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Deciphering a Timeline of Demise at Medieval Angkor, Cambodia Using Remote Sensing

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Abstract: The Greater Angkor Region was the center of the Khmer Empire from the 9th until the 13th to the 14th centuries CE, when it entered a period of decline. Many studies have suggested that the decline of Angkor was precipitated by several factors, including severe monsoons, geopolitical shifts, and invasions. In this paper, we use light detection and ranging and ground penetrating radar to investigate the possible intersection of two of these existential threats in one feature: the North Bank Wall. Our results indicate that this feature was designed with dual functionality of extending the urban area's defenses to the east of Angkor Thom while maintaining the existing infrastructure for the distribution and disposal of water. These findings suggest that the North Bank Wall was built before the severe droughts in the mid-13th century. The timing of the construction indicates that the perceived need for additional security—whether from internal factional disputes or external adversaries—predated the final adaptations to the hydraulic network during the unprecedented monsoon variability of the 14th century. These results indicate that perceived political unrest may have played a more important role in the decline of the site than previously known.

Keywords: ground penetrating radar; light detection and ranging; lidar; water management; urbanism; Angkor; decline

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1. Introduction

The Greater Angkor Region was home to an expansive urban site in central Cambodia that thrived from the 9th century until the 13th to 14th centuries CE, when it entered a period of gradual depopulation [1,2]. Researchers have argued that the decline of Angkor was precipitated by many factors, including a series of severe monsoons and droughts that stressed the water management system [2–5], an increasing economic reliance on international trade [6,7], and foreign conflict and invasions [8]. However, despite the eventual relocation of the capital to Longvek in the Phnom Penh area, recent research suggests that the city was not completely abandoned at the end of the 14th century but had areas of continuing habitation, some until the present day [1,9,10]. In this paper, we explore the consequences of compounding forces on the settlement of Angkor and the decisions made to adjust and adapt pre-existing infrastructure to two of the challenges mentioned above: water management and defense against internal or external threats.

The need to address concerns of both water management and defense led to variations in design and adaptation of water management features over time. Old features related to water management were repurposed to also provide defense [11,12]. Here, we use light detection and ranging (lidar) and ground penetrating radar (GPR) reflection profiles, to investigate the juxtaposition of both these needs at one location within the Greater Angkor Region: the North Bank Wall (Figures 1 and 2). The North Bank Wall runs between the northeast corner of Angkor Thom and the East Baray's northwest corner. It is an earthwork consisting of sandy clay (the prevalent substrate), which was reinforced with a laterite retaining wall and a moat running along its northern side. Brotherson et al. [5] suggest that this embankment was built in the first half of the 13th century to expand the defended space (the 'Intended Enclosure') of the central urban area to the east of Angkor Thom (Figure 2). While built for defensive purposes, this structure overlays a highly complex water management system.

The current research aims to clarify the North Bank Wall's construction date, by determining whether it was built to allow the pre-existing water management system to continue to function. In 1933, Georges Trouvé identified a channel connecting the Jayatataka Outlet to the North Bank Wall's moat. However, the lidar data, collected in 2012 by the Khmer Archaeological Lidar Consortium (KALC) (Evans et al., 2013), suggests that this channel was contiguous with an equivalent feature in alignment further south, both of which are designated to the (Jayatataka) Outlet Channel. Since the North Bank Wall is superimposed over the Outlet Channel, this implies that the channel was in place prior to the embankment's construction (Figure 2). In this paper, we ask if the superposition of the North Bank Wall interrupted the Jayatataka Outlet Channel to the south, or whether there was provision for water to continue flowing under it? For the latter, we would expect to find a laterite culvert underneath the embankment in alignment with the Outlet Channel. The Jayatataka and its Outlet Channel were only in use until they were bypassed (see below), which we posit was another alteration that occurred during protracted periods of weak monsoons in the early- to mid-13th century, as has been argued by Buckley et al. [13]. If the North Bank Wall allowed the flow of water, we can narrow its potential construction date to a relatively brief period after the construction of Angkor Thom in the late 12th to early 13th century, but before the Outlet Channel was bypassed in the mid 13th century.

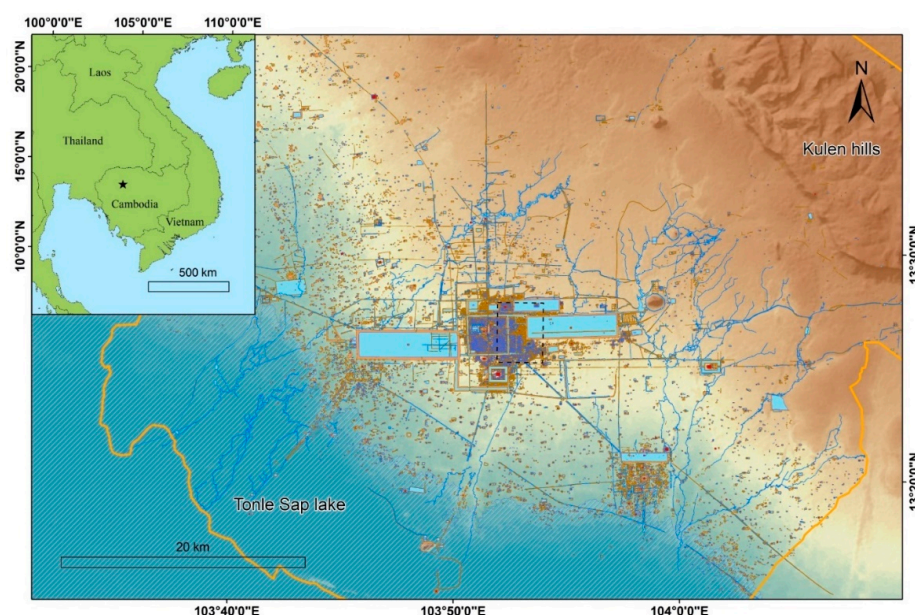


Figure 1. Location of Angkor (star, inset); archaeological landscape and topography of Angkor showing earthworks (brown), hydraulic features (blue); extent of study area (orange) and Figure 2 (black dash). Archaeological mapping courtesy of Evans, Pottier, Klassen and Wijker; topography (DTM and hillshade) courtesy of Shuttle Radar Topography Mission.



Figure 2. The engineered landscape of central Angkor with locations mentioned in the text. Outer enclosure of Ta Prohm (black dash) and 'Intended Enclosure' (white dash). Lidar DTM and hillshade courtesy of Khmer Archaeological Lidar Consortium.

2. Study Area

2.1. Historical Background

Angkor rose as the chief political center of the Khmer in the early 9th century and remained so for hundreds of years. By the mid-12th century, their dominion encompassed much of what is now Cambodia, Thailand, and southern Vietnam, with the capital based within the dispersed, urban-agrarian landscape of the 3000 km² Greater Angkor Region [14–16]. The Kulen hills, which characterize the landscape northeast of Angkor, are the source of the rivers that meander down a gentle gradient to the Tonle Sap lake in the southwest. Water was an intrinsic element in Angkorian religious ceremony and architecture. In the “dry zone” of mainland Southeast Asia, it typically rains from May to November, with virtually no precipitation for the rest of the year. This is largely a byproduct of coastal mountain ranges in the southwest, which form a “rain shadow” by forcing moisture-laden onshore winds to higher altitudes where it condenses into precipitation. Thus, as the winds continue further inland, they are largely devoid of moisture, which leaves the interior relatively dry between monsoons [17]. As such, Angkor’s elaborate water management system was also key to the expansion of the urban complex [18].

To even out the seasonality of the water supply, the Khmer devised an integrated network of water catchment, storage, and redistribution [19]. The hydraulic network is characterized by thousands of ponds, temple moats, channels, and vast *baray* (aboveground reservoirs). The reservoirs facilitated irrigation in some regions of farmland, but equally significantly, the large amounts of water retained above the surface raised the water table [20]. This phenomenon made the water more accessible to village and household ponds throughout the dry season. As rainfall is the single most significant factor affecting rice crop yields [17], favorable monsoon conditions enhanced with landscape-scale engineering allowed Angkor’s agrarian economy to flourish. Consistent crop surpluses and agricultural extensification at the capital [21] enabled the population to grow to up to 900,000 people [16]. As the army, drawing on a larger labor pool, repeatedly pushed the frontier outwards, the regional expansion would have brought additional resources into the capital [22].

2.2. Previous Research: Angkor Thom

As the chief power of the Southeast Asian mainland, Angkor’s dominance was rarely challenged, and for several centuries (c. 9th to the late 12th century), it had no durable defensive installations. Yet, as noted in documentary sources, during the 12th century there was an increase of conflicts between the Khmer, Dai Viet, and Champa, and instances of internal rebellions [11]. Coinciding with these shifts in geopolitical power, a great citadel was built in the urban center of Angkor. Now known as Angkor Thom (“big city”), this citadel was the centerpiece of the monumental construction program of Jayavarman VII (r. 1182–c. 1220). It was defined by a sheer, 8 m high wall surrounded by a moat (c. 110 m wide) which enclosed 9 km². The wall retained a massive embankment (c. 90 m wide) that sloped downwards into the interior, including a 20 m wide level crest upon which soldiers could be positioned. Within the enclosure, axial roadways and perimeter channels partition space, while a rectangular grid of smaller but distinct, linear depressions characterizes the rest of the interior. Conventionally, the impetus behind Angkor Thom’s construction has been attributed to the 1177 invasion of Angkor by a Cham army (see, for example, [23]). However, the reality was likely more complicated. Battle scenes depicted in the bas reliefs of the Bayon, Jayavarman VII’s state temple, show conflict between armies consisting of both Khmer and Cham combatants [23]. The implication is that Angkor was increasingly concerned with both domestic and foreign enemies.

Although Angkor Thom points to a growing concern for improved security, the multitude of temples built during Jayavarman VII’s reign suggests it was a time of prosperity with plentiful resources. He continued the trend of royal foundations [24], building a state temple-mountain (the Bayon), ancestral temples (Ta Prohm and Preah Khan), amongst numerous other lesser shrines. He also built the Jayatataka *baray* (reservoir), which was

placed to serve Angkor Thom. Unlike earlier examples, the Jayatataka had a single Outlet situated near its southwest corner. This feature and the associated Outlet Channel connect it to the residential areas of central Angkor, which is the focus of this research.

Despite his enduring legacy, the latter part of Jayavarman VII's reign and his successors are poorly documented. However, significant additions to the built environment that postdate Angkor Thom—embankments, walls, moats, and channels—related to defense and water management occurred during this period. All the features discussed in this research were first recorded, at least in part, by Georges Trouvé in 1933 during his survey of central Angkor [25]. These include (i) a large moated embankment with a retaining wall (“North Bank Wall,” but also known as “Tumnup Touich”) connecting the northeast corner of the moat of Angkor Thom to the East Baray; (ii) an embankment extending from the southeast corner of the moat of Angkor Thom (the South Bank) to connect with the southwest corner of Ta Prohm, and (iii) a channel connecting the Jayatataka Outlet to the moat of the North Bank Wall. These earthworks have no associated inscriptions, so dating them has been difficult and, until recently, a detailed understanding of their morphology and spatial context has been hindered by the forest. Nevertheless, Trouvé could trace the South Bank east until it turns north to connect with the Ta Prohm enclosure wall. He also noted that the Jayatataka Outlet Channel and the moat along the North Bank Wall were integrated entities with laterite culverts that allowed east-west terrestrial traffic to cross the north-south channel ([26]: Pl. XXXV).

The North Bank Wall is structurally similar in profile to the Angkor Thom enclosure, with a broad earthwork held up by a sheer retaining wall. This morphology, and its implications for defense, has been noted previously [27]. However, because its full spatial context was not yet known, the North Bank Wall appeared to be in isolation, such that “the defense formed by [it] seems to have been useless” ([26]: 312). Previous evaluations of its chronology have placed it in the 9th century, and it was later argued to date to the early 11th century ([26]: 286, 312). However, recent excavations by the Greater Angkor Project have revealed that the west end of the North Bank Wall is built on top of the excavated upcast for the Angkor Thom moat's east edge, so it must postdate the late 12th century. At its east end, the North Bank Wall is cut by the Siem Reap channel erosion during the monsoons during the 14th century (Figure 3) [13]. Brotherson et al. have therefore argued that the North Bank Wall most likely dates to the first half of the 13th century.

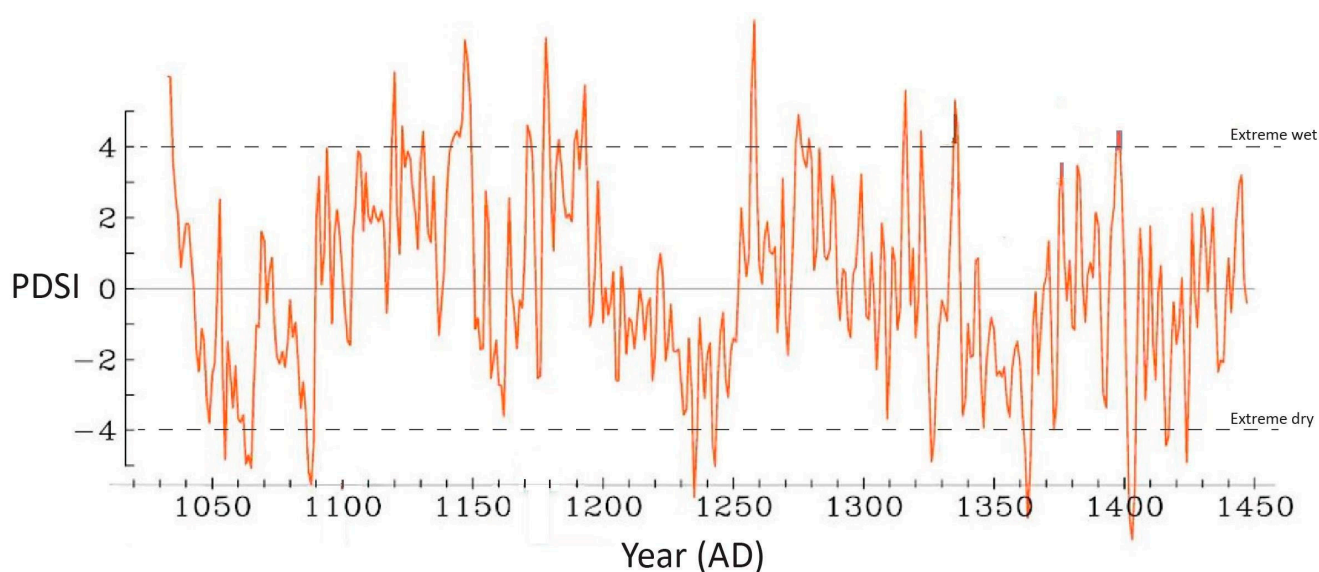


Figure 3. Pacific Drought Severity Index (PDSI) showing monsoon strength over time, derived from dendrochronology records (Adapted with permission from ref. [13]. Copyright 2014 Quaternary Science Reviews).

3. Materials and Methods

3.1. Lidar

The lidar data was acquired in one contiguous block, covering 370 km², by the Khmer Archaeological Lidar Consortium (KALC) in 2012. To acquire the lidar data across such a large area, a Leica ALS60 and 40-megapixel Leica RCD105 was affixed to one of the skids of a Eurocopter AS350 B2 helicopter. The resulting lidar data was collected at 200,000 laser pulses per second, which returned an average of 2 ground points per square meter. This allowed us to generate a digital terrain model with >1 m resolution, which was originally published in 2013 by Evans et al. (for further details on the lidar acquisition, see [28]). In this paper, we use the pre-existing lidar data to further investigate the area of the landscape where the North Bank Wall was constructed.

3.2. GPR

Ground penetrating radar (GPR) was used to investigate the internal structure of the North Bank Wall and thereby assess whether it was constructed to allow the continual flow of water from the Jayatakata into the intended enclosure. We used a Mala X3M unit equipped with a shielded 500 MHz antenna and a survey wheel to acquire reflection profiles over the designed transects Figure 4).

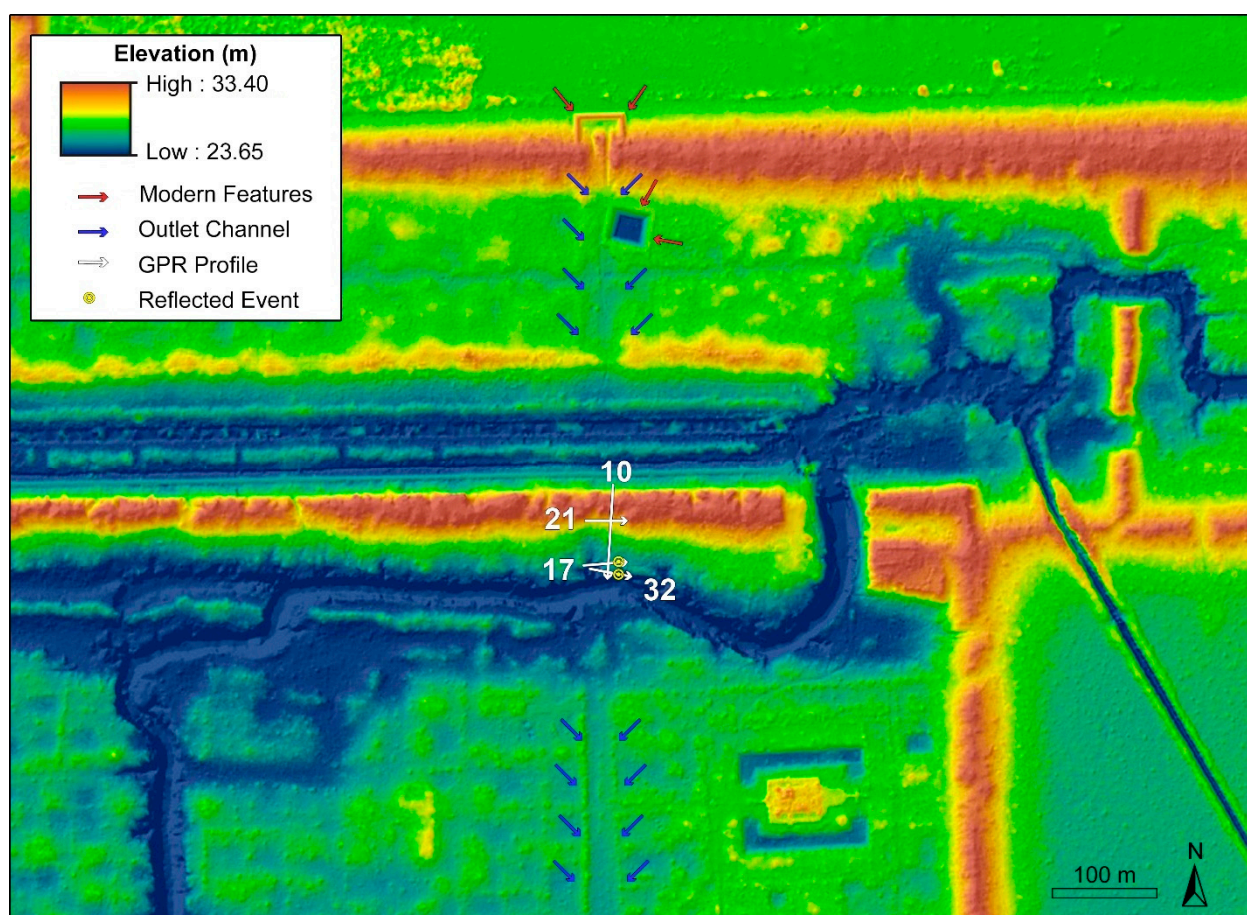


Figure 4. GPR Transects collected at the North Bank and “V” shaped features (reflected events) annotated. The channel to the north and south of the North Bank wall are indicated with white arrows. Lidar DTM and hillshade courtesy of Khmer Archaeological Lidar Consortium.

Most of the profiles were acquired on pre-existing footpaths. When necessary, we cleared light vegetation in consultation with the Authority for the Protection of the Site and Management of the Region of Angkor (APSARA) personnel. As a result, the acquisition

took place over rough surfaces, and some decoupling and survey wheel errors are to be expected. The spatial distribution was controlled by GPS points taken with a handheld unit (Garmin CS60) with an approximate accuracy of three to five meters. It is interesting to notice that this was a cost-effective method that allowed us to integrate our survey with the previous lidar survey data [28]. GPS coordinates were acquired at the beginning and end of each transect, while the system was dragged in a line between the points. Later, those points were projected over the lidar data and an elevation profile was generated for each transect. These values were used to correct the reflection profiles for the topographical variation along each transect, and the results were consistent at this scale—despite the low accuracy of the GPS coordinates.

Most profiles were collected with a very high rate of traces per meter (260). Later, processing traces were downsampled using horizontal stacking (by a factor of four) to present the images in a more appropriate scale. Each trace comprises 934 samples with no vertical stacking applied to it. All profiles were subject to basic processing (using Radan), including time-zero, low, and high pass filters and gain. Hyperbola fitting was done for every profile to better estimate the relative dielectric permittivity value [29] and, in turn, the depth of the sensed events. However, data was not always migrated to keep the hyperbolas in the images, as they are usually helpful in interpreting the data. The estimated relative dielectric permittivity was updated in the file header of each profile. For some transect profiles, deconvolution was applied, and to others, the Hilbert Transform.

4. Results

4.1. Lidar Results

Despite the general spatial characteristics of the North Bank Wall and the South Bank being identified in the 1930s, the functional relationship between the two was forgotten and only became apparent through the lidar-based digital terrain model (DTM) made available by KALC in 2012 [28]. The lidar DTM verifies Trouvé's survey showing the full extent of the inner part of the South Bank connecting with Ta Prohm. The lidar also reveals another feature that Trouvé had identified, but only in part—the Jayatataka Outlet channel. This channel connects with the North Bank Wall's moat and continues for several kilometers to the south.

4.2. GPR Results

From the eight collected transects at the North Bank Wall, four (Transect 10, running N–S, and transects 17, 21, and 32 running E–W) presented relevant data to assess the structure of the embankment and its surroundings (see Supplementary Materials). The other transects suffered too much decoupling due to the rough terrain to be useful for defining stratigraphic features. In general, signal penetration varied from one to three meters in depth, calculated based on a RDP of 12.7 for all transects. Variations in penetration are caused by attenuation or loss of signal and can have multiple causes.

Transect 10 running N–S shows the most signal attenuation (Figure 5) on the highest part of the embankment with noticeable changes on the slopes, markedly at the South slope. As we look at the top of the embankment in more detail (Figure 6), with the Hilbert transform applied to the migrated data, some large reflection areas close to the surface presenting a somewhat regular spacing can be seen throughout the highest region. The reflections after the Hilbert transform can better represent the structures in the subsurface for the oscillating elements of the radar pulse are now represented by the envelope of the trace [30]. In any event, the radar energy does not penetrate much further than this layer, which is similar to the results of a survey at Koh Ker [31,32]. Following the transect South, through the more moderate slope, the reflectors near the surface become smaller, more irregularly spaced, and signal penetration improves. Although, around meter 74, another acute attenuation occurs (dashed line Figure 7) with layered deposition on both sides of the attenuated area. To the south side, a striking layered deposition presents a polarity inversion between the layers (arrow on Figure 7). Transect 21, perpendicular to transect 10

and parallel to the embankment, presents the same low penetration and shallow reflectors. As the slope tends to flatten near the base of the embankment, penetration improves and an interface can be seen on Transects 17 and 32 (Figures 8 and 9) that is also parallel to the embankment.

The results from these four transects suggest that there was a subsurface structure running below the North Bank Wall in line with the Jayatataka Outlet Channel. If it is a masonry feature, this is significant because Angkorian channels are typically simple earthworks, with only key components such as spillways, bridges or culverts made in durable materials such as laterite. Given this cultural context, any masonry feature located under the embankment is unlikely to relate to the channel's original "open air" configuration but would indicate a specialized installation contemporary with the North Bank Wall's construction.

A few meters south, in the same direction, Transect 32 presents a similar channel-like feature with approximately the same size, shape, and depth as seen in Transect 17. Both are approximately 30 m wide, with a depth of more than 2 m, filled with layered and convoluted depositions and they align perfectly on the N–S axis (Figure 4). Throughout most of Transect 17, a "V" shaped interface reflects from around 50 cm from the surface up to 2.6 m in depth at its lowest point. This feature is filled with complicated stratigraphy with many horizontally discrete reflectors and an attenuated area can be seen as a disruption at the lowest point of the feature.

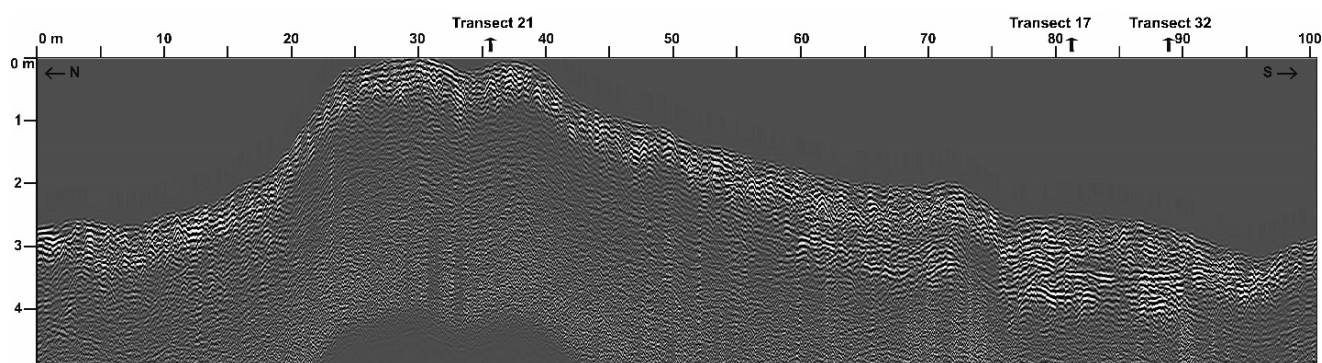


Figure 5. Transect 10, running N–S, after topographical correction.

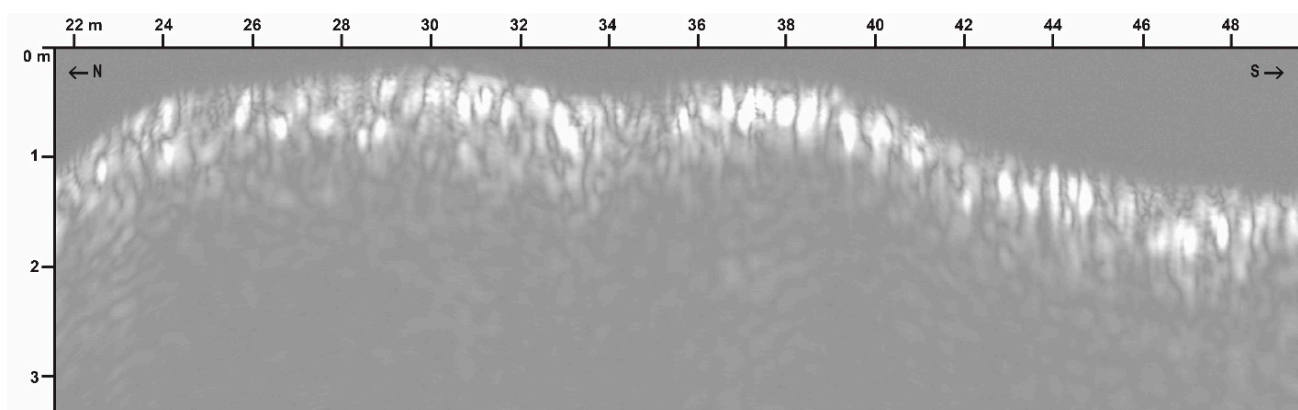


Figure 6. Detail of transect 10 at the top of the embankment, after migration and Hilbert Transform.

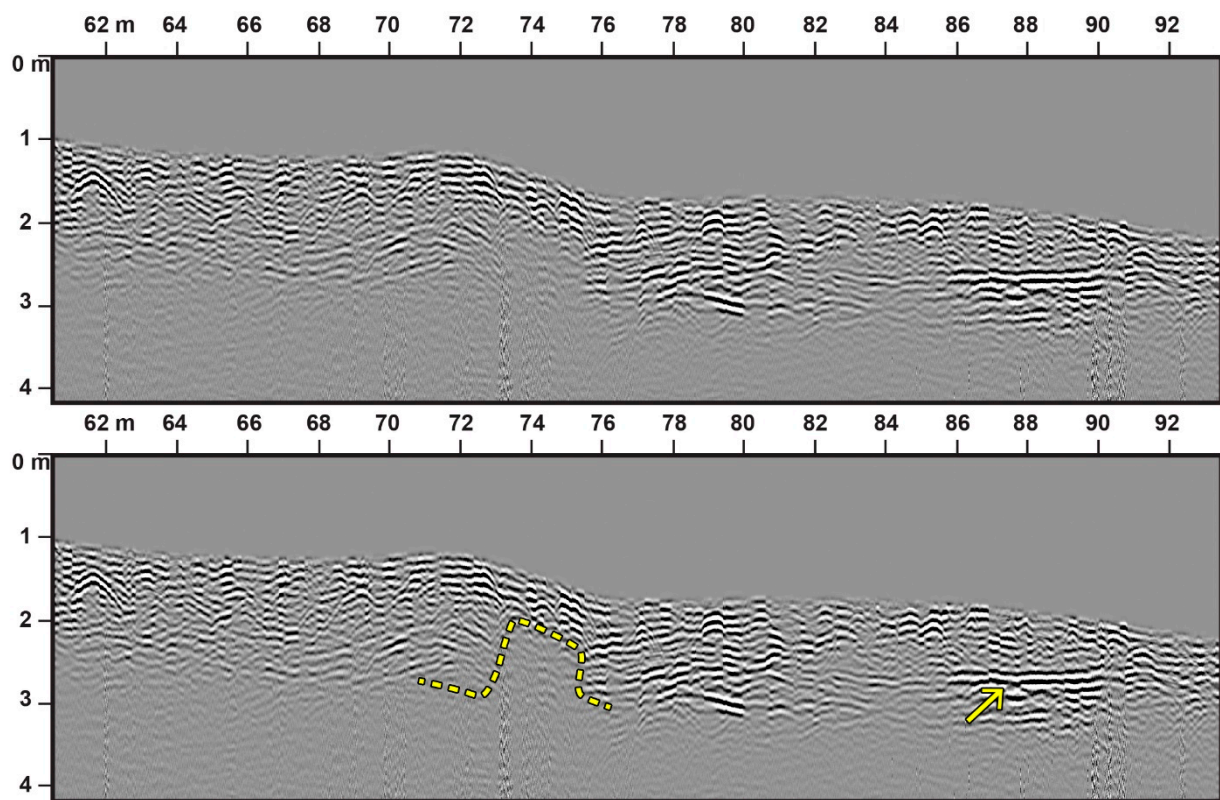


Figure 7. Detail of the South slope on transect 10 (**top**) with annotated events (**bottom**). The dashed line indicates an acute attenuation and the arrow indicates a striking layered deposition that presents a polarity inversion between the layers.

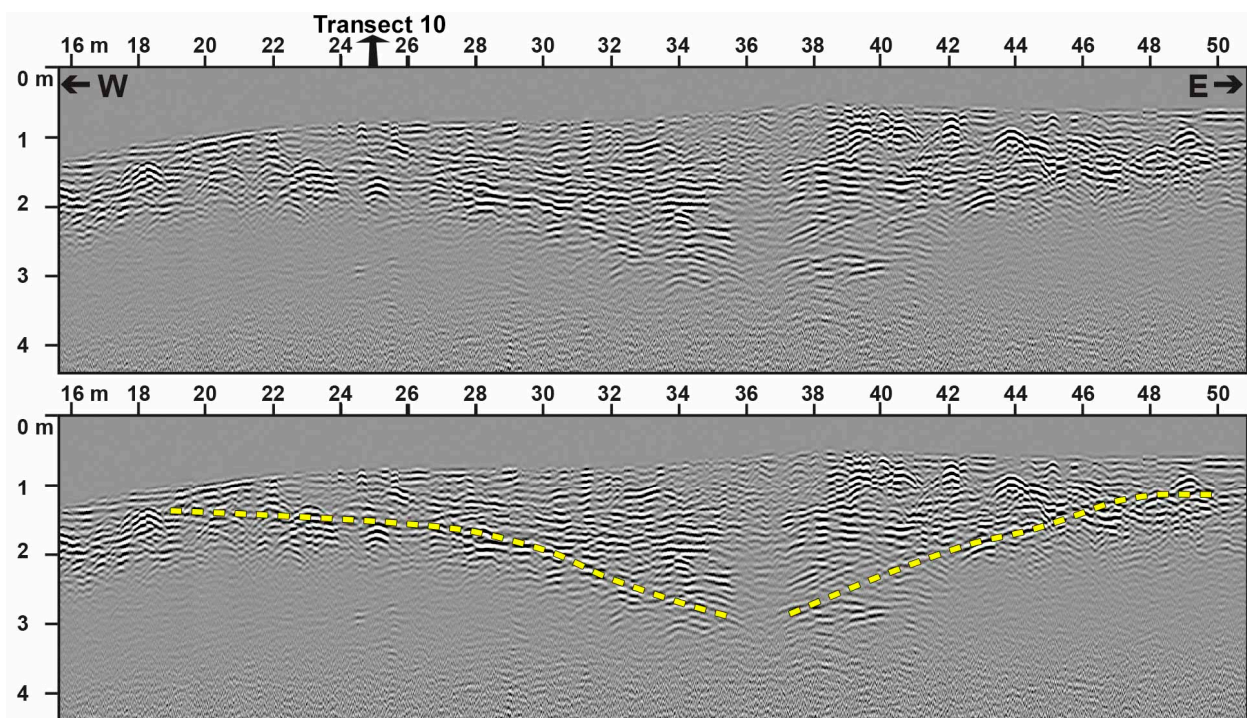


Figure 8. Transect 17 (**top**) with the annotated interface (**bottom**).

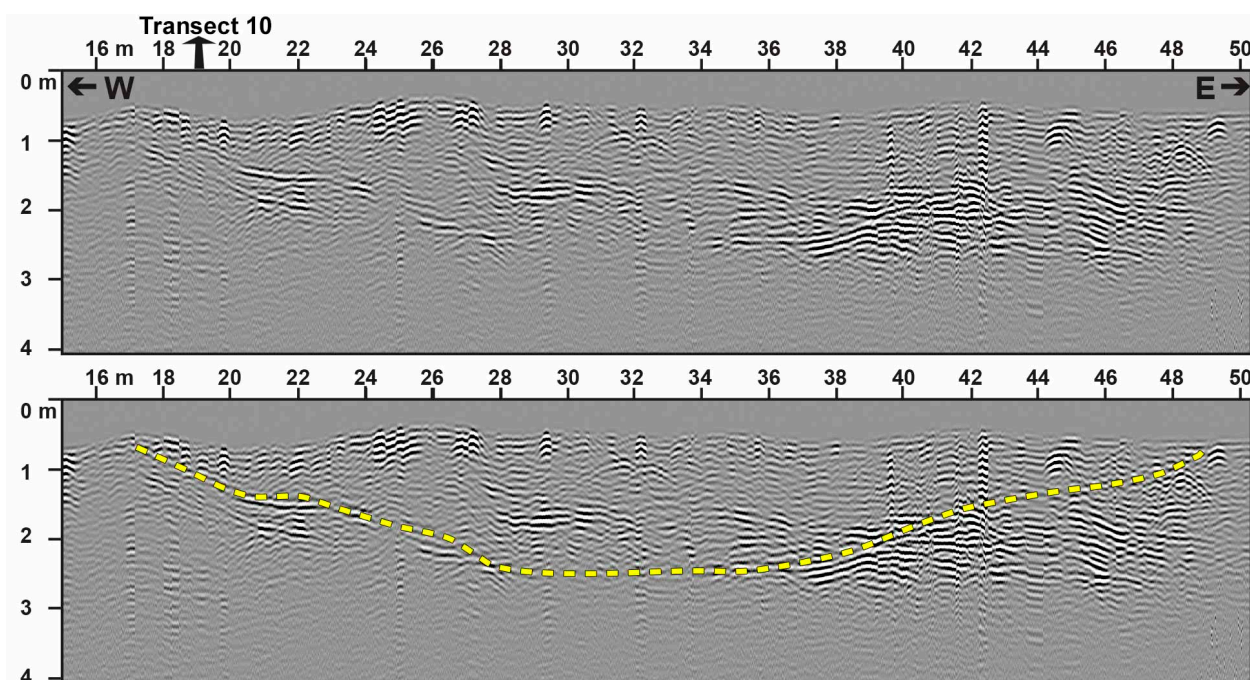


Figure 9. Transect 32 (top) with annotated interface (bottom).

5. Discussion

5.1. Lidar

Trouvé was able to identify the western part of the outer bank, and with the results from the lidar we can appreciate why he was unable to identify the intended design of the South Bank Wall, as it was never completed. The excavation of the moat, located between the inner and outer banks and the source of the earth to make them, is evident at the South Bank's west end. However, further to the east, these become less distinct, and are disrupted where the inner bank turns north. While the moat's outline is distinct along the section running north to Ta Prohm, the depression is so shallow that no outer bank is discernible. Thus, although it was never completed, the South Bank's spatial extent and connection to the Ta Prohm enclosure wall are crucial to our interpretation of its *intended* function. This is because the Ta Prohm enclosure also adjoins the west bank of the East Baray, which in turn is connected to the North Bank Wall. Thus, had it been completed, a well-defined area—the Intended Enclosure—would have been contained to the east of Angkor Thom (Figure 2). Yet, for whatever reason, it was never fully realized. Any lingering doubts as to the intent of these earthworks should be put to rest by the morphology of the North Bank Wall, which is nearly identical to the Angkor Thom wall, whose defensive impetus is questioned by no one. Likewise, sheer 8 m-high retaining walls are simply not found in association with embankments simply intended for water management—indeed, there is no need for them in such a scenario.

5.2. GPR

We can infer insight into the materials present in the subsurface when the attenuation varies along with a reflection profile. The acute attenuation on top of the embankment could be caused by strong reflectors close to the surface that would reflect most of the transmitted energy right back to the antenna [33] and also from compacted materials, as they present less air between the particles, or both. The inverted polarity could be a result of a void within the deposition [29] which, in turn, suggests a more intricate structure.

Transect 21, perpendicular to transect 10 and parallel to the embankment, presents the same low penetration and shallow reflectors that resemble laterite blocks or other large pieces of stone. Similar reflections of laterite blocks have been documented at other surveys

in Cambodia [31]. These reflections also resemble the laterite block reflections at the top of the profile (Figure 10). Close to the “V” shaped interface on Transect 17, an empty shell case of heavy artillery was found at the surface. This empty shell indicates that this area has seen recent conflict and suggests that some of the attenuated areas seen near the top of the embankment may be a result of subsurface disturbance associated with this conflict over the last century. Further, the fact that the disruption comes from the surface all the way to the bottom of the feature, suggests that the layers within the feature were disturbed after deposition by a very restricted one-off event.

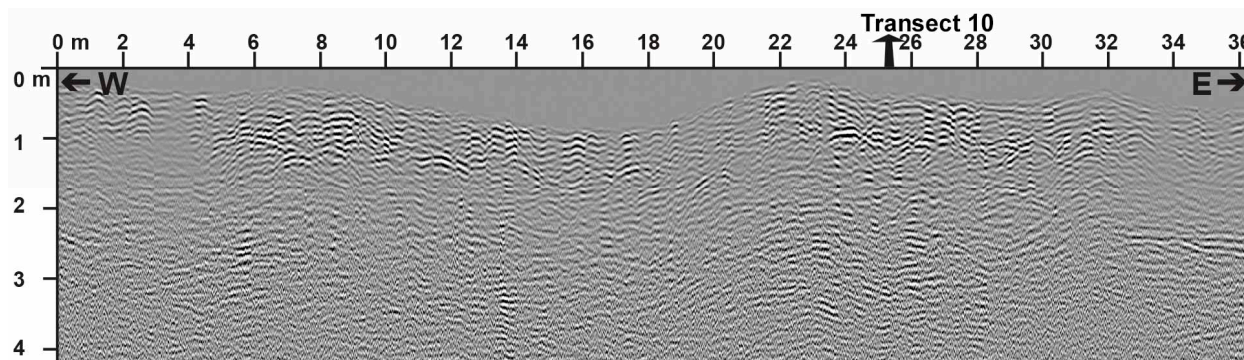


Figure 10. Transect 21.

The results from these four transects suggest that there was a subsurface structure running below the North Bank Wall in line with the Jayatataka Outlet Channel. If it is a masonry feature, this is significant because Angkorian channels are typically simple earthworks, with only key components such as spillways, bridges or culverts made in durable materials such as laterite. Given this cultural context, any masonry feature located under the embankment is unlikely to relate to the channel's original “open air” configuration but would indicate a specialized installation contemporary with the North Bank Wall's construction.

The results from the GPR provide evidence of a subsurface feature, perhaps a laterite culvert, running under the North Bank Wall, connecting the north and south segments of the Outlet channel to maintain water delivery to the Intended Enclosure. Recent research indicates that the severe water shortages that prompted the bypassing of the Jayatataka most likely occurred sometime between the 1220s and 1250 [13], and that the diversion of the Siem Reap river through the North Bank Wall happened shortly thereafter [5]. Our results suggest that the North Bank Wall may have been built with a channel that allowed the Outlet Channel to remain operational. This, in turn, implies that the installation of defense enhancements of the Intended Enclosure occurred prior to any significant period of drought (i.e., before the mid-13th century). Once the Jayatataka *baray* was bypassed, these various components' functional relationship became inconsequential, as the Outlet no longer had water to provide. Another possibility is if the proposed connection did exist, it may have collapsed under the weight of the overlying embankment, which may have prompted the Siem Reap channel's cutting through the North Bank Wall.

Finally, the present course of the Siem Reap channel, which bypasses the Jayatataka *baray*, requires comment. As such, the Jayatataka was disconnected from the hydraulic network, and so too its Outlet Channel had ceased operation. Functionally the *baray* altered the drainage characteristics of the landscape, and provided key benefits for the immense, perennial settlement at Angkor by storing water throughout the dry season, slowing the flowrate to minimize erosion damage, and raising the water table through ground seepage which made groundwater more accessible throughout the year. So why then bypass the Jayatataka and do away with these advantages? The primary distinction is that a *baseline* amount of water was required for the *baray* to function and, in the event of a prolonged drought, an insufficient supply of water at the inlet would evaporate or soak into the

ground before it could be used. Thus, we argue that the environmental conditions in which such measures were taken would be a period of severe water shortage, of which there are several that occur from the early 13th century onwards [13]. If the Outlet Channel continued to function beneath the North Bank Wall, it presumably predates that period.

6. Conclusions

In this paper, we used lidar and GPR to determine whether steps were taken to allow the Jayatataka Outlet channel to continue functioning after the construction of the North Bank Wall. The results from the lidar investigation indicate the exact location where the North Bank Wall was built over the channel and the ground penetrating radar revealed what looks like an internal structure built of laterite connecting the northern and southern parts of the channel underneath the North Bank Wall. The presence of this internal structure, with what appears to be laterite blocks, indicates that the feature was not solely built for defense and most likely enabled the flow of water from the Jayatataka to continue into the habitation zones within the Intended Enclosure. This feature would have functioned together with the moat along the northern side of the North Bank Wall that delivered water to Angkor Thom.

This study not only highlights the complicated nature of the intersection of water management and defensive engineering, but also suggests that the construction of the North Bank Wall likely dates to the period before the severe water droughts in the mid-13th century, which provides further evidence to support the date proposed by Brotherson et al. [5]. If our hypothesis is correct, this indicates that works toward the Intended Enclosure also predates the period of extended drought. Indeed, this same drought might also explain why the South Bank was never finished, and the enlarged defended space never materialized. With the original impetus of a burgeoning, urbanized population within a secured environment becoming untenable, the political and religious elite eventually relocated.

This study informs our understanding of the decline of Angkor, because it suggests that issues with water management alone were not the only existential threat faced by the religious and political elite at Angkor during the 12th and 13th centuries, the latter of which is poorly documented by written sources. However, it increasingly appears to have been a highly eventful century, our knowledge of which will mainly be based on the archaeological record. Our study indicates that a range of stimuli prompted additions to and modifications of the engineered landscape throughout the later stages of the Angkorian period. These features were bulky, inert, and en masse worked to further constrain the options available to Angkor's engineers to adapt to changing social and environmental circumstances. The likelihood that the North Bank Wall was built for defense purposes before the droughts suggest that the perceived threat from attacks, whether foreign or domestic, predated the damage done to the water management infrastructure at the end of the 13th century CE. This suggests that increasing concerns of political stability may have played a more influential role in relocating the capital. Further, this relocation and subsequent demographic decline of the region may have predated Angkor's water management network's functional demise, as others have argued [34]. Indeed, this study suggests that growing threats from attack may have been as much a concern even earlier than expected and the material consequences of which are still visible in the landscape, despite conflicting narratives derived from historical sources. Interestingly, the threats of invasion may not have only been from foreign forces. Documentary sources seem to indicate that there were domestic uprisings [23]. When juxtaposed with recent research suggesting the concentration of landownership with the king and upper elites [21,35], it seems possible that growing inequality may have been yet another factor in the eventual decline of Angkor. However, more work is needed to determine the correlation of the two.

While we have found evidence that the North Bank Wall had an internal structure, further investigations should be undertaken to better understand the nature of the internal structures, whose characteristics, function, and date are of consequence for the developmental history of Angkor. The GPR transects on the North Bank, as with the previous GPR

surveys by Till Sonneman for the Greater Angkor Project [36,37], demonstrate that GPR survey is an economical way to locate buried features and, when possible, infer its nature based on other known elements. The method, however, cannot be used to identify the exact nature and functioning of the located features, unless in extraordinary circumstances, which usually requires additional investigation. In the case of archaeology, this can be done by coring or further excavations.

Supplementary Materials: The following are available online at <https://osf.io/g65xu/>.

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