River and its capture of the Tonlé Sap River
595 drainage network. Our new synthesis reconciles past anomalies in interpretation of Holocene palaeo-
596 environmental change and sedimentation rates within the Tonlé Sap region, and demonstrates that
597 interpretations of lacustrine sedimentation from cores must be set within the context of their broader
598 spatial thickness changes as revealed by subsurface geophysical surveys. Establishing long-term
599 sedimentation rates, or their fluctuation through time, cannot be assessed meaningfully without this
600 broader context.

601 The present study demonstrates that longer-term landscape evolution of the Tonlé Sap region
602 was thus punctuated by a rapid, river capture-induced, lake drainage that established the ecosystem
603 that flourishes today. The scale of change induced by the capture illustrates the susceptibility of such
604 systems to thresholds in geomorphic response, and highlights the perilous nature of ecosystem
605 functioning in the Tonlé Sap to ongoing anthropogenic changes in hydrology and sediment flux
606 within the Mekong River Basin.

607

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615

616 **Author Contributions**

617 S.E.D, P.G.L, J.L., J.L.B, A.P.N, R.A and D.R.P jointly conceived the supporting grants; all authors co-
618 designed the field investigations. P.G.L, J.L, S.E.D, M.J.L, S.B. and P.R.M collected and processed the

RAPID DRAINAGE OF THE TONLE SAP LAKE

619 sediment cores, while J.L.B, C.R.H and M.M. collected and processed the sub-bottom geophysical data. S.E.D,
620 J.L.B, P.G.L and J.L jointly drafted the manuscript, which all authors then edited.
621

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RAPID DRAINAGE OF THE TONLE SAP LAKE

Table 1. Description and Interpretation of PES Facies Characteristics

PES Facies	Reflector Characteristics	Interpretation
1	Marked by a strong upper reflection than most often has no, or very faint, reflections beneath (Fig. 2 inset; labelled 'a'). Where present, most of these underlying reflectors are non-parallel and discontinuous and cannot be traced over distances greater than c. 100m. The strong upper reflection horizon may be very close to, or at, the present-day lake surface (Figs 2 and 3; labelled 1), but is often markedly erosional with a relief of up to c. 15m, with broad depressions that may be up to c. 1.2km in width (Fig. 2) but are frequently 50-200m wide (Fig. 2). This strong reflection is present within the vast majority of PES lines over the entire lake.	Eroded surface of a buried Pleistocene valley network
2	Lies directly above Facies 1, and consists of either structureless, or faintly bedded, sediments that are either non-parallel or downlap onto, and truncate against, the lower basal reflection (Figs 2 and 3, labelled '2'). Some of these surfaces are inclined, and define accretion onto the underlying basal erosion surface and lateral to the underlying valley margins (Fig. 2; labelled '2'). Facies 2 is up to 2 m thick but occurs in only a few of the PES survey lines.	Fluvial, or subaerial slope deposits. Initial stages of Pleistocene valley infill.
3	Dominant PES facies within the Tonlé Sap Lake in terms of thickness and volume of deposits, and consists of strong reflections that are largely parallel, and sub-parallel, to each other and the underlying reflections, and drape the underlying topography (Figs 2 and 3, labelled '3'). These reflections sometimes drape the entire topography of Facies 1, but may also taper out laterally (Fig. 2; labelled '1'). Facies 3 does not possess any clear internal cross-cutting relationships between reflections, but a range of different strength reflections can be used to subdivide the facies into three subunits (Fig. 3), although all these reflections are conformable and drape the underlying topography. The lower reflections (Facies 3a; Fig. 3) consist of rather weak parallel beds, with several stronger reflections within the middle of this package. Facies 3a ranges from c. 0.5 to 6m thick. Facies 3b conformably overlies Facies 3a (Fig. 3) but is noticeable for possessing a series of much stronger reflections, that in total may be up to 2 m in thickness. Lastly, Facies 3c possesses a series of more diffuse and weaker reflections (Fig. 3), but that are still parallel bedded, drape the underlying sediments conformably and may be up to 1.5m thick. Facies 3 shows a wide variation in thickness, from a maximum of c. 10 m to a minimum of zero where the present day lake surface intersects the strong reflections of Facies 1.	Lacustrine sedimentation with conformable deposition of sediment from suspension. Some of the lower drapes mantle the entire topography at the valley edges (Figs 2 & 3) and demonstrate that the lake was deep enough to drown the palaeo-valley landscape and was established by the commencement of Facies 3 deposition.
4	Facies 4 lies unconformably on Facies 3 and is c. 0.7-1m thick over much of the northern and southern parts of the lake (Figs 2 and 3). Characterised by very strong flat, parallel, reflections that are laterally extensive, and the basal reflector of this facies is often very strong (Figs 2 and 3, labelled 'e') and notably has a markedly erosive contact with the underlying Facies 3 (Fig. 2 inset p x). This unit is characterised by frequent parabolic reflections that may occur singly or in clusters (Fig. 2, inset, labelled 'p'), and when in groups these parabolic reflections may lessen the strength of the underlying reflections, highlighting their probable high density in attenuating acoustic penetration. The nature of the unconformable lower contact may show a very marked angular divergence with the underlying sediments (Fig. 2, inset panel x, dashed line). If the thickness of the parallel reflectors that are truncated is examined, this indicates erosion of c. 1.2m of sediment (Fig. 2, inset panel x) during this erosive event. However, the amplitude of relief along this erosional surface is small, with one N-S transect line in the north of the Tonlé Sap Lake (labelled line 'L' on Fig. 1) showing an erosional relief of 0.95m along a transect length of c. 28 km.	Sedimentation in Tonlé Sap lake due to sediment suspension settling, but after a period of widespread erosion that generated the extensive erosion surface that separates Facies 3 and 4 across all of the Tonlé Sap lake. Parabolic point reflections generated from diagenetic siderite concretions (Pottier <i>et al.</i> , 2012), or accumulations of the clam <i>Corbicula fluminea</i> (Penny, 2006) within the sediments.

RAPID DRAINAGE OF THE TONLE SAP LAKE

Table 2. Synthesis of ¹⁴C dates for Tonlé Sap lake core records. Core depth (in cm) is given below the sediment-water interface adjusted to a common datum. See Figure 1 for the locations of each core. Calibration of the ¹⁴C dates was made using Calib 7.0 and IntCal13 (Reimer *et al.*, 2013). Age ranges shown are the highest relative probability for the calibrated ¹⁴C dates.

Lab ID	Core depth (cm)	¹⁴ C BP ± 1σ	Material	Calibrated age range (2σ)	Source
Beta-463010	28.5	1910 ± 30	Plant material	1857 ± 94	This study
Beta-463011	39.5	5450 ± 30	Bulk sediment	6247 ± 48	This study
Beta-463012	49.5	5520 ± 30	Bulk sediment	6312 ± 59	This study
Beta-463013	59.5	5610 ± 30	Bulk sediment	6375 ± 68	This study
Beta-444816	69.5	5680 ± 30	Bulk sediment	6459 ± 68	This study
Beta-444817	99.5	5810 ± 30	Bulk sediment	6616 ± 106	This study
Beta-444818	175.5	6420 ± 30	Bulk sediment	7360 ± 71	This study
Beta-444819	249.5	6960 ± 30	Bulk sediment	7790 ± 111	This study
OxA-28154	324.5	7308 ± 30	Wood	8107 ± 74	This study
OxA-28155	411.5	7864 ± 33	Wood	8641 ± 106	This study
OxA-28156	419.5	7834 ± 33	Wood	8610 ± 80	This study
AA-39964	7	650 ± 35	Pollen grains	603 ± 59	Penny (2006)
CAM-66653	16	2070 ± 40	Pollen grains	2040 ± 105	Penny (2006)
CAM-66654	72	4990 ± 40	Pollen grains	5717 ± 139	Penny (2006)
AA-39963	221	6345 ± 45	Pollen grains	7280 ± 122	Penny (2006)
CAM-66655	378	7090 ± 40	Pollen grains	7923 ± 78	Penny (2006)
CAMS-137174	53	1530 ± 35	Shell	1425 ± 87	Day <i>et al.</i> (2011)*
CAMS-137172	54	1800 ± 30	Shell	1732 ± 98	Day <i>et al.</i> (2011)*
CAMS-137173	55	1800 ± 30	Shell	1732 ± 98	Day <i>et al.</i> (2011)*
CAMS-121346	86	2845 ± 35	Wood	2954 ± 98	Day <i>et al.</i> (2011)*
CAMS-138882	86	3605 ± 35	Bulk sediment	3914 ± 117	Day <i>et al.</i> (2011)*
CAMS-140615	106	5580 ± 40	Bulk sediment	6360 ± 70	Day <i>et al.</i> (2011)*
CAMS-140616	223	6465 ± 40	Bulk sediment	7373 ± 75	Day <i>et al.</i> (2011)*
CAMS-138883	497	7545 ± 40	Bulk sediment	8369 ± 101	Day <i>et al.</i> (2011)*
CAMS-121347	497	7570 ± 60	Wood	8381 ± 155	Day <i>et al.</i> (2011)*
SUERC-29792	52	1663 ± 37	Bulk sediment	1568 ± 138	Day <i>et al.</i> (2011)+
SUERC-29793	55	3978 ± 36	Bulk sediment	4462 ± 115	Day <i>et al.</i> (2011)+
SUERC-29794	542	7228 ± 40	Bulk sediment	8040 ± 95	Day <i>et al.</i> (2011)+
POZ-45741	16	535 ± 30	Shell	543 ± 60	Fukomoto (2014)
POZ-45742	80	4910 ± 40	Bulk sediment	5637 ± 65	Fukomoto (2014)
POZ-45743	198	5530 ± 40	Bulk sediment	6332 ± 62	Fukomoto (2014)
POZ-45745	797	7180 ± 50	Bulk sediment	7995 ± 139	Fukomoto (2014)
POZ-37573	1375	9680 ± 50	Wood	11110 ± 213	Fukomoto (2014)
POZ-37574	1380	9950 ± 50	Plant charcoal	11373 ± 186	Fukomoto (2014)
Not reported	46	5081 ± 86	Bulk sediment	5816 ± 189	Mildenhall (1996)
Not reported	102	6233 ± 84	Bulk sediment	7133 ± 206	Mildenhall (1996)
Not reported	114	6505 ± 88	Bulk sediment	7415 ± 149	Mildenhall (1996)
Not reported	20	620 ± 100	Mollusc shell	605 ± 130	Tsukawaki <i>et al.</i> (1997)
Not reported	50	5620 ± 120	Bulk sediment	6421 ± 266	Tsukawaki <i>et al.</i> (1997)
Not reported	106	6070 ± 90	Bulk sediment	6939 ± 239	Tsukawaki <i>et al.</i> (1997)

Notes: Dates from This Study, Penny (2006), Fukomoto (2014), Mildenhall (1996) and Tsukawaki *et al.* (1997) are for ¹⁴C samples taken from Cores LC2, S2C1, CT10, TS96-1 and TS96-2, respectively. For the ¹⁴C dates from Day *et al.* (2011), the symbol * indicates dates taken from core TS-18-XII-03 whereas + indicates dates taken from core CHH-17-XII-03.

RAPID DRAINAGE OF THE TONLE SAP LAKE

Table 3. Characteristics of the PES Facies compared with palaeo-environmental data from this and other studies.

PES Facies	PES Interpretation	LC2 core interpretation (this study)	Day (2011): 2 cores, both have 4 distinct units	Fukumoto (2014)	Penny (2006)
1	Eroded surface of a buried Pleistocene valley network				Not present
2	Fluvial, or subaerial slope deposits. Initial stages of Pleistocene valley infill.	457-434cm (older than 8760 cal. yr BP). Low %C, C/N and $\delta^{13}\text{C}$. A freshwater open system with low productivity. 434-332cm (>8760 – 8190 cal. yr BP). Relatively high but variable %C, C/N, and initially high Ti. High precipitation with large inwash of terrestrial C3 plants.	Unit 1 (older than 8380 cal yr BP). Low %C, C/N. Interpreted as wetland/lacustrine. Unit 2 (age centred on 8380 cal yr BP). Increase %C and C/N. Very depleted $\delta^{13}\text{C}$. Wetland interpretation.	Zone 1 and part zone 2? (from 12.3k cal yr. BP). Development of lake, with some evidence of marsh. End of zone 2 (ends 8000 cal. yr BP). Diatoms indicate possible increased production between 8400-8000 cal. yr BP.	Likely not present
3	Lacustrine sedimentation with conformable deposition of sediment from suspension. Some of lower drapes mantle the entire topography at the valley edges (Figs 2 & 3) and demonstrate that the lake was deep enough to drown the palaeo-valley landscape and was established by the commencement of Facies 3 deposition.	332-32cm (8190-6170 cal. yr BP). Low %C, C/N, and enriched $\delta^{13}\text{C}$, with declining Ti and stable particle size. Likely increased production, algal dominated freshwater lake system. From 170cm onwards (7250 cal. yr BP) production increases, which may be linked to a drying climate (reduced Ti), with finer grain size and more closed evaporative system. 7250 cal. yr BP is seen as a clear reflector in PES.	Unit 3. (age c. 8300-6360 cal yr BP). Initial phase of low %C but increasing after c. 7370 cal. yr BP. Interpreted as shallow non-pulsing lake, with greater detrital input pre c. 7370 cal. yr BP, and diminished detrital input thereafter.	Zones 3-5 (8000-6400 cal. yr BP). Low %C and diatoms indicate a strongly turbid lake, possibly enhanced in size early in the zone (wetter). Clear change at 7300 cal. yr BP, after which lake levels may be lower and finer grain size input.	Zones 1 and 2 (from c. 8000 cal. yr BP. Unclear end of zone, but pre-5890 cal. yr BP). Argues for some marine influence and mangrove pollen possibly being local. There is no clear indication of a reflector around 7300 cal. yr BP, but zone change in vegetation occurs c. 6500 cal yr. BP.
4	Sedimentation in Tonlé Sap lake due to sediment suspension settling, but after a period of widespread erosion that generated the extensive erosion surface that separates PES Facies 3 and 4 across all of the Tonlé Sap lake. Parabolic point reflections generated from diagenetic <u>siderite</u> concretions, of siderite and manganese (Pottier <i>et al.</i> , 2012), ⁵ or accumulations of the clam <u><i>Corbicula fluminaea</i></u> (Penny, 2006) within the sediments.	32-0cm. (age uncertain due to erosive events below this unit). Large changes in organics and large increases in K suggests an erosive surface, with an algal dominated lake. Lower relative production as indicated by the lower %C and relatively depleted $\delta^{13}\text{C}$. Flood-pulsing lake connected to the Mekong River.	Unit 4 (age relatively uncertain, but estimate to begin between c. 4,450 and 3,910 cal. year BP). Large change into this unit indicated by altered Sr and Nd isotopes, and broad changes in geochemistry. Interpreted as now flood-pulsing lake, connected to Mekong River.	Zones 6 and 7 (post 6400 cal yr BP). Complete change in diatom flora. Lower lake levels and increased bottom water anoxia.	Zone 2 and 3. The major change in sedimentological data, coupled with a change in vegetation (relative increase in <i>Macaranga</i>) occurs around 100cm. Difficult to date but the signature compares clearly with a shift from Facies 3 to 4.

RAPID DRAINAGE OF THE TONLE SAP LAKE