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Unearthing an Atlantean myth in Angkor: geoarchaeological investigation of the ‘underwater road’ crossing the Tonle Sap Lake, Cambodia

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ABSTRACT

Of the many myths surrounding the medieval city of Angkor, Cambodia, one of the most obscure but pervasive is the existence of a road built across the Tonle Sap Lake. This road supposedly ran from the Angkorian ‘port’ at Phnom Krom to the temples situated in the Battambang district some 70 km southwest of capital. New geoarchaeological information demonstrates that the ‘road’ is actually a series of localised occurrences of authegenic calcite, which probably formed approximately 5500 years Before Present. Our results demystify this intractable Cambodian legend expand on the dynamic history of this important water body in mainland Southeast Asia.

1. Introduction

Parallel to the scientific rediscovery of Angkor by the west in the mid-19th century was the compilation of a body of Khmer legends that provide an evocative account of medieval Khmer society and its historic landscape. These myths appear at various times from the union of the Naga princess and an Indian prince marking the foundation of Angkor (Népote, 1999), to the construction of Angkor Wat by the semi-divine architect Pisnoukar and his magical powers (Fabricius, 1970), or the 19th century Cambodian tradition that the great temples of Angkor were built by giants (Mouhot, 1863). Other modern myths appeared during the 20th century, like the presence of underground labyrinths within the Terrace of Leper King (Marchal, 1923, 1930), and the universal paving of the Angkor’s roads (Ishizawa and Tamura, 2004). Proliferation of scientific research in Cambodia over the past decade has now clarified some of these myths (Pottier, 2001; Hendrickson, 2010). However, one pervasive ‘memory’, sustained by generations of local Khmer fishermen since the start of the 20th century, is a road built across the Tonle Sap or ‘Great Lake’, linking the capital to the rich rice-growing lands on its southern shore.

1.1. The Tonle Sap Lake

The Tonle Sap is a large mesotrophic, polymictic freshwater lake that, under the influence of monsoon related flooding in the Mekong River, increases in area from approximately 2500 km^2 to approximately 15,000 km^2, in volume from 1.3 km^3 to more than 60 km^3 (see Fig. 1) and in depth from <1 m to 7–9 m (MRCS/WUP-FIN, 2003). While this brings essential nutrients that drive the productive floodplain ecosystems of the lake, it also means that settlements and land transport routes that link them must be raised above or positioned beyond the maximum flood level in order to permit the movement of people and goods during the wet season months. The position of large Angkorian-period settlements and the associated road network, particularly the historic roads from Angkor to Sambor Prei Kuk, are direct responses to the seasonal loss of land to the flood. Notionally, a direct route from Angkor across the lake would have dramatically reduced transportation times between the capital and the fertile provinces to the southwest.

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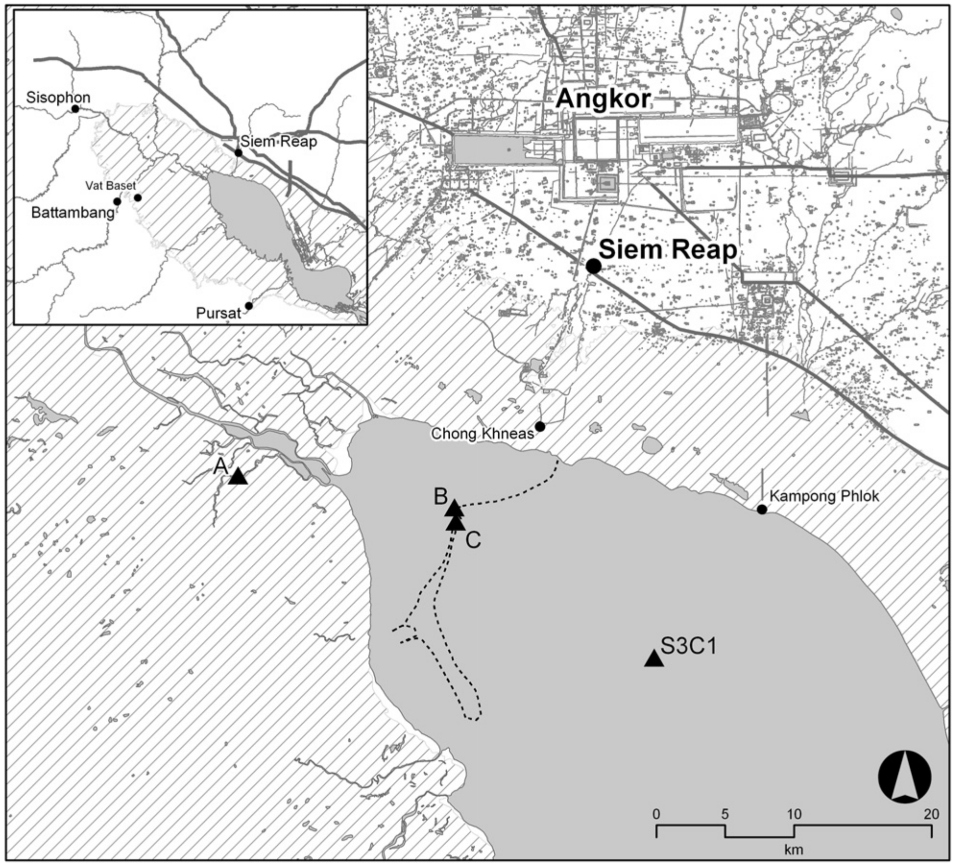

Fig. 1. Map of the Tonle Sap Lake, showing maximum extent of the flood zone, major Angkorian roads, survey and sample locations. Waypoint coordinates: A: N13.219234, E103.619684. B: N13.198854, E103.764762. C: N13.189638, E103.765916. S3C1: N13.100736, E103.899218. Data sources: Pottier, 1999; Evans, 2007; Hendrickson, 2007 and JICA, 1998.

The south, and particularly the southwest side of the Tonle Sap basin likely played an important economic role in both recent and historic times. The province of Battambang is and has long been the 'rice bowl' of Cambodia, particularly since the establishment of large-scale rice plantations there during the French colonial period (Helmers, 1997). The city of Battambang itself is an important entrepôt, facilitating the movement of goods between the populations of the Mekong and Chao Phraya valleys (Pavie, 1901). Moreover, in contrast to other parts of the Tonle Sap's southern shore, this region has a marked density of Angkorian-period settlements illustrated by numerous water tanks (*trapeang*) and temples including three major foundations (i.e., Vat Ek, Banon, Vat Baset) with historic ties to Angkor. This medieval political influence, combined with the economic potential of the region, could explain the existence of a route linking this region to the capital and, in fact, legitimate the need to exercise political control and ensure the efficient movement of goods.

1.2. The Tonle Sap road myth and past research

The first recorded 'evidence' of the Tonle Sap 'road' is the isolated presence of man-made dikes or canals on both side of the lake, mentioned in maps and accounts of 19th century French expeditions. Henri Mouhot, who came to Angkor by boat from Battambang, mentions the ancient dike on the north shore (Mouhot, 1863) while the southern embankment appears on the first map of Étienne Aymonier (1876) connecting to Vat Baset. Interestingly, two maps published in 1901 provide different information about these features. Aymonier's (1901) map depicts the north dike but fails to identify its counterpart on the southern shore, and Auguste Pavie describes a man-made canal called the Au Dombang, or "old river", said to have been constructed by the 'ancients' to shorten the distance between Battambang and the Tonle Sap (Pavie, 1901).

The first scientific investigation of the Tonle Sap myth appears in 1910 as a brief note published into the *Bulletin de l'École Française d'Extrême-Orient* (BEFEO), one of the region's most reputable journals (Basse-Brioulé, 1910). Transmitted by the General Léon de Beylié, the article presents the results of an administrative inquiry launched by the French Protectorate's Commissioner-Delegate to evaluate the existence of the ancient causeway crossing the Tonle Sap Lake. Written by military officer named Lt. Félicien Basse-Brioulé, the report and its associated map summarise the responses of Cambodian authorities about the existence of this road. The Governor at Mong Don Tri, (now Srok Moung Ruessei, on the Battambang side), meticulously sent fishermen to carry out soundings in the lake and search for toponyms such as *Than Chas* (old dyke). Neither enterprise proved successful. On the north side, investigation by the Governor of Siem Reap similarly failed to identify any remains, but he notes that, "the fishermen…have heard their ancestors say that there was a causeway" (Basse-Brioulé, 1910). By contrast, the sub-Governor of the district of *Bac Prâ* in the northwest corner of the lake (now *Bac Prea* at *Prey Chas*) was less circumspect, and described a series of almost continuous dikes across the lake, only interrupted in a place named *Bankol Pi* by a "deep passage for junks" (Basse-Brioulé, 1910). In response to these variable reports Lt. Basse-Brioulé felt obliged to distinguish between 'verifiable facts' (some "collapsed stones" at the end of the dyke south of Phnom Krom, the pass of Bankol Pi) and 'unproven' statements (the dykes), and to seek a non-anthropogenic explanation for the sandbanks. His final report concluded that, "only the

Balat [sub-Governor] of *Bac Prâ* believes that the dyke exists, but his suppositions are not based on any precise data. On the other hand the governors of Siem Reap and Mông are united in denying the existence of the dyke" (Basse-Brioulé, 1910).

Twenty-two years later, a second inquiry into the existence of the Tonle Sap 'road' appears in the BEFEO led by Victor Goloubew, an aerial survey pioneer and EFEO scholar, assisted by two riverine gunboats of the French Navy (Marchal, 1933). Again, the basis for this mission relied on 'local information' transmitted to the EFEO by the respectable Director of the Oceanographic Institute at Nhatrang after his brief visit to Angkor. Despite their detailed reconnaissance and soundings, the expedition identified "no relevant findings to support the tradition" (Marchal, 1933).

In 1937, the last investigation was conducted by Henri Marchal, one of Angkor's most experienced scholars who, irritated by the rumour he had heard for 20 years while he was Conservateur of Angkor, set out to test the story himself. The monthly *Rapport de la Conservation d'Angkor*, written by his successor Maurice Glaize (1937), gives a brief summary, noting the ambiguous nature of the features encountered and the inability to substantiate the existence of the supposed causeway. Marchal (1937) gives a more lively account, both humorous and sincere. He describes his voyage, explaining that he was relying on the exceptionally low water level "to get some precise information on this causeway and above all to see it for [him]self". Pragmatic as ever, he "took a sampan with some locals who knew where to find the causeway (*spean thom* [big bridge], they say)". En route he received some information from his guides, but noted that this was "hearsay from fishermen who claim to have seen bits of the causeway, [and specifically] know it is paved because they were unable to plant their posts in those spots". The expedition finally reached its goal, where:

> "about 6–7 km SSW of Phnom Krom, the boatmen go into the water and at a depth of 0.60 m claim to have found with their feet, about 0.30 m below the mud, a paved area or hard surface. They bring up some pebbles of a very friable blackish rock, but it's hard to know whether this is paving or a stony bottom. 20 m to the east the hard surface disappears and the natives feel only mud beneath their feet", (Marchal, 1937).

After hours on the sampan in the middle of the muddy lake, Marchal ended the expedition and concluded, phlegmatically, that another expedition with "bathing costumes and…sounding instruments" would be required to reach a conclusion. Marchal's successors seem not to have felt the need for such an experiment, and no further expeditions were mounted for 65 years.

On 26 March 2002, the lead author, guided by local fishermen, identified a discontinuous consolidated surface and some clusters of gravels under ~2 m of water in a section of Prek Da canal (Fig. 1A), whilst investigating a report of a submerged stone bridge, measuring 25 m by 100 m. Despite the numerous core samples taken from the lake since the early 1960's (Carbonnel and Guiscafré, 1965; Carbonnel, 1972; Day et al., 2011; Penny, 2006; Tsukawaki et al., 1994, 1997; Tsukawaki, 1997) – making the Tonle Sap one of the most intensively sampled lakes in Southeast Asia – there are no reports of Marchal's "friable blackish rock", or indeed any other consolidated surface which might be confused with a paved road. Pale-brown to dark-brown coloured sand has been observed in the northern part of the basin (at S3C1, Fig. 1; Penny, 2006), but is unclear if these sands are related to, or derived from, any consolidated surface in the northern part of the Tonle Sap Lake basin.

2. Deconstructing the myth: archaeological evidence

The existence of a road across the Tonle Sap Lake is plausible, in principal, given the prodigious road network identified and mapped around the lake since the first explorers. A century of research revealed an exceptional construction programme that produced a 1000 km-long road system (Fig. 1 inset) radiating out from the capital of Angkor across the medieval Khmer Empire. Earthen roads raised up to 5 m above the ground and laterite masonry bridges, some extending over 140 m, point to the magnitude and capability of Khmer engineering. In combination with the scale of Angkorian temples, these roads have deeply and durably impressed the academic world (Hendrickson, 2007). Logically, with the absence of any peripheral roads linking the Khmer settlements on the south bank of the lake to the broader network, such a direct route may have been possible, despite significant practical hurdles in constructing a road across a lake.

However, two important characteristics of the road system raise significant doubts about its viability. First, contrary to the compacted surface identified by Marchal, the Khmer did not pave their roads (Hendrickson, 2010). Second, while roads often double as canals and water distribution infrastructure, they are generally positioned above the floodplain. The 'Southeast Lower' road, for example, ran parallel to the Tonle Sap but was situated well above the maximum flood zone illustrated in Fig. 1. Similarly, old linear embankments connecting successive Angkor centres to the lake, such as the 15 km-long structure between the 9th century capital of Hariharâlaya and the stilt village of Kampong Phlok, connect to the floodplain, but go no further.

A further consideration is that, prior to the roads network developed by the French protectorate in the first half of the 20th century, regional communication in Cambodia relied on a combination of terrestrial and fluvial transport adapted to the variability of the seasonal monsoon. The Angkorian roads are positioned perpendicular to the natural river system, providing access around the Tonle Sap basin for the medieval Khmer. Boats depicted on the *bas-reliefs* of the Bayon temple indicate the significance of water transport during the Angkorian period. Chinese (Pelliot, 1951) and early European accounts illustrate how boats played a primary role in transportation prior to the 20th century (Hendrickson, 2007).

The case of Kampong Phlok is a living example of a fixed nodal interface positioned between terrestrial and lacustrine systems. Another type of connection is illustrated by the present day floating village of Chong Khneas, south of Siem Reap, oscillating with the annual fluctuations of the Tonle Sap Lake. Archaeological evidence indicates that these types of interfaces were already in use in the time of Angkor making it highly unlikely that a road was ever constructed across the lake.

3. Materials and methods

After a century of opportunistic research, an exceptional drought in Cambodia (2003–2004) provided the opportunity to finally resolve the issue of Tonle Sap 'road'. In an attempt to identify the precise location and recover a sample of the surface for analysis, the lead author launched an expedition on the 14th of May 2004 from Siem Reap guided – like Marchal – by local fishermen who claimed to know the location of the 'ancient road'. Positions and track logs were recorded using a Garmin II plus GPS (Fig. 1). The northwest part of the lake was explored systematically and the 'hard' surface was recorded in two areas approximately 1 km apart (Fig. 1B and C). At B, the surface was an isolated occurrence while at C is part of strip extending ~300 m. A 1.366 kg sample of the material was recovered from C. This sample was recovered by hand and allowed to air dry before being transported to the laboratory.

A sub-sample of the primary 'road' sample was analysed using Raman spectroscopy, a non-destructive technique that employs monochromatic light to identify the distinctive chemical signatures (i.e., functional groups) associated with the molecular structure of a material (Carter et al., 2006). The sub-sample was mounted on a glass microscope slide and ground to create a relatively smooth surface suitable for analysis. Spectra were collected using a Renishaw Raman inVia Reflex Microscope (Renishaw plc., Wotton-under-Edge, UK) coupled to a FEI Quanta 200 3D scanning electron microscope (SEM). A structural and chemical analyser (SCA) transmitted the incident light from the Raman microscope into the SEM vacuum chamber via an optical transfer tube (OTT), which is inserted between the electron gun and the sample under low vacuum.

Sample excitation was achieved using an argon ion laser emitting at 514 nm. A semi-conductor chip was placed into the SEM chamber and the electron beam was focussed on a distinctive area of the sample. The beam shift was then used to align the SEM and visible images (from the SCA OTT) such that they were coincident. Calibration of the Raman spectrometer was achieved by collecting a spectrum from a silicon area of the same semi-conductor chip used to align the electron and laser beams. An offset correction was performed on the grating to ensure that the position of the silicon band was 520.50 ± 0.10 cm^{-1}.

Dark-coloured mineral clasts reported by Penny (2006) from 7.5 to 14 cm depth below the contemporary lakebed (site S3C1 in Fig. 1) were analysed to determine if they were of the same composition as, or derived directly from, the 'paved' surface. Lake sediment samples were disaggregated with sodium hexametaphospate, and clasts 125 μm in diameter or greater were recovered using a wire mesh sieve. The >125 μm fraction was mounted in epoxy resin, ground, and carbon-coated for elemental analysis using a Philips XL30CP scanning electron microscope coupled with a PGT Spirit energy dispersive X-ray spectrometer (EDS).

Three sub-samples, taken at random locations from the primary sample, were analysed for their mineral particle size characteristics in order to understand the likely source of the component siliciclastic materials. The 1.03 ± 0.03 g (dry weight) samples were digested in 10 ml of 32% w:w hydrochloric acid for 48 h followed by disaggregation with sodium hexametaphosphate in an ultrasonic bath (47 kHz) for 1 h. The disaggregated samples were analysed using a Malvern 2000 Laser Diffraction Particle Size Analyser with a HydroG dispersion unit. Each sample was measured three times to ensure high precision.

A final sub-sample was submitted for accelerator mass spectrometer (AMS) radiocarbon dating. 500 g of the material was powdered and digested in heated phosphoric acid, yielding 22.5 cc CO_2. The result was calibrated (Stuiver and Reimer, 1993, version 5.0) to years Before Present (BP) using the IntCal04 curve (Reimer et al., 2004).

4. Results

The 'paved' surface proved to be a crust of dark friable material, reaching only ~10 cm in thickness, overlain by approximately 40 cm of fine unconsolidated lacustrine mud. While the area of the consolidated surface could not be mapped precisely, it appeared to maintain a narrow and elongated form with a distinct edge that could be identified by probing beneath the mud. The upper surface of the consolidated surface is relatively flat and has an acute boundary with the overlying mud. The lower boundary is acute and irregularly undulating. Below this surface is an unknown depth of the same dark unconsolidated lacustrine silt and clay that overlies the feature. *Corbicula fluminaea* L. shells, common in the lake sediments (Penny, 2006), are cemented within the consolidated surface.

The material was weakly reactive with hydrochloric acid, and 74% of the dry weight of the sample was lost during acid digestion. Particle size analysis of the remaining siliciclastic fraction reveals a very poorly sorted (inclusive standard deviation $= 2.5\ \phi$) platykurtic (inclusive kurtosis $= 0.8 \pm 0.02\ \phi$), and strongly coarse skewed (inclusive skewness $= -0.29 \pm 0.06$) distribution. Inclusive mean clast size was $4.34 \pm 0.07\ \phi$ (silt).

Viewed under electron magnification, the material cementing the mineral clasts appears highly uniform, having passively filled all of the available pore space. Raman spectra collected from this cementing matrix are presented in Figs. 2 and 3. Raman bands observed at ~1085, 730, 281 and 183 cm^{-1} are characteristic of siderite, iron carbonate ($FeCO_3$). The Raman spectra of carbonates differ due to the presence of the divalent cations (e.g. Ca^{2+}, Fe^{2+}, Mn, Mg) that coordinate to the carbonate ion (CO_3^{2-}). Specifically, differences are observed in the position of Raman bands within the 1100–1080 (carbonate ion) and 450-120 cm^{-1} spectral regions. The band at 1085 cm^{-1} is assigned to the í$_1$ Raman band of the C–O symmetric stretching mode of the carbonate ion, the band at 730 cm^{-1} is the í$_4$ (O–C–O in-plane bending) mode and the bands at 281 and 183 cm^{-1} are assigned to lattice modes (Rividi et al., 2010; Isambert et al., 2006; Rutt and Nicola, 1974).

EDS spectra acquired from sand-sized mineral clasts indicate them to be siderite spherulites (Fig. 4B and C; Matthiesen et al., 2003; McMillan and Schwetmann, 1998), ~125–300 μm in

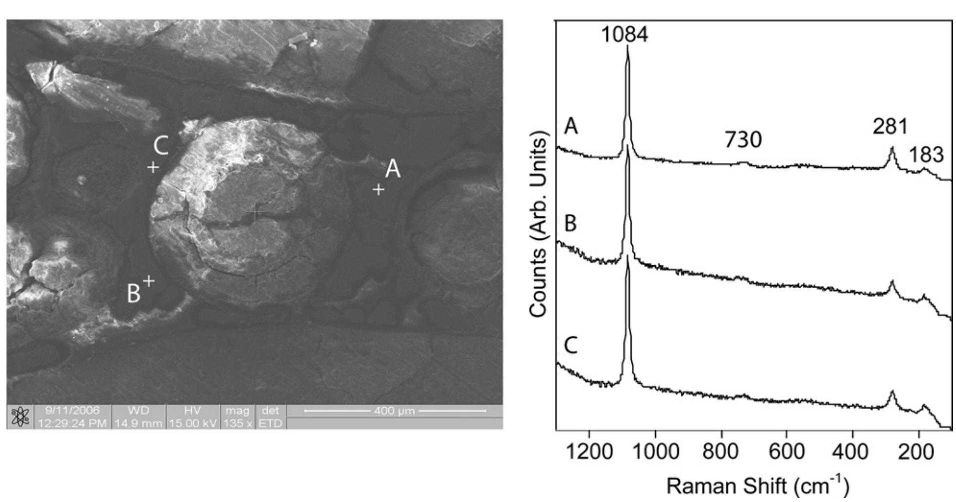

Fig. 2. Raman spectra from the road.

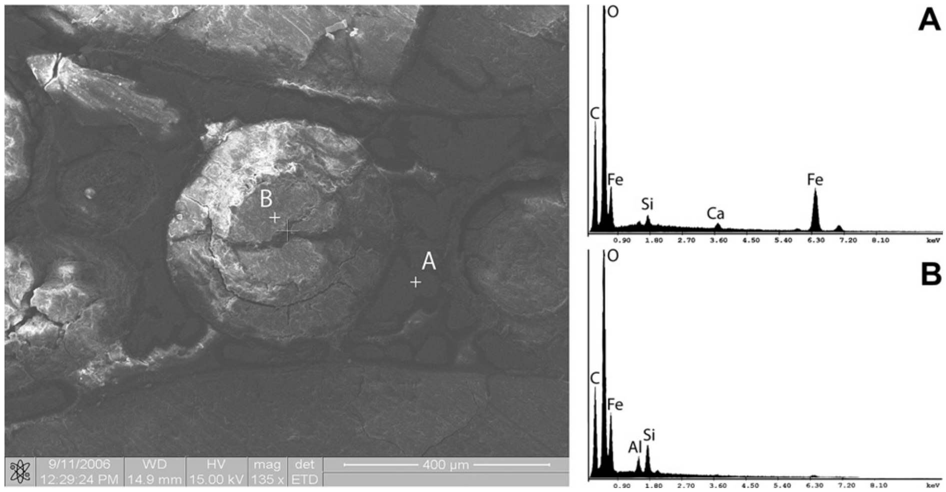

Fig. 3. EDS spectra measured from the road.

diameter. Inclusions of mineral clasts (Fig. 4A and C) within the spherulites imply relatively unrestricted crystal growth at the sediment–water interface or within the uppermost, poorly-consolidated sediment (Sapota et al., 2006). In thin section these spherulites maintain a concentric/radial crystal habit (Fig. 5A), with the same diffuse concentric colour variations described by Seiglie et al. (1979) from Oligocene-aged rocks in northern Puerto Rico, reflecting differential enrichment by various elements during crystal growth (Sapota et al., 2006).

AMS radiocarbon dating (BETA 215878) returned an age of 5550 ± 40 ^{14}C years Before Present (BP), which calibrates to 6287–6406 years BP (2 σ range).

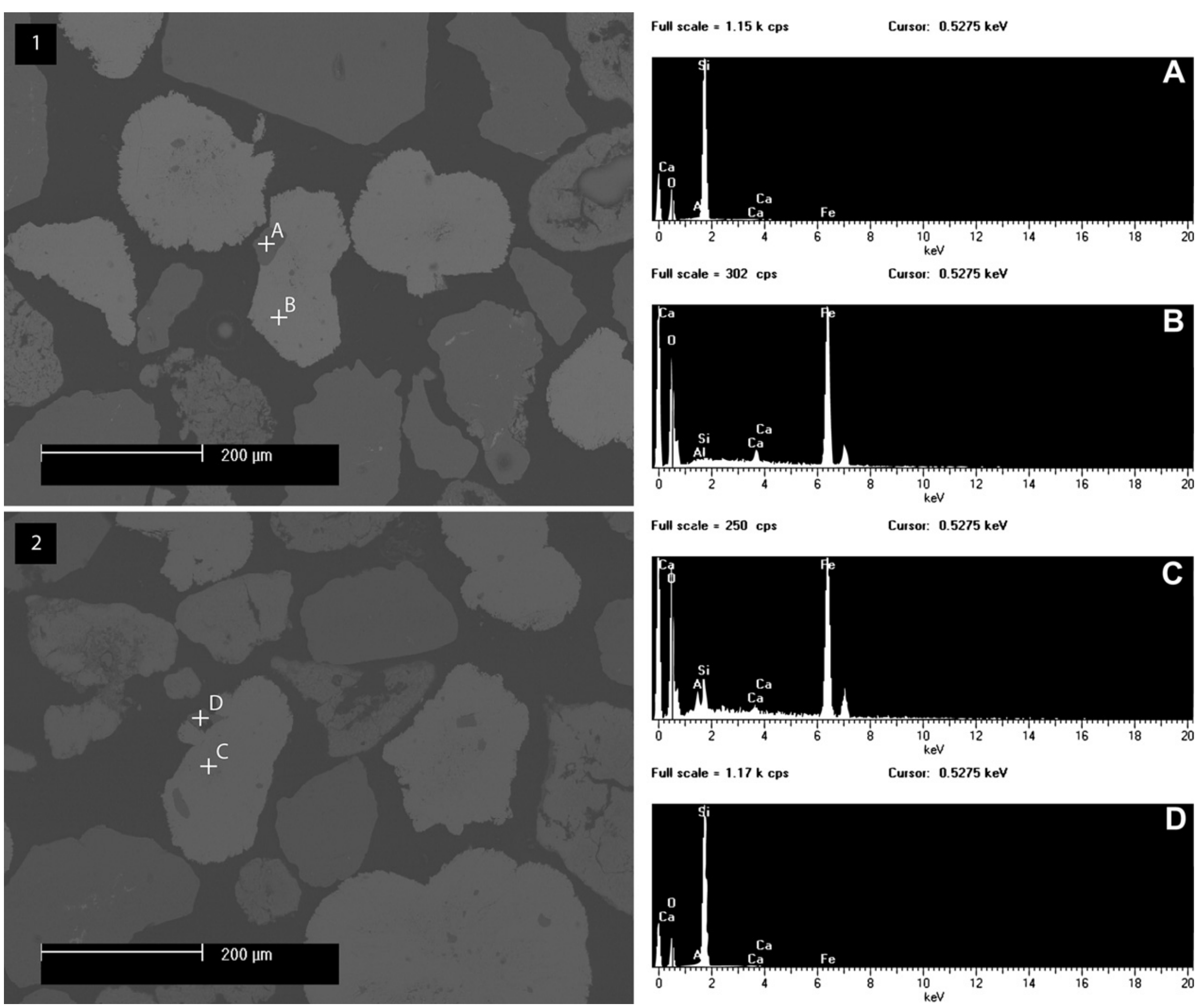

Fig. 4. Backscatter electron micrographs (1 & 2) of the >125 µm fraction from S2C3 (see Fig. 1 for location), mounted in epoxy. Crosses denote location of EDS measurements (A–D).

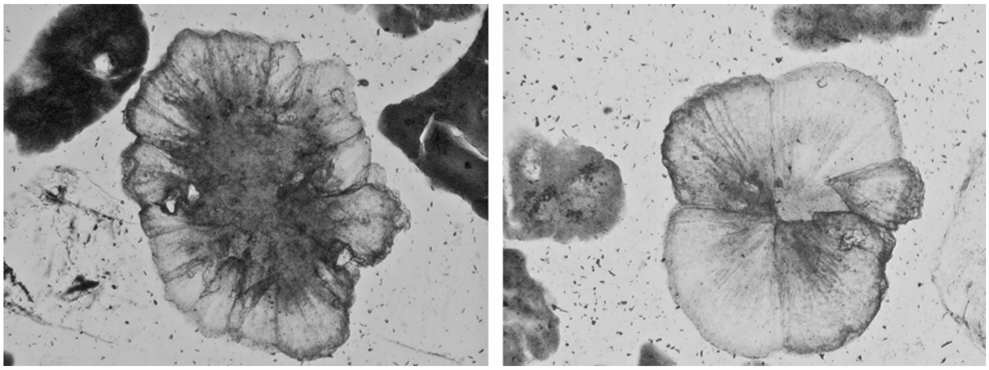

Fig. 5. Thin sections of siderite spherulites from S3C1 under LM × 400 magnification, showing crystal growth pattern and (in A) concentric banding. Matrix is epoxy.

5. Discussion

The formation of early diagentic carbonate phases, either as spherulites, nodules or sheets, is often related to microbial activity at some depth in the sediment profile, in turn mediated by the amount of organic material in the sediment (and thus the amount of energy available) and the chemistry of the pore waters. Decomposition of organic material by microorganisms produces hydrogen sulphide (H_2S) in anoxic interstitial waters, encouraging the reduction of Fe^{3+} (Mortimer et al., 1997), buffered by the precipitation of carbonate (Coleman et al., 1993; Coleman, 1993). The waters of the Mekong River are relatively enriched in iron (Carbonnel, 1965), and the lake sediment contains relatively high concentrations, certainly sufficient to meet the requirements of the process described above. Reducible iron is most abundant at the base of the poorly-consolidated "modern sediment" (Carbonnel, 1972: pp. 93–95), which may explain the sheet-like form of the siderite concretions described here (Coleman, 1993). Almost identical siderite crusts, extending laterally over several metres and incorporating *Cerastoderma* and *Hydrobia* shells (Allison and Pye, 1994), have been shown to form very rapidly (<30 years) and at shallow depths (<1 m) in inter-tidal marsh sediments on the south coast of England (Pye et al., 1990; Pye, 1984).

The concentration of major cations in the waters of the Tonle Sap changes during the course of the year (Fig. 6), with the highest concentrations occurring in the wet season months from May–October (for example, 0.241 ± 0.093 mEq/l^{-1} for Mg and 0.536 ± 0.204 mEq/l^{-1} for Ca; $n = 90$). Conductivity ranges from a minimum of 6.996 ± 1.135 mS/m in the late dry season (April) to a maximum of 12.179 ± 5.2 mS/m in the early wet season (June). This implies that the relatively enriched waters of the Mekong River (Carbonnel and Meybeck, 1975) presently dominate ionic chemistry of the Tonle Sap, and that even in the dry season when lake waters are very shallow (<1 m) the lake waters remain soft. The precipitation of siderite at the sediment surface as a result of the super-saturation of lake waters in isolated pools (Browne and Kingston, 1993; Fritz et al., 1971) is judged improbable under these circumstances, although there is no analogue in the instrumental water-chemistry record for extremely low lake levels in the Tonle Sap. However, there is no evidence of substantially reduced water levels during the middle Holocene in any of the numerous sediment cores taken from the lake (Carbonnel, 1972; Day et al., 2011; Penny, 2006; Tsukawaki, 1997; Tsukawaki et al., 1997).

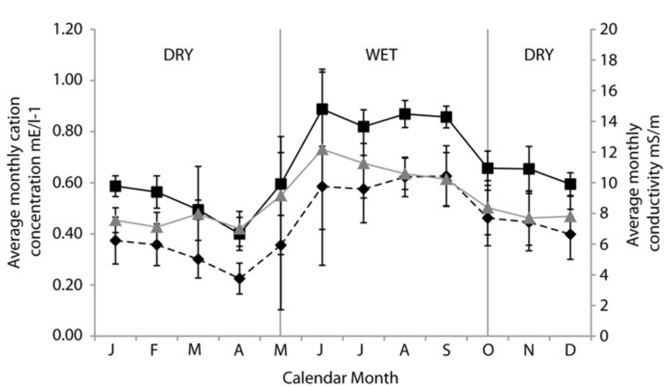

Fig. 6. Average monthly conductivity (triangles), Ca (squares) and Mg (diamonds) ± 1 σ for three stations in the Tonle Sap Lake (Kompong Luuong H020106; Prek Dam H020102; Kompong Chnang H020103) for the period 1995–2000. Data Source: Mekong River Commission Environment Program Database.

The mid-Holocene age of the siderite concretion reported here is uncertain. The age is broadly consistent with current models of sediment accumulation in the basin (Kummu et al., 2008), but may be biased by 'old carbon' due the hydraulically open lake basin and the presence of outcropping Permian-aged limestone in the Cambodian catchments, particularly in the Battambang Province west of the lake. The presence of siderite spherulites in sediments deposited during the period c. 900–400 years BP (ages based on correlation with a ^{14}C dated record from the southern part of the lake, in Penny, 2006) is relevant to this, and implies; A) active and ongoing diagenetic siderite precipitation throughout the Holocene in the northern part of the basin; B) re-working of spherulites from the vicinity of the siderite concretions as a result of re-entrainment of sediments through mixing; or C) that the reported age of the siderite concretion is a result from the incorporation of geologically 'old' carbonate from the catchment into modern carbonates (for example, Goodfriend and Stipp, 1983). Our data are inconclusive on this matter, but our suggestion that these deposits are bacterially mediated rather than the result of super-saturation of lake waters by endogenic cations may support the accuracy of the reported age. Therefore, the hard crust sampled from the 'road' surface is the result of a non-anthropogenic process that most probably pre-dates the Angkorian period by thousands of years.

6. Conclusions

The data presented here demonstrate conclusively that the consolidated surface at the centre of the Tonle Sap road hypothesis is a naturally occurring siderite concretion, possibly of mid-Holocene age and certainly pre-dating the Angkorian period by millennia. The only physical evidence in support of the ancient submerged causeway is therefore proven irrelevant.

We interpret the formation of iron-carbonate lenses as a function of bacterial activity within the sediment column, rather than a product of ionic saturation of lake waters due to extremely low lake levels. This being the case, it is unclear why similar deposits are not more widespread in the lake sediments, both spatially and through time. We note also that the siderite appears to be of middle Holocene age, coincident with a period of dramatic change in the Tonle Sap Lake related to the initiation of a permanent connection with the Mekong River (Day et al., 2011; Tsukawaki et al., 1997) and/or changes in the magnitude of seasonal variability related to regressing sea-levels (Penny, 2006).

Beyond the perpetuation of traditions among local communities, what remains now is mostly a matter of Euro-centric speculation. The unique status of the Tonle Sap myth, persistent but marginalised within academic discourses, is intimately related to its position between two rationalistic, and contradictory, views: the seemingly technical impossibility of constructing a road across a lake versus the functional over-interpretation of the super-capabilities of Angkorian society, in particular its massive infrastructure. Historically, the myth became an archaeological question when the French protectorate was developing its terrestrial network throughout Cambodia, even if primary communication at that time relied on the riverine system. From this perspective, it is now time to draw to a close more than a century of speculation and opportunistic research of this 'Atlantean' myth.

Finally, and perhaps more significantly, our results emphasise the importance of the ancient ports for understanding the economics and transportation networks of Angkor. These sites are yet to be formally and precisely identified, and no archaeological research has been undertaken. However, the continuous connections between the successive urban centres and the lake, and the absence of any road crossing the latter, strongly implies that these ports were critical nodes at the interface between the terrestrial and fluvial transportation networks. The locations of the current harbours of Kampong Phlok and Chong Khneas likely overlap their Angkorian antecedents and deserve appropriate investigation and, if necessary, conservation.

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References

Allison, P.A., Pye, K., 1994. Early diagenetic mineralization and fossil preservation in modern carbonate concretions. Palaios 9, 561–575.
Aymonier, É., 1876. Géographie du Cambodge. E. Leroux, Paris.
Aymonier, É., 1901. Le Cambodge: les provinces siamoises. E. Leroux, Paris.
Basse-Brioulé, F., 1910. Note sur les digues du Cambodge. Bulletin de l'École française d'Extrême-Orient 10 (1), 451–453.
Browne, G.H., Kingston, D.M., 1993. Early diagenetic spherulitic siderites from Pennsylvanian palaeosols in the Boss Point Formation, Maritime Canada. Sedimentology 40, 467–474.
Carbonnel, J.P., 1972. Le Quaternaire Cambodgien: structure et stratigraphie. ORSTOM Memoire No 60, Paris.
Carbonnel, J.P., 1965. Sur les cycles de mise en solution du fer et de la silice en milieu tropical. C. R. Acad. Sci., Paris 260. 4035–4038.
Carbonnel, J.P., Guiscafré, J., 1965. Grand Lac du Cambodge: sédimentologie et hydrologie 1962–63. Museum National d'Histoire Naturelle de Paris, Paris.
Carbonnel, J.P., Meybeck, M., 1975. Quality variations of the Mekong river at Phnom Penh, Cambodia, and chemical transport in the Mekong basin. Journal of Hydrology 27 (3–4), 249–265.
Carter, E.A., Privat, K.L., Penny, D., 2006. Vibrational spectroscopy for the rapid and non-destructive analysis of materials. Materials Australia 39 (5), 23–25.
Coleman, M., Raiswell, R., Brown, A., Curtis, C., Aplin, A.C., Ortoleva, P.J., Gruszczynski, M., Lyons, T., Lovley, D.R., Eglinton, G., 1993. Microbial mineralization of organic matter: mechanisms of self-organization and inferred rates of precipitation of diagenetic minerals. Philosophical Transactions: Physical Sciences and Engineering 344 (1670), 69–87.
Coleman, M.L., 1993. Microbial processes: controls on the shape and composition of carbonate concretions. Marine Geology 113, 127–140.
Day, M.B., Hodell, D.A., Brenner, M., Curtis, J.H., Kamenov, G.D., Guilderson, T.P., Peterson, L.C., Kenney, W.F., Kolata, A.L., 2011. Middle to late Holocene initiation of the annual flood pulse in Tonle Sap Lake, Cambodia. Journal of Paleolimnology 45 (1), 85–99.
Evans, D., 2007. Putting Angkor on the Map: a New Survey of a Khmer 'Hydraulic City' in Historical and Theoretical Context, PhD Thesis, University of Sydney.
Fabricius, P., 1970. Le Prasad Angkor-Vat. Nokor Khmer 2, Phnom Penh, 46–61 pp.
Fritz, P., Binda, P.L., Folinsbee, F.E., Krouse, H.R., 1971. Isotopic composition of diagenetic siderites from Cretaceous sediments in Western Canada. Journal of Sedimentary Petrology 41 (1), 282–288.
Glaize, M., 1937. Rapports de la Conservation d'Angkor, May 1937, typescript. EFEO archives, Paris.
Goodfriend, G.A., Stipp, J.J., 1983. Limestone and the problem of radiocarbon dating of land-snail shell carbonate. Geology 11, 575–577.
Helmers, K., 1997. Rice in the Cambodian Economy. In: Nesbit, H.J. (Ed.), Rice Production in Cambodia. International Rice Research Institute, Manila, Philippines, pp. 1–14.
Hendrickson, M., 2007. Arteries of empire: an operational study of transport and communication in Angkorian Southeast Asia (9th to 15th centuries CE). Doctoral dissertation. Department of Archaeology, University of Sydney. http://ses.library.usyd.edu.au/handle/2123/6135.
Hendrickson, M., 2010. La Voie Royale était-elle dallée? Reappraising a myth of the Angkorian period road system (ninth to fifteenth centuries CE). Aséanie 26, 83–109.
Isambert, A., De Resseguier, T., Gloter, A., Reynard, B., Guyot, F., Valet, J.-P., 2006. Magnetite-like nanocrystals formed by laser-driven shocks in siderite. Earth and Planetary Science Letters 243, 820–827.
Ishizawa, Y., Tamura, H., 2004. Along the Royal Roads to Angkor. Weatherhill, Tokyo.
JICA (Japan International Cooperation Agency), 1998. Cambodia Reconnaissance Survey Digital Data. Japan.
Kummu, M., Penny, D., Sarkkula, J., Koponen, J., 2008. Sediment: curse or blessing for the Tonle Sap lake? Ambio 37 (3), 158–163.
Marchal, H., 1923. Rapports de la Conservation d'Angkor, July 1923, typescript. EFEO archives, Paris.
Marchal, H., 1930. Rapports de la Conservation d'Angkor, April 1930, typescript. EFEO archives, Paris.
Marchal, H., 1933. Chronique de l'année 1932. Bulletin de l'École française d'Extrême-Orient 33, 520–521.
Marchal, H., 1937. Journal de fouilles de la Conservation d'Angkor, vol. 13, Manuscript. EFEO archives, Paris.
Matthiesen, H., Hilbert, L.R., Gregory, D.J., 2003. Siderite as a corrosion product on archaeological iron from a waterlogged environment. Studies in Conservation 48-3, 183–194.
McMillan, S.G., Schwetmann, U., 1998. Morphological and genetic relations between siderite, calcite and goethite in a Low Moor Peat from southern Germany. European Journal of Soil Science 49, 283–293.
Mortimer, R.J.G., Coleman, M.L., Rae, J.E., 1997. Effect of bacteria on the elemental composition of early diagenetic siderite: implications for palaeoenvironmental interpretations. Sedimentology 44, 759–765.
Mouhot, H., 1863. Voyage dans les royaumes de Siam, de Cambodge, de Laos et autres parties centrales de l'Indo-Chine. Le Tour du Monde 8, 219–352.
MRCS/WUP-FIN, 2003. WUP-FIN Phase I: Modelling Tonle Sap for Environmental Impact Assessment and Management Support. Final Report. Mekong River Commission and Finnish Environment Institute Consultancy Consortium, Phnom Penh, 107 pp.
Népote, J., 1999. Mythes de fondation et fonctionnement de l'ordre social dans la basse vallée du Mékong, accompagnés de considérations sur l'indianisation. Péninsule 38 (1), 33–64.
Pavie, A., 1901. Mission Pavie Indo-Chine 1879–1895. Geographie et voyages 1. Exposé des travaux de la mission. E. Leroux, Paris.
Pelliot, P., 1951. Mémoires sur les coutumes du Cambodge de Tcheou Ta-kouan. Adrien-Maisonneuve, Paris.
Penny, D., 2006. The Holocene history and development of the Tonle Sap, Cambodia. Quaternary Science Reviews 25, 310–322.
Pottier, C., 1999. Carte archéologique de la région d'Angkor Zone sud. PhD thesis, Université Paris III Sorbonne Nouvelle, Paris.
Pottier, C., 2001. Some evidence of an inter-relationship between hydraulic features and rice field patterns at Angkor during ancient times. The Journal of Sophia Asian Studies 18, 99–119.
Pye, K., 1984. SEM analysis of siderite cements in intertidal marsh sediments, Norfolk, England. Marine Geology 56 (1–4), 1–12.
Pye, K., Dickson, J.A.D., Schiavon, N., Coleman, M.L., Cox, M., 1990. Formation of siderite-Mg-calcite-iron sulphide concretions in intertidal marsh and sandflat sediments, Norfolk, England. Sedimentology 37, 325–343.
Reimer, Paula J., Baillie, Mike G.L., Bard, Edouard, Bayliss, Alex, Beck, J. Warren, Bertrand, Chanda J.H., Blackwell, Paul G., Buck, Caitlin E., Burr, George S., Cutler, Kirsten B., Damon, Paul E., Edwards, R. Lawrence, Fairbanks, Richard G., Friedrich, Michael, Guilderson, Thomas P., Hogg, Alan G., Hughen, Konrad A., Kromer, Bernd, McCormac, Gerry, Manning, Sturt, Ramsey, C. Bronk, Reimer, Ron W., Remmele, Sabine, Southon, John R., Stuiver, Minze, Talamo, Sahra, Taylor, F.W.,

van der Plicht, Johannes, Weyhenmeyer, Constanze E., 2004. IntCal04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP. Radiocarbon 46 (3), 1029–1058.
Rividi, N., van Zuilen, M., Philippot, P., Menez, B., Godard, G., Poidatz, E., 2010. Calibration of carbonate composition using micro-Raman analysis: application to planetary surface exploration. Astrobiology 10 (3), 293–309.
Rutt, H.N., Nicola, J.H., 1974. Raman spectra of carbonates of calcite structure. Journal of Physics C: Solid State Physics 7, 4522–4528.
Sapota, T., Aldahan, A., Al-Aasm, I.S., 2006. Sedimentary facies and climate control on formation of vivianite and siderite microconcretions in sediments of Lake Baikal, Siberia. Journal of Paleolimnology 36 (3), 245–257.
Seiglie, G.A., Pannella, G., Smith, A.L., 1979. Siderite spherulites of San Sebastian formation (Oligocene) Northern Puerto Rico. Bulletin of the American Association of Petroleum Geologists 63, 370–375.
Stuiver, M., Reimer, P.J., 1993. Extended 14C data base and revised CALIB 3.0 14C age calibration program. In: Stuiver, M., Long, A., Kra, R.S. (Eds.), Calibration 1993. Radiocarbon, 35(1), pp. 215–230.
Tsukawaki, S., 1997. Lithological features of cored sediments from the northern part of lake Tonle Sap, Cambodia. In: The International Conference of Stratigraphy and Tectonic Evolution of Southeast Asia and the South Pacific. Bangkok, pp. 232–239.
Tsukawaki, S., Okawara, M., Lao, K.-L., Tada, M., 1994. Preliminary study of sedimentation in Lake Tonle Sap, Cambodia. Chigaku Zasshi [Journal of Geography] 103, 623–636.
Tsukawaki, S., Okuno, M., Nakamura, T., 1997. Sedimentation Rates in the Northern Part of Lake Tonle Sap, Cambodia, During the Last 6000 Years. In: Summaries of Researchers Using AMS at Nagoya University, vol. 8, 125–133 pp.