Thesis for the Award of

Doctor of Philosophy

Angkor Underground

APPLYING GPR TO ANALYSE THE DIACHRONIC STRUCTURE OF A GREAT URBAN COMPLEX

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2011

ABSTRACT

This thesis is based on surveys of ground-penetrating radar (GPR) conducted at Angkor, Cambodia. The appraisal of preceding remote sensing surveys led to selective ground based prospection for archaeological objects of interest on different scales.

The successive relocation of the political and religious centre from the 9th to the 14th century has left a palimpsest landscape that reaches from small artificial habitation mounds, masonry monuments and their enclosures, to the extensive water management network of channels and earthworks that covered large parts of the floodplain between the Kulen Hills and Lake Tonle Sap.

To make efficient use of the technique, the GPR survey had to be adjusted to those dimensions. The area-covering grid method was chosen for small scale surveys on habitation patterns, production sites and cemeteries, testing potential and limits in the application. A major factor in the measuring and processing of data was the floodplain geology of predominantly clayey sand and an environment prone to inundation that provided varying signal penetration depths depending on either compact or soft soil.

For the larger scales, GPR was used in combination with GPS, GIS and remote sensing data sets. The concept of spatial configuration of monuments in and outside of enclosures led the search for remains of missing laterite and sandstone structures. A survey in the centre of Angkor Wat revealed the outline of six towers as part of a potential quincunx formation. They were further analysed by excavations to establish a preliminary construction history of the area. Surveys inside the peripheral enclosures of Chau Srei Vibol, Banteay Sra and Prasat Komnap showed evidence of demolished structures, some of it possibly from the Angkorian period.

For questions concerning the functioning of a water management system in the Angkorian floodplain, GPR profiles in search for infrastructure were conducted alongside and over the embankments of the giant reservoirs. Evidence of outlets in the central areas of the eastern embankments of all four baray at Angkor confirmed them being part of the network.

On the largest scale, GPR transects were run across parts of the floodplain to investigate the network of canals and earthworks that had been mapped by remote sensing. Obstacles, profiles and grids as well as the detected anomalies were integrated into a geo-referenced GIS database. Potential connections between centres and temples were integrated at areas where associated and previously mapped earthworks discontinued.

Anomalies associated to the water management features were classified according to their characteristics and potential function as former artificial and natural channels, moats, ponds as well as masonry remains, and analysed with regard to archaeological maps and available remote sensing data. Newly acquired high resolution satellite radar (TerraSAR-X) data was used to evaluate a potential relation between water saturation and anomalies.

The complete dataset was analysed for a complementation of archaeological maps and with the intent to separate features of the artificial canal network of Angkor from the natural landscape and the original distribution of rivers.

FIG. [1]: THE GPR CART IN FRONT OF THE SOUTH GATE OF BANTEAY KDEI.

'If he smiled much more, the ends of his mouth might meet behind,' she thought: 'and then I don't know what would happen to his head! I'm afraid it would come off!' (Lewis Carroll, Through the looking Glass, Ch.VI)

PREFACE

'Would you tell me, please, which way I ought to go from here?' 'That depends a good deal on where you want to get to,' said the Cat. 'I don't much care where…' said Alice. 'Then it doesn't matter which way you go,' said the Cat. '…so long as I get somewhere,' Alice added as an explanation. 'Oh, you're sure to do that,' said the Cat, 'if you only walk long enough.' (Alice in Wonderland, Ch. VI)

Following the White Rabbit

The decision to do a PhD thesis on Angkorian archaeology at the University of Sydney developed step by step over time, and has turned into a rather long and quite exciting journey.

I graduated from the *Westfälische Wilhelms-Universität Münster* in Germany with a diploma in geophysics, which, besides being a degree heavily based on mathematics and physics, also included an introduction to geophysical field methods and small surveys concerning archaeological problems. My interest in heritage studies had developed within my university career, when attending classes in art history and historical city development at the universities of Münster and Berlin, and the *Universidad de Granada* in Spain.

Being interested in applied geophysics and fascinated by space sciences, I wrote my diploma thesis on the analysis of moonquake data in the *Planetary Physics* research group of Prof. Doris Breuer at the *Institute of Planetary Research* at the *German Aerospace Center* (DLR e.v.) in Berlin, supervised by Prof. Tilman Spohn and Dr. Martin Knapmeyer, and presented the results[1] inter alia at the *International Astronautical Congress (IAC)* in Fukuoka in late 2005. There I was fascinated by Dr. Mario Hernandez's presentation concerning the *UNESCO Open Initiative*, a concept that connected remote sensing data (provided by space agencies) with analysing skills (provided by universities) to map and solve tasks concerning global heritage sites. At that time I was at the *Universidad de Colima* in Mexico (assisting to collect geophysical data of the near volcano) and Dr. Hernandez invited me to participate in a UNESCO conference in Campeche, where among site managers, representatives of space agencies and researchers were Prof. Armin Grün and Dr. Fabio Remondino from *ETH Zürich*.

I was given the opportunity to work with Dr. Martin Sauerbier within Prof. Grün's *Photogrammetry and Remote Sensing Group* at ETHZ for ten months. There we created a 3-dimensional model of the temples of Angkor[2] based on Japanese JICA aerial images. The work involved a very detailed look at the central monuments of Angkor and gave me an idea of the dimensions and problems I was going to face later in my research.

As a geophysicist, I was looking for applied work that would on the one hand be a combination of fieldwork and analysis, and on the other hand meet my interest in heritage and archaeology. Such an opportunity came up at a workshop on "Geophysical applications in Archaeology" in Grosseto, Italy. I was thrilled by the rapid development of GPR analysis which Dr. Dean Goodman of the *Geophysical Archaeometry Laboratory* presented, and took the offer by Prof. Henrique Lorenzo and Dr. Alexandre Novo to learn the principles of GPR in the *Close Range Remote Sensing Group* at the *Universidade de Vigo* in Spain for several months.

Having been in contact with the University of Sydney to get additional information for the images, I became interested in the available PhD thesis, apparently requiring the necessary skills and knowledge I had developed over the years: to use Geophysics, GIS, Remote Sensing and Heritage Studies at Angkor.

Please, Ma'am, is this New Zealand or Australia? (AW, I)

I arrived in Australia in July 2007. Over the next three years I conducted four research trips to Cambodia which predominantly focussed on recording GPR data in the area, followed by the data analysis at the *University of Sydney*, in which I was supervised by Prof. Roland Fletcher in Sydney, in Cambodia and later also in Sydney by Associate Prof. Christophe Pottier of the *École Française d'Extrême Orient*.

The opportunity to work for *Alpha Geosciences Pty. Ltd.* in the first semester, and in the following years to tutor and lecture at the *School of Geosciences*, and to be contracted by a number of Australian heritage organisations to conduct GPR surveys, financed my living and kept my eyes as well on Geophysics.

Looking backward, the road to the thesis was paved by the support and interest of many people, and included a few bends in the road - before leading to the completion of this thesis.

My own perception of Angkor has of course also changed over the four years of the PhD, and was heavily influenced by the research conducted, from the" lost ruins," known from movies and documentaries, to the "bird view" impressions I received of the Angkorian landscape in Zürich, over the reading of publications, discussions with other scholars and visiting the temples; finally trying to understand this immense landscape using a technique that is limited by various factors, but allows us to see beyond the surface. I also assisted in and conducted excavations looking for confirmation of GPR results, and so gathering additional archaeological information.

A word about the use of quotes from Lewis Carroll's *Alice in Wonderland* (1865) and *Through the Looking Glass* (1872)[3] in this thesis: When reading about the Angkorian rulers' demand to relocate and construct new centres in Angkor and the following gradual spread of urbanization, which left behind a complex and a disturbed archaeological landscape reminded me of the famous Hatter's Tea Party. Here, the (mad) hatter calls to move around the table to get to a new and fresh tea service, letting the other guests behind him sit at messy plates. While searching for this quote, I came upon more phrases resonated with my experience in Angkor - in fact, it is a *Wonderland* in the subsurface that opens up to Alice when she follows the White Rabbit to experience *Adventures Underground*, as the draft manuscript was originally named, and stepping *Through the Looking Glass* she is confronted by astonishing geometrical configurations of the landscape.

Lewis Carroll was the pseudonym of Charles Lutwidge Dodgson, a lecturer of mathematics and logic at Christ Church College in Oxford. In the 1850s when Carroll wrote the story, he led Alice - and with her his readers - into a fantastic world. Approximately at the same time European explorers entered continental Southeast Asia and "re-discovered" Angkor, coming back to Europe with tales about a *"wondrous enigma which challenges the wisdom of the world to fathom."*[4] The landscape of Angkor remains to be a wonderland for archaeological studies.

ACKNOWLEDGEMENTS

'Must a name mean something?' Alice asked doubtfully. (LG, VI)

Writing this thesis has been an effort that would not have been possible without the support, influence and inspiration of many people on at least four continents. My gratitude goes to:

My supervisors: Prof. Roland Fletcher (University of Sydney) and Associate Prof. Christophe Pottier (École Française d'Extrême Orient).

At the University of Sydney: Dr. Dougald O'Reilly, Luke Benbow, Dr. Mitch Hendrickson, Dr. Dan Penny, Gaby Ewington, Rosemarie Whitecross, Dr. Li Baoping, Dr. Terry Lustig, Dr. Eileen Lustig, Dr. Damian Evans, Dr. Georgie Lloyd, Dr. Martin King, Dr. Martin Gibbs, Michelle Negus-Cleary, Andrew Wilson, Dr. Ina Kehrberg-Ostrasz, Steven Fehir, Rena McGrogan, David Mitchell, Daravy Khiev, Prof. Dietmar Mueller, Associate Prof. Patrice Rey, Dr. Maria Seton, Dr. Gabriele Morra, and Yu Liu.

In Cambodia: Malay So, Chhay Rachna, Aaron Otte, Dr. Dominique Soutif, Dr. Julia Estève, Prof Miriam Stark, Hen Chenda, Suy Pov, Long Chanta, Lam Touch, Mom Douk Vantha, and Prof. Michael Vickery.

Globally: Dr. Dean Goodman, Dr. Alex Novo, Dr. Christian Hüttig, Dr. Yasushi Nishimura, Dr. Ichita Shimoda, Dr. Katsura Sato, and María Isabel Ramirez Magallón.

The organisers who arranged and the audience who listened to my presentations: at the Department of Archaeology of the *University of Sydney*, the *EFEO* in Siem Reap, the *Royal University of Fine Arts* in Phnom Penh, the *National University of Singapore*, the *DLR* in Berlin, and *Heidelberg University*. This also accounts for the conferences of *EurASEAA 2010* in Berlin, *CAA 2011* in Beijing, and the research groups I visited at *Waseda University*, *Sophia University*, *Tokyo Institute of Technology*, the *Nara Institute*, the *Saitobaru Museum* in Japan, as well as the *National Research Institute of Cultural Heritage* in Daejon, South Korea.

My family Gyburg, Hans-Jürgen, Jan Sonnemann, and my grandma, for having been there for me with great support, interest and advice.

The Department of Archaeology's *Carlyle Greenwell Bequest* 2007, 2008 and 2009, the *Postgraduate Support Scheme* 2009 and the *University of Sydney Travel Grant* 2010 provided financial help to conduct the surveys in Cambodia. The *Robert Christie Research Centre* (RCRC) and the *École Française d'Extrême Orient* (EFEO) in Siem Reap provided an excellent research environment in Cambodia. Initially the Archaeological Computing Laboratory, and from 2009 on the Angkor Research Program provided the working facilities at the University of Sydney.

The University of Sydney's *Department of Archaeology* (Martin Gibbs) provided the GPR equipment, the *ACL* and the *School of Geosciences* the GPS. The *Greater Angkor Project* (GAP) financed the additional transport costs, the check and repair of the equipment, and covered the lease of the processing and imaging software *GPR Slice,* developed by the Geophysical Archaeometry Laboratory. Accurate GIS data sets were made available by the Japanese International Cooperation Agency (JICA). TerraSAR-X satellite data was provided free of charge by the *German Aerospace Centre* (DLR) e. V. as part of the *UNESCO Open Initiative*. The *University of Sydney Library*, *BEFEO* online (persee.fr), Christophe Pottier's database of research articles, and Google applications (-Earth, -Scholar, and -Books) were frequently consulted and immensely helpful to obtain relevant information and sources. *APSARA Authority* and the *Ministry of Culture and Fine Arts* of the Cambodian Government and local chiefs permitted the research work to be conducted at specific archaeological sites.

CONTENTS

INTRODUCTION

> *I almost wish I hadn't gone down that rabbit-hole - and yet - and yet - it's rather curious, you know, this sort of life. (AW, IV)*

Information gathered from the subsurface of the historic site of Angkor in Cambodia, the capital of the Khmer Empire from the 9th to the 15th century, was the research focus of this thesis. Of course it is first the monuments of Angkor's centre, the splendid temple structures and their enclosures, sometimes collapsed and overgrown by dense forest, which catch the visitor's eye and imagination. The surrounding landscape expands into an immense floodplain, the hinterland of Angkor. A maze of earthworks and reservoirs display the infrastructure that once was used as transport routes and waterways serving the construction and maintenance of the monuments: the setting of Greater Angkor.

That 'archaeological landscape' has been investigated over the past century by means of various techniques and methods, aiming at a comprehensive picture of Angkor's development and decline. Hundreds of years of landscape remodelling due to the successive relocation of the political and ceremonial centre following the construction of new state temples, have created a palimpsest, of which much evidence can be expected left in the underground. Taking a geophysical approach, by collecting and processing GPR data about the subsurface, supported by remote-sensing information and targeted excavations, this thesis aims to add to the story of Angkor.

The potential of GPR in archaeology lies in fast and precise data acquisition. GPR is a close-range non-invasive technique that targets the electromagnetic properties of the subsurface. It converts reflected radio signals of varying strength into a set of numerical data. After a number of processing steps an image of the subsurface is created. The resulting radargram is used for an assessment of anomalies, - i.e., signal changes that are derived from a disturbance in the ground composition. Displayed anomalies can be interpreted by their depth, size, reflection strength and form, and analysed how they correspond with human interference of the subsurface. The survey is strongly dependent on environmental attributes, e.g. ground composition and water content, which influence the signal and impact the quality of results.

Previously GPR was applied in Angkor only for very limited circumstances which targeted a specific problem and generally served as a secondary research method to aid further investigations. For this thesis surveys were conducted at a variety of places with potential archaeological subsurface remains of different characteristic. While the research was concentrated on the region of Greater Angkor, selective GPR surveys were done at other locations in northwest Cambodia to crosscheck the results. The survey technique is used as a primary research method showing, that GPR can be applied as a discrete research method at Angkor that produces independently interpretable results. This particular approach adds another mode of perception to Angkor by broadening the knowledge about its subsurface structure and pattern. There are generally two ways of applying GPR, as single profiles, displaying a vertical transect through the subsurface - and by combining and processing the data from parallel profiles in a grid to gain information of an area.

With the growing interest concerning Angkor over its history of research, different aspects of the archaeological site have been analysed with a diverse range of techniques. The immense size of Greater Angkor, the extensive region surrounding the monuments, has had an impact on any data acquisition. The use and organization of the once occupied space is a major issue. From traditional scholarly to modern technological, from fieldwork to laboratory use, from non- to invasive and from remote to close range sensing, the use of GPR as an investigative tool stands in a long tradition of research methods.

The mapping of the archaeological landscape has tremendously changed the perception of the "lost city" since the 19th century, the maps displaying predominantly what is visible on the surface. Most of the archaeological evidence stems from the monumental construction periods of the 9th to 13th century. In this Angkorian period the centre was relocated several times, older structures have disappeared under new constructions, or were reused for different purposes, creating a reworked cultural landscape better described as a palimpsest. The foundations of preceding structures are still detectable; their location can be revealed by GPR enabling further investigation by excavation.

Extensive GPR survey grids cover a number of areas to identify structural patterns mainly inside the large enclosures and in relation to visible monuments. Architectural plans provide information on the configuration of the monuments which at Angkor often include a geometric aspect. Remains of missing architectural elements can be identified by a GPR analysis in the direct surrounding of structures, displaying the original outline of the monument and complementing the base plans.

Evidence of the people who created the cultural landscape is sparse. Rice field patterns explain to some extent the once urbanized area; however earth mounds of varying dimensions have been understood as living grounds and as a retreat from the floods. The GPR is useful to detect remaining traces of the settlements and productions sites. The technique was tried at habitation patterns, production sites and cemeteries to work out its potential at this type of tropical environment.

Interpretation of larger areas is done in association with remote sensing data. The archaeological maps are useful for the development of a hypothesis and on target areas as well as for the analysis of results. The maps display a network consisting of hundreds of kilometres of linear earthworks and channels that cross the floodplain. Due to the strong seasonal variation of rainfall and groundwater, this water management network of canals and reservoirs played a particular role at Angkor, directing water from the hills in the northeast towards the centre and from there to the lake in the southwest. However, parts of the system have remained undetected under densely forested areas or due to reuse of the area.

Long GPR profiles were conducted to crossing the landscape at irregular intervals. The intent was to measure the elements of the network appraise the archaeological maps, and detect missing connections of potentially related earthworks. All profiles were searched for anomalies, classified and entered into a GIS data base, to link the GPR with the remote sensing data. By embedding the GPR into the GIS environment of the archaeological landscape, the 2-dimensional vertical radargrams complement the 2-dimensional horizontal map of the visible surface pattern into a 3-dimensional research environment. For two regions newly acquired high resolution radar images of the satellite TerraSAR-X complement the data for soil saturation, to assist in the detection and identification of channel features. The available GIS remotes sensing data sets served as additional source for the interpretation of the discovered anomalies.

The existence of inlets and outlets in the embankments of the giant reservoirs is part of the theory that the network had been used to regulate floodwater, and distributing water to the rice fields; maintenance and risk management strategy as proposed in the hydraulic city theory. GPR can search reservoir and canals embankments for buried infrastructure that could explain the flow of water into and out of the *baray*.

The results can be used to assess the established view on water management or may raise new questions concerning its function. The information gained from the collected data complements and enhances the archaeological maps of Angkor.

Significant References

The research was directly influenced by the research and publications of a number of people, whose work is regularly mentioned in the thesis. Victor Goloubew and George Trouvé initiated the systematic aerial mapping of Angkor's landscape and integrated the earthworks as a critical part of Angkor. Bernard-Philippe Groslier's innovative approach to see the network of earthworks as a "*cité hydraulique*," the successive development of an artificial landscape engineered to direct water, created a new understanding of Angkor. The discussion about the use of the reservoirs and canal system, initiated by Willem J. van Liere, has provided pivotal targets for the investigation. Elisabeth Moore and Anthony Freeman have shown the importance of SAR remote sensing as an additional technique to search for Angkorian temples. Christophe Pottier mapped the archaeological landscape in detail and classified earthen features as part of the water management system. His critical comments on the *baray* discussion were taken as reference points. The Greater Angkor Project (GAP) digitized the information and made it available to a wider research community. The mapping area was extended by Damian Evans to produce an archaeological GIS map of the Angkor floodplain, which in combination with JICA data and Google Earth served for orientation and choice of research areas. Roland Fletcher's low density settlement theory has influenced strongly the decision for survey areas and interpretation of results. For architectural understanding the publications of Jean Boisselier, Jacques Dumarçay & Pascal Royère were questioned. The publications of George Cœdès, Bruno Dagens, Claude Jacques and Michael Vickery were used as main references for construction and ruling dates. The development of GPR as a leading prospection method follows mainly the introduction to GPR by Lawrence Conyers. Yasushi Nishimura and Dean Goodman have shown the need and potential to integrate the geophysical surveys into the archaeology of Angkor.

Structure of the Thesis

The presentation of the research starts with an introduction of the 'object of research' (chapters 1 and 2), which is followed by a preparatory part on the geophysical approach (chapters 3 and 4). The survey results are first presented for areas that were investigated by the grid approach (starting in chapter 3, then chapters 5 and 6) and then by the 'profile-approach' (chapters 7 and 8), so moving from small areas to larger areas of surveys on Greater Angkor.

In **CHAPTER (1)** the object of research is described - geography, geology and climate of the Angkor region, focussing on what has significance for the GPR surveys. It gives an overview of the historic development and decline of Angkor. As main issues on Angkorian landscape archaeology that directed the research for this thesis are addressed: the outline of the centres, the debate on the water management network and the *baray*. In **CHAPTER (2)** the change in perception of Angkor as an archaeological site is discussed with the consecutive development and application of new research techniques. Starting with the impressions of the early explorers that found a “lost civilization,” it turns to the ensuing scholarly and institutional research whose investigations and descriptions have formed the current views on Angkor.

In **CHAPTER (3)** the methodological and technical aspects of this particular approach of Ground Penetrating Radar are introduced. The theory behind the method is discussed and its application within the unique environmental attributes of Angkor that influenced the survey results. The successive steps for processing and analysing the data are described. Limits and potential of the prospection method are tested on a variety of archaeological sample sites. In **CHAPTER (4)** is explained how the GPR data is integrated into a GIS environment, where it can be further analysed by using and appraising remote sensing data. The technical aspects of the new acquired high resolution TerraSAR-X images are described. The importance of the available archaeological and topographic maps for choice of survey areas and interpretation of 2-dimensional anomalies are pointed out, of which potential components of the network are classified.

In **CHAPTER (5)** the focus lies on the search for masonry structural remains in the vicinity of known monuments. Predominantly the 3-dimensional gridding technique is used to map subsurface elements of temple areas. The GPR discovery and the confirming excavation of the tower bases at Gopura 4 West of Angkor Wat is described, the collected data interpreted to integrate the towers into the construction history of the site. In **CHAPTER (6)** the aspect of large area coverage is extended to the subsurface of enclosures for masonry remains. One part covers the search for masonry causeways in alignment with temple axes. Enclosures in the periphery are represented by the hilltop temple of Chau Srei Vibol, the mounds of Banteay Sra, and one of the *asrama*, Prasat Komnap. A variety of masonry remains were detected that provide additional information on the use of those enclosures.

CHAPTER (7) deals with the giant reservoirs and their water management infrastructure. The 2-dimensional GPR landscape survey is introduced which was run over embankments of all four *baray* at Angkor. Inlets and outlets as well as additional surveys on other reservoirs are described and possible functions of the *baray* discussed. **CHAPTER (8)** covers the largest scale of research, the network of canals and embankments. By combining the GPR data set with the high resolution TerraSAR-X and other remote sensing data, the mapped canal network is appraised. The recorded anomalies are tried to distinguish between artificial channels and natural streams, all leading to considerations on the functioning of the network.

FIG. [2]: MAIN GPR-SURVEY SITES AND THEIR FOREMOST APPEARANCE IN CHAPTERS (IMAGE: LANDSAT7/NASA).

Since this is not an epigraphic study, the Sanskrit and Khmer names mentioned in the thesis have been simplified using an accepted common spelling without the use of diacritics (e.g. *asrama*, Yasodharapura, Yasovarman). Concerning modern location names the most common writing is used (e. g. Tonle Sap or Óc Eo).

CHAPTER (1) THE ANGKOR REGION

Of course the first thing to do was to make a grand survey of the country she was going to travel through. 'It's something very like learning geography, 'thought Alice, as she stood on tiptoe in hopes of being able to see a little further. (LG, III)

The landscape of Angkor is a floodplain bounded to the north by the Kulen and Khror Hills and to the south by the Tonle Sap Lake. The subtropical climate has a distinctive and particular effect on local ecology, as large portions of the region are flooded part of the year due to the seasonal monsoon.

The first section of this chapter deals with the regional geology, as well as the weather and climate phenomena which influenced the development of settlement on the northern shore of the Tonle Sap, and facilitated the rise of Angkor from the 9th century onwards. While in the following 500 years the Khmer Empire expanded its rule over large parts of Southeast Asia, the political centre of Angkor was relocated repeatedly within the Greater Angkor urban complex between 700 and 1200 CE/AD, - initiating several major construction periods that urbanized large areas of the landscape. The main construction material for the religious monuments - sand, sandstone and laterite - was obtained locally or quarried in the nearby hills. The regional topography provided the base for the development of a sophisticated water management system. While there remain questions concerning the functioning of this network and its giant reservoirs, its breakdown has been regarded as a potential cause of the demise of Greater Angkor.

(a) THE LANDSCAPE - PHYSICAL GEOGRAPHY

Principal rivers - there are none. Principal mountains - I'm on the only one, but I don't think it's got any name. (LG, III)

Geological research in Cambodia started in the end of the 19th century. The first geological map was published in 1882 by E. Fuchs and Saladin,[5] and the "*Service Géologique de l'Indochine established by the French colonial administration in 1898.*"[6] Because of rising interest in natural resources in Southeast Asia and the potential for exploration, large geological campaigns were carried out in the mid 20th century[7] by the officials of the French protectorate and later by independent Cambodia. Those regional geological surveys provided an overview of the geological formations and the mineral resources in Cambodia and still are the base of our knowledge.[8] In the 1990s the return of the research community to Angkor pushed geological and soil studies and provided for an assessment the state of the ruins to prevent further decay. Discussion ranged from the regional geology to soil properties and their influence on the development of Angkor. Recently the influence of the climate has received a great deal of attention.[9]

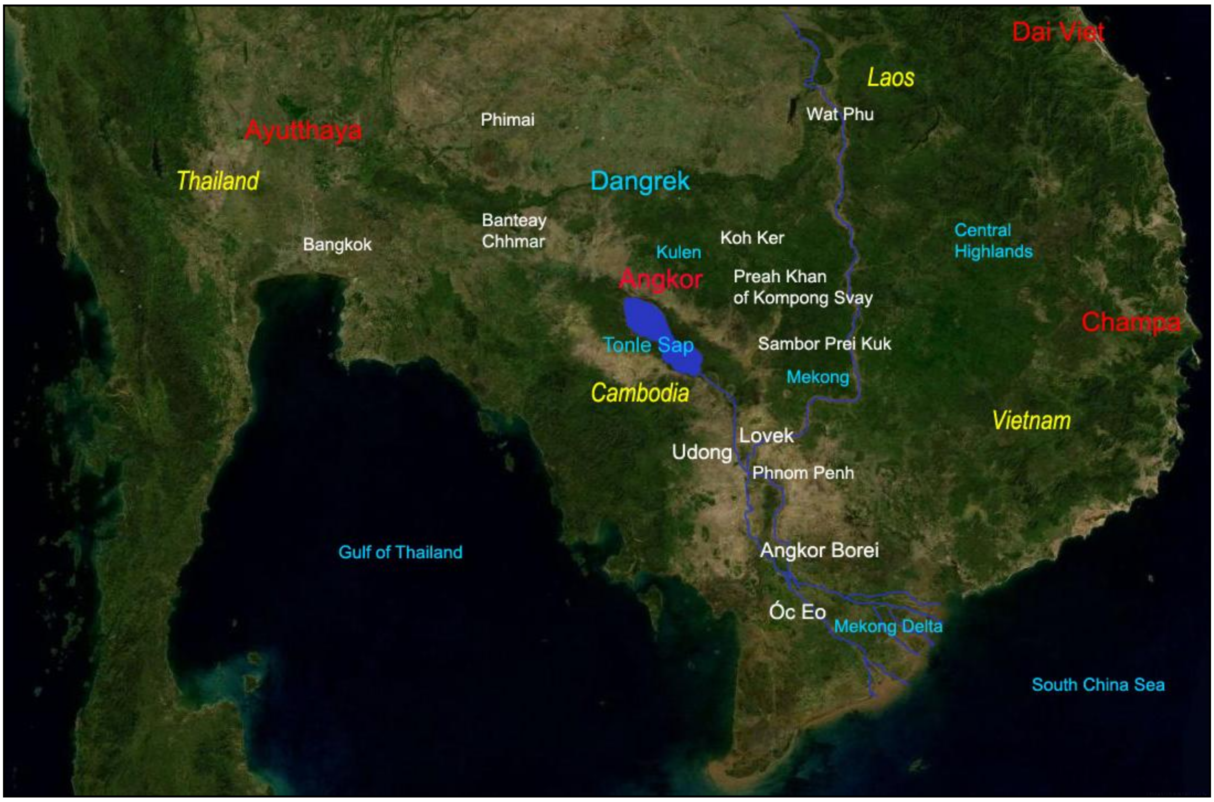


FIG. [3]: SATELLITE OVERVIEW OF MAINLAND SOUTH-EAST ASIA AND MENTIONED LOCATIONS (IMAGE: NASA).

The Angkor region is a plain of approximately 2500km^2 delimited by two natural boundaries that greatly influenced the settlement in the region: the mountain ranges in the northeast and the lake to the south. The Angkor plain opens out to the west in the direction of Sisophon, to the east there is a gap between the foothills of the Kulen and the lake. The plain slopes gently from the base of the northern hills at about 40m above sea level in direction southeast towards the Tonle Sap. The location of the shoreline is dependent on seasonal changes as the water level ranges between 6m above sea level - and 16m during the monsoon. The gentle slope has an inclination of approximately 1/1000.[10] It includes several hills - large rock outcrops of volcanic origin - which in the Khmer language are called *phnom*, meaning mountain or hill.

i. ROCKS AND SOIL

The Kulen - Sandstone and Laterite

The Kulen massif (in Khmer: Phnom Kulen) to the northeast of the Angkor plain forms a plateau that is nearly 50km long and varies between 2km and 12km in width, see Fig. [4]. The larger north-eastern part, which includes the highest elevation of the area at 487m above sea level, is separated by a gap from another plateau, the Khror hills to the west. The Kulen is the remnant of a sedimentary sandstone formation, formed in the Middle Jurassic to Early Cretaceous.[11] The formation extends up to the Dangrek Mountain Range in the north and is part of the sub-horizontal tablelands that include the Khorat Plateau[12] at the Thai border and the Phnom Tbaeng east of Koh Ker.

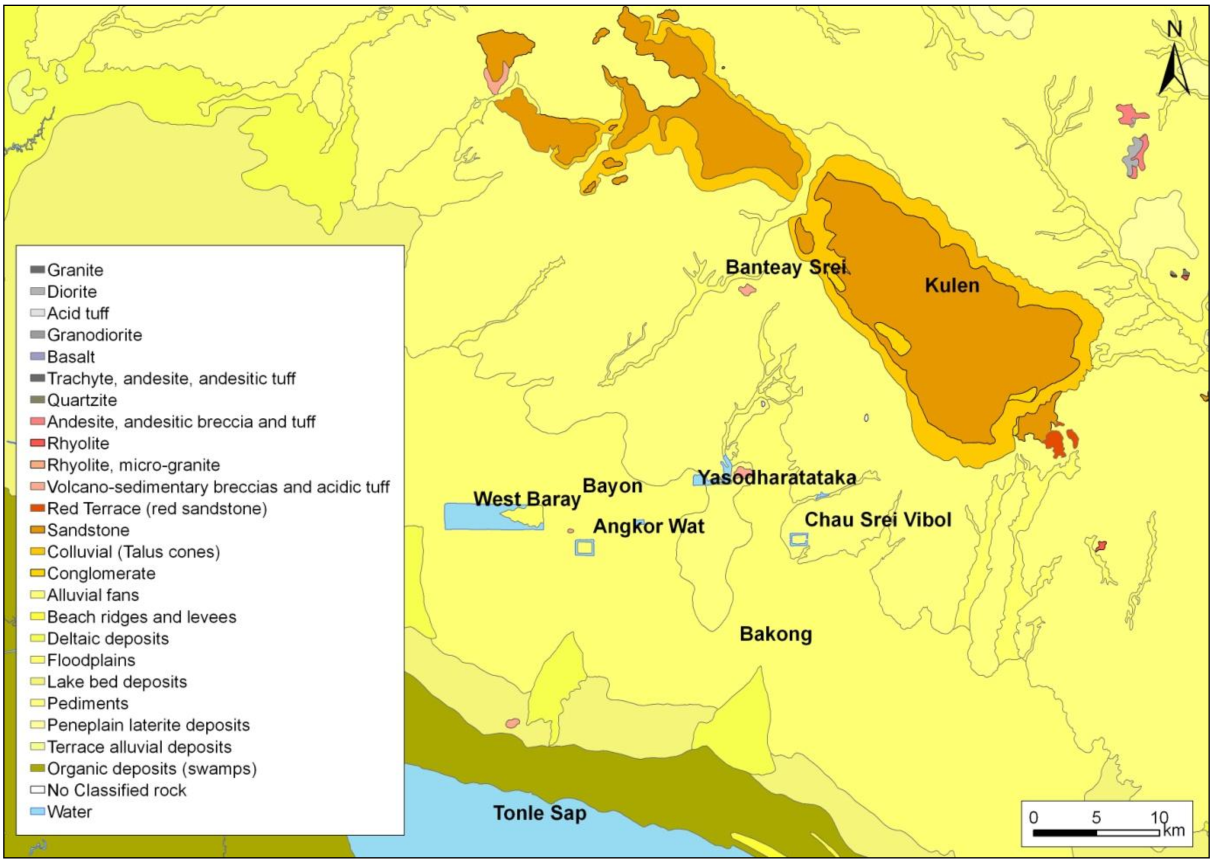


FIG. [4]: GEOLOGICAL MAP OF THE ANGKOR AREA (SOURCE: JICA, 2003).

Those *mesas* mount over the western plain of Cambodia due to an uplift of the region in the Paleogene (65-23 Mio years BP) and have since then undergone severe erosion.[13] Sandstone of a Lower-Middle Jurassic formation crops out on the southern foothills of the Phnom Kulen, 50km to the east of Angkor, just northwest of the Angkorian temple of Beng Mealea. The region is regarded as the main source for temple construction material in the Angkor region; the widely spread remnants of medieval quarries are evidence of multiple episodes of stone quarrying.[14] The sandstone was used to carve the decorative façades of the monuments. Generally the different types of sandstones in the region, were simply divided into pink sandstone,[15] a harder type of sandstone identified as greywacke,[16] and grey sandstone. Those sedimentary rocks were used in the construction of all major temples.[17] Several studies have shown the elements and attributes of the different sandstones used,[18] and it is intended to relate material used in the individual buildings to the source quarries.[19]

Another important building material in Khmer temples was laterite, a type of sediment that was early recognized as very abundant in tropical climate.[20] At Angkor laterite is the product of eroded conglomerate deposits of aluminium and iron rich sediments.[21] The intense weathering processes in the tropics and seasonal groundwater changes affect surface soils up to a depth of several meters which dissolve constituent minerals such as *kaolinite*[22] to leave a matrix of insoluble material,[23] forming a cellular, slag-like structure of iron concretions, clay and other aluminium compounds.[24] The red colour, resulting from the corroded iron, the structure of the sediment, inspired, the Khmer name for the laterite: "*bai kriem (broiled rice)*."[25] The rough surface and the difficulty of carving the laterite made it best suited as a supporting material.

While used in large quantities it was primarily reserved for the structural parts of the monuments such as foundations, platforms or inner walls that were hidden in the interior behind a face of sandstone. Laterite has an advantage over sandstone as a construction material because it is easier to quarry. It is "*softer in its normal position in the soil than when exposed at the surface of the ground. Laterite quarried from a depth below the level of the plains must have been rather soft; and it must have been quarried only in the dry season.*"[26] This attribute, the hardening of the rock following its extraction, and its use as a construction material was described by Scotsman F. Buchanan in 1807, suggesting the name "*laterite*" from the Latin word *later* for brick.[27]

Initially it was believed that the laterite was quarried from the ponds and reservoirs adjacent to the monuments.[28] This might have been the case for temples in other areas, but not in the Angkor plain where cores from the basin have shown that *"no laterite was found in the boreholes made below the ancient buildings."*[29] A drill core from the Angkor area displayed to a depth of 80m only sand and clay deposits, and no signs of laterite.[30] The laterite used for construction must have come from the eastern part of the plain from quarries that are close to the Phnom Kulen. Jacques Dumarçay mentioned that a "*large quarry was discovered near the temple of Banteay Srei of which the working face measured about 3 kilometers."*[31] Recent petrologic studies have shown, that, while the constituent minerals of the laterite that was used in the construction of the monuments were the same for most sites, the mineral proportion varied, indicating that they came from different quarries.[32]

The Angkor Plain – Sand, Clay and Andesite

Sandstone and laterite had to be brought in from further away, because in the centre of the Angkor plain, similar to other regions in Cambodia, the original sandstone formation had "been completely eroded forming vast gently undulating plains."[33] The plain starting at the foot of the Kulen Hills was an example of a colluvial-alluvial[34] floodplain, a landform that resulted "*from erosion of the surrounding hills and mountains and the movement of the eroded material to the lowlands, initially forming a fan.*"[35] The sedimentation of the eroded sandstone from the Kulen created a quaternary alluvial floodplain which covered the complete Angkor basin with sand and clay deposits of several tens of meters in depth. Closer to the lake the sediments are lacustrine.[36]

While there seems to be an overall agreement on the geology of the Phnom Kulen, several authors give contradictory information about the geological formations of the Angkor Basin. R. Acker describes the surface deposit as "*very nutrient-poor, very permeable sandy soil*"[37] Heng Thung describes the formations below Angkor: "*The sand and clays lie on top of a thin layer of mudstone, which lies unconformable over bedrock, initially identified as rhyolite, eighty metres below.*"[38] The original source or location where the coring took place is not mentioned. A drill core conducted in 1994 and interpreted within the *Bayon Master Plan*[39] supported those results and provided until now the most complete information regarding the near surface geology in the Angkor Park. For the first 16m Holocene (12000BP until now) deposits dominate, alternating gravel, sand and clay. Between 16m and 40m depth, a strong quaternary formation was identified mainly consisting of sandy clay and sand overlying tertiary sediments of sand and sandy clay.[40] There is a contradicting terminology used for the Tertiary formation called "volcanic sandstone" between 40m and 82.5m. At 82.5 meters depth, the corer encountered the sandstone bedrock. Summarizing those results, the soil is alternating “*mainly fine sand and salty clay layers in yellow brown color.*”[41] The results rule out any implications that laterite quarries existed close to the central temples.

The solitary hills Phnom Bok, Phnom Dei, Phnom Bakheng and Phnom Krom that are scattered over the floodplain were displayed in geological maps by *DanIDA* as some type of *andesite*[42] that occur as volcanic outcrops. This is partly in agreement with the geology GIS layer of JICA 2003, which label them as volcano-sedimentary breccias and acidic tuff from the Jurassic-Cretaceous, speaking for localized volcanic activity in the region over a longer period of time. In Cambodia stones from those hills are used as a minor supportive filling material for the foundation trenches in the temple construction and are incorrectly referred to as “Phnom Krom *rhyolite.*”[43] According to JICA the only *rhyolite*[44] on the surface in the region exists in patches on the western foothills of Phnom Kulen,[45] therefore if the geologic maps are correct, the term *andesite* should be used for the filling material.

So it seems that for their construction the Khmer used all four main deposited materials that were available in the vicinity of Angkor, the main stone materials though were not directly available in the plain: while the foundation material sand and clay came directly from the construction sites in the alluvial plain and the andesite was available from the volcanic outcrops, sandstone and laterite had to be brought in from or from close to the Kulen Hills.

Discrepancies in the Description of the Geology

Along the foothills both to the west and east of Angkor and best detectable to the northeast of Phnom Bok are circular pond-like features that are connected by streams coming from the hills. It has been debated whether they were natural or human made. Engelhard referred to them as “*some ancient limestone deposits, which are characterized by sinkholes visible on the satellite imagery northeast of the Angkor complex.*”[46] Limestone as a cause however is unlikely, as the only occurrence of limestone in the UN report is given for Battambang province far to the west, and no other publication or geological map indicates limestone near the Kulen. Considering the size and quantity of the ponds in a historically sparsely populated region[47] they are probably natural. The circular features, which are not very deep and filled with water only in the wet season,[48] relate rather to a slow running stream that carved a number of ponds out of the alluvial plains.[49] This area could be important as it possibly represents one of the few undisturbed areas of the Angkor floodplain and could usefully be a topic of further investigation. Studying it could improve the understanding about the original landscape of the region.

Although no arguments are given for any tectonic movement in recent history, the UN report names the Mae Ping Fault Zone as crossing Cambodia east to west that would have tectonically affected the area north of Tonle Sap, perhaps generating the andesite outcrops at some but probably not recent time. “*Since the Mid-Late Quaternary major tectonic movements have been absent.*”[50] The reference to a fault could have been the reason though, that geologist Heng Thung suggests a geologic uplift[51] to explain the deep entrenching of the modern rivers in the Angkor basin during and after the time of the Khmer empire, yet the temples do not appear to show the effects of earthquakes. There is though a more obvious reason however for the entrenching of the river, related directly to human interaction when the rivers were redirected and channelled which increased the flow velocity and the erosion of the sandy soil.

ii. FLOODPLAIN AND CLIMATE

Rivers and Streams

Several streams originate from the Phnom Kulen and cross the Angkor basin. In Angkorian times, part of the rivers' water was directed from their original beds through artificial canals to the south into large reservoirs.[52] The diversions were mapped in aerial surveys by archaeologist B.P. Groslier who sketched a map of the probable course of the original rivers.[53] Groslier noticed that the Puok River had been split at Bam Penh Reach[54] and part of the water followed the artificial bed of the Siem Reap River running into Angkor's centre and through the modern province's capital of the same name. The other part of the Puok River continued to run from Bam Penh Reach towards the west, passing the the village with the same name. Another off take was at the North Canal, from where water was directed towards Angkor Thom.[55] The Roluos River appears to be running in its original bed until it reaches the centre of Hariharalaya to the east of Angkor. The original rivers would have followed the natural slope of the basin, predominantly northeast to southwest to flow into the Tonle Sap. Recently A. Traviglia has shown that paleochannels cross the Angkor plain.[56] It is not known when those river beds formed or if they were flowing during the Angkor period. Some are traceable running through or by the centres of Angkor and could have influenced the decision to settle at those spots. Others possibly ceased to run before the development of Angkor, as they show little correlation to the location of the historical centres.

Regional Weather and Climate

The subtropical climate of Cambodia and its strong seasonal differences heavily influenced the formation of the landscape. The Angkor Region has a comparatively dry tropical climate with an annual rainfall of approximately 1370mm/year for the years 1950-2000 and 1425mm in the years 1980-2000.[57] The monsoon brings 88% of precipitation during the wet season months, with irregular heavy storms and strong rainfall lasting from April to October. The streams from the Kulen swell and leave their beds, resulting in flooding of most of the Angkor plain.[58] This leads to a strongly fluctuating ground water table. At the end of the rainy season this was measured at about one meter in JSA drill cores, at the end of the dry season just below five meters.[59] The climate contributes to the unique features of the Tonle Sap, and is a major factor in the development and demise of Angkor, as recent studies suggest.[60] As streams of the Angkor basin depend on regular rainfall, it should be mentioned, that, due to climate changes and El Niño events, there were irregularities over periods of time. Analysis of tree ring records from the Vietnam highlands indicated that severe droughts interspersed with strong monsoons resulting in heavy flooding affected the region in the 14th-15th century.[61]

The Great Lake

The 120km long Tonle Sap ("Great Lake" in Khmer) is the largest lake in the Indochina Peninsula.[62] From cores in the northern part of the lake, the historic coverage and time of existence of Tonle Sap has been estimated. The resulting data reveals that it was disconnected from the Mekong about 18,000 years ago.[63] When the lake reconnected to the Mekong about 5500 BP,[64] the sedimentation rate dropped to about 0.1 mm/year and has not changed since. Penny et al determined a sedimentation "*average long-term rate of less than 1 mm / year.*"[65] These facts led to the conclusion that "*presumably the lake of today is little different from that of* *the 9th to 13th century."*[66] The sandy surface sediments derive "*only from the alluvial plain around the lake, and no sandy sediments from the Mekong River via the Tonlé Sap River [reach] the northern part of the lake even during flooding periods in the beginning of the rainy seasons.*"[67]

In the wet season the strong south-eastern monsoon wind produces a surge that pushes up the Mekong delta. The flooded channels of the river prevent the water from escaping into the sea. At Phnom Penh, where the Mekong is already close to sea level, the slow running water of the river is forced into the Tonle Sap River. This transports fresh water and nutrition from the Mekong to the Tonle Sap, thereby fertilizing the lake. This natural phenomenon of a biannual change in flow direction exchanges more than 80% of the lake's water every year.[68] The width of the lake increases in the wet season in north south direction from about 10km to nearly 50km, flooding an area of over 7000km². Its water level rises by seven to ten metres.[69] With the beginning of the dry season in November the flow direction changes again and the water escapes through Stung Tonle Sap into the Mekong and from there into the South-China Sea. White & Oberthur use this unique situation to explain the complex soil pattern of the upper deposition in the vicinity of the lake.[70] While the sediments further away are of alternating coarse-textured material deposited by the rivers from the mountains, closer to the lake they are succeeded by fine material as deposit from the extended lake shore.[71] They conclude that "*such floodplains are generally featureless with fine-textured sediments*."[72]

(b) URBAN DEVELOPMENT

> *'Then you keep moving round, I suppose?' said Alice. 'Exactly so,' said the Hatter: 'as things get used up.' (AW, VII)*

The development and demise of Angkor from the 9th to the 16th century included successive relocations of its political centre. Each move boosted the construction of new monuments. The geographical transfer of power in the pre-Angkorian and Angkorian period had varying reasons. In irregular intervals empty space was occupied, transformed and later left for new territory. This had been a practice in Cambodian history starting with earliest formation of city states in the Mekong delta, long before the rise of Angkor, and continued after the collapse of the empire and the move of the political elite to the Mekong. The relocation of centres at Angkor however differed from their predecessors of Funan and Chenla in the first millennium. The Khmer Empire was predominantly a single state with an effectively permanent capital at Angkor within which the political centre was moved. The successive state temples stand out in size as well as their proximity to each other, as the new state temples were consecutively built closer to what ultimately was the centre of Greater Angkor. From their capital the Khmer began to dominate large parts of continental Southeast Asia; at its greatest extent the area of influence far exceeded the borders of modern Cambodia. Angkor was rivalled to the east by Champa, at a later stage to the west by Ayutthaya, and after the defeat of the Cham by the Dai Viet.

i. THE PRE-ANGKORIAN PERIOD

Knowledge about the development of this part of Southeast Asia has thrived since George Cœdès translated pre-Angkorian inscriptions in the early 20th century. Several comprehensive summaries cover in detail the pre-Angkorian time period, highlighting the research field from different angles, e. g. epigraphy, archaeology and anthropology.[73]

Early Development and Funan

Bernard-Philippe Groslier regarded the early prehistoric societies of continental Southeast Asia as "*food-gatherers, rather than permanent farmers.*"[74] In his account they preferred living in the mountains rather than the "*swampy deltas or flooded alluviums, which could not be cultivated without extensive drainage or water-control system.*"[75] More recently Charles Higham classified hunter-gatherer societies into inland and coastal dwellers; knowledge about inland occupation is almost exclusively based on remains found in rock shelters that involved "*only brief periods of occupancy*"[76] while permanent occupation developed in the coastal regions.[77]

Settlements in the Mekong delta thrived from 300 BC to at least AD 300 as hubs for the southern silk route,[78] international maritime trade that linked the Han Chinese Empire with India and even Rome, as evidence excavated at Óc Eo has shown.[79] Chinese documents are the only historic sources that describe the coastal region of continental Southeast Asia at a time[80] when the Vietnamese coast, "*offered safe harbours and fresh water for trading ships.*"[81] The large walled settlements in the Mekong delta, most prominently Óc Eo and later Angkor Borei,[82] were part of a group of individual and competing chiefdoms[83] or city states[84] collectively named by Chinese sources as Funan, which Higham, regarding to archaeological finds, classified as *"in the transition to statehood."*[85] Chinese sources describe that *"the ruler of Funan, during the third century, expanded its power towards the Malay Peninsula, bringing most of the east coast city-states into its sphere of influence."*[86] The Chinese were especially interested in the harbours that provided safe shipping for the trade goods from India and Western Asia.[87] *"Funan soon grew into the privileged partner of the Chinese in Southeast Asia and remained so until the fourth or fifth century."*[88]

The demise of Funan occurred in the same time period as the rise of the Tang Dynasty in China, a stable period for Asia that secured the *Silk Road* and provided safer travel through Central Asia.[89] Vickery argues that the demise of the port towns could be seen in relation to the improving seaworthiness of Chinese junks,[90] which allowed the merchants to use new trade routes over the Philippines and the Indonesian islands,[91] and therefore circumnavigated the Southeast Asian peninsula. Without the merchant ships, the Funan settlements lost the connection to the maritime trade. Miksic argues that the all-sea route *"already existed at the beginning of the fourth century,"*[92] and gives a number of arguments, economic, religious, and climatic, that have been named for the decline of the coastal cities. He proposes the possibility of *"more internal than external"*[93] influences that led to the demise of Funan, but regards it unanswerable with the presently available data.[94]

Chenla

In the mid 6th century new political and religious centres formed further up the Mekong and in fertile areas north of the Tonle Sap, in Chinese source referred to as Chenla.[95] Whether Funan was overpowered by Chenla, as initially proposed by Cœdès,[96] or developed in the tradition of the coastal state, as more recently suggested by Vickery,[97] has not been answered. Over some time a coastal and interior centre, in Chinese sources named Sea-Chenla (the old Funan), and Land-Chenla, might have coexisted, but Óc Eo was probably abandoned in the mid 7th century.[98]

Similar to Funan, Vickery describes the beginning of Chenla as loosely connected, decentralized and rivalling chiefdoms of comparable strength.[99] The move of authority from the coast to inland might have had, at least partly, some economic reasons.[100] The new centres were closer to the trade route between the Cham settlements and Thailand. An important centre in this period was Wat Phu in the second half of the 6th century,[101] however the location of the early capitals of Chenla are disputed.[102] Vickery argues they may have been within the borders of modern Cambodia.[103] Over the next few centuries the region went through a cultural transformation, in which several chiefdoms were unified paving the road to a centralized state. Under King Isanavarman the city *Isanapura,* associated with Sambor Prei Kuk, was capital from around AD 616,[104] while about two decades later Jayavarman I moved the royal court to *Vyadhapura* or *Indrapura*, that M. Vickery relates to Banteay Prei Nokor further south.[105] Reasons for the successive relocation of political centres in the Chenla period are not explicitly described but show the pre-Angkorian tradition of shifting centres with succeeding rulers. Nevertheless the settlements still existed and retained local importance when the power had moved to Angkor.[106]

In the Angkor Region

While the coastal region was thriving, the Angkor floodplain became the cradle for settlements in the region. To Groslier the region was initially not the perfect spot for development. From excavations in the 1950s that provided sequenced stratigraphic pollen data, he concluded, that before urbanization "*[…] the Angkor country side was mostly swamp-land with flooded forests.*"[107] Regarding the difficult natural environment, he asked "*[…] why these gigantic temples of Angkor were built in what was not very fertile country, indeed in the worst part of an area that was not very fertile.*"[108] However, the annual water exchange makes the Tonle Sap one of the most productive inland fishery areas on earth. The predictable flooding also supported the development of early rice agriculture near the lake shore and so invited human occupation. The first settlements had formed next to the lake or in the upper regions next to streams. The "*fertile soils [were] exploited for receding rice, which is planted as soon as the soils [were] dry enough for cultivation after the retreat of the water.*"[109] Groslier concluded that the reason for the prosperity of the population was based on the regional climate once the seasonal flooding was tamed. The lake has the least horizontal fluctuation in the Siem Reap area and the shoreline here is a bit higher than in other areas, which prevents flooding,[110] and Groslier emphasized that by then floating rice had been the dominant agricultural food source.[111] The coastal area is also sloping more steeply to the lake and the water will not recede for kilometres in the dry season, providing access to the water and fishing all year round.

C^{14} dates from archaeological excavation provide evidence that the region had been occupied over periods of time at least since the Bronze Age.[112] Earliest occupants would have mainly used the conditions as they were given, starting to build raised mounds as a safe retreat from the annual inundation. Engelhard states that "*early human settlements were often located on ecotones,*"[113] as environmental transition zones are called.[114] "*This is especially true for cultures, like that of Angkor, where both agriculture and gathering/ hunting / fishing were important in the subsistence base.*"[115] Excavations conducted on pre-Angkorian settlements near the West Baray,[116] to the north of the Phnom Bakheng and earthen mounds south of the Bakong temple[117] showed long-term occupation. All early settlements were close to the boundary of the Tonle Sap flooding zone,[118] as well as in vicinity of a stream.[119] Besides evidence of prehistoric settlements in the region,[120] centres developed in the region within the Chenla period (AD 550-~700).[121]

Dominating the largest pre-Angkorian centre, of which several temples are evidence, such as Prei Kmeng or Vat Khnat,[122] was the pyramid of Ak Yum, almost certainly the earliest monumental structure in the Siem Reap basin and dated to the second half of the 7th century (AD 670).[123] The monument was later covered by the south embankment of the West Baray. Since its rediscovery in 1932[124] and partial excavation by George Trouvé of the EFEO,[125] this was reason for discussion[126] of its importance and period of use. An inscription discovered in the temple which dated to the beginning of the 11th century[127] indicated that Ak Yum was of importance and part of Angkor over long period of time. While the lower terraces disappeared under the embankment, the uppermost platform might even have been in use for a while within the existence of the *baray*, which is believed to have been constructed in the early 11th century.[128]

What is under discussion is the question whether Angkor really could count as a direct successor state of Chenla. Vickery suggests that the absence of dated inscriptions from the end of the 8th to the end of the 9th century and the change in vocabulary with the beginning of the Angkor period imply a turbulent time and noticeably separate Chenla and Angkor.[129] The adoption of the *devaraja* rite as a state religion supporting the instalment of a powerful ruler has been regarded as a reason for the flourishing of Angkor.[130] Based on legends Jayavarman II ascended the throne and declared himself *chakravartim maharadjadhiraja* (Great Prince over Princes) in AD 802. While the actual location and the process of taking power, as well as the often mentioned liberation from Java is closer to mythology than history,[131] the approximate time of inauguration of the first “supreme king of the great kings” certainly marked the initiation of the 500 year regional dominance of the Angkorian Empire. The vast construction process of the same architectural style of monuments on the Phnom Kulen is evidence of a royal presence on the mountain range around this time.

Concerning Indianization

Groslier called Funan the *“first large Indianized state between the golf of Siam and the Mekong.”*[132] He asserted that the Indianization of Southeast Asia, including the spread of Hindu and Buddhist traditions as well as economic and technological development without the use of fire or sword. The changing monsoon winds meant according to Groslier, that Indian merchants had to stay onshore for some time before heading back to India, which would tend to lead to a “*permanent installation*”[133] in Southeast Asia. “*It is therefore likely that the settlers recreated ‘cells’ of Indian life, wherever they established themselves, exactly according to the pattern of their original homes.*”[134] How Indianization occurred is however under discussion. According to Manguin, Indian pottery at the river town of Óc Eo was found in a level dated to AD50-250, but *“artefacts from across the bay of Bengal [...] do not demonstrate any Indianization of Funanese society at this time.”*[135] Between the 3rd and 5th centuries, Sanskrit writing and the Hindu names mentioned in Chinese sources, as well as roof tiles of foreign technique that indicate early Hindu and Buddhist temples, bear witness to the rising Indian influence at the time.[136] One of the few dated inscriptions states that in AD514 a king bearing the Hindu name Rudravarman, inaugurated his capital further upriver from Óc Eo.[137] Manguin proposes that the influence of India and China for the development of the region needs to be reconsidered, as “*local factors that provided Southeast Asia with its cultural, economic and political autonomy and dynamics,”*[138] had been overlooked by earlier scholars. One example is the network of canals,[139] most prominently the large canal that connected Óc Eo with Angkor Borei, another settlement to the north.[140] The network is evidence for a sophisticated water management in an advanced proto-urban environment on the fertile alluvial banks of the lower Mekong. Considering the pre-existing water culture on the Indian subcontinent, Groslier believed in the adoption of the water management from there.[141] This has been doubted, since the Indian and Sri Lankan water management is considerably different from what developed in Southeast Asia.[142] Concerning Angkor, Groslier argued that the strong cultural influence of India had already ceased at the time Angkor developed. While *"from a certain time onwards, they no longer had direct contact with the 'mother-country',"*[143] the Indian culture had been absorbed to a level of complete identification, "*at least by the time of Angkor, from the IXth century onwards – was entirely assimilated after centuries of Fou-nan, then Tschen-la culture*"[144] and Groslier pointed out that it is "*pointless if not misleading, to speak of Indian "colonies", even of Indian "culture" in Cambodia during the classical period,*"[145] with which he referred to the pre-Angkorian (7th-8th century) and Angkorian period (9th-14th century).[146]

ii. The Angkorian Period

'I want a new cup,' interrupted the hatter, 'let's all move one place on.' (AW, VII)

Hariharalaya

The Angkor plain already had two regional centres before a new royal court was established in the region in the early ninth century. Besides Ak Yum, which almost certainly was still occupied at that time, the detection and dating of agricultural plants from drill cores of the Bakong temple moat[147] implies an earlier construction than the proclaimed inauguration dates of the ninth century suggest. Results from excavations conducted by EFEO at Trapeang Phong[148] and several other earthen mounds about three kilometres south of Bakong temple have revealed early occupation that presuppose the existence of an additional ritual centre. In the wet season Trapeang Phong could however only be reached over earthen embankments and became probably too small for the growing population.[149] When Indravarman I (reigning 877-886/889)[150] settled at Hariharalaya, he initiated the construction of the major monuments in the Roluos region. Groslier commented the drastic change from its predecessors and the importance of its development:

> *"Before Indravarman, a Khmer city was only a small urban nucleus of temples, palaces and habitation of the elite. Around it inhabitants farmed the soil in an empirical way, or rather cultivated it only according to the rhythm of natural factors, depending upon actual levelling rains or periodic floods to fill rice fields. Pre-Angkor Cambodia was but the juxtaposition of small groups in geographical units, living in accordance with the natural capacity of these units. In complete contrast with this "natural" structure, Angkorian Cambodia appears as a systematic and artificial organization of the whole available space, favourable or not, made cultivable by a huge hydraulic network, and farmed to the limits of its capacity."*[151]

Bakong, Preah Ko, Prei Monti and the first large reservoir Indratataka, made Hariharalaya the first true Angkorian capital, see Fig. [5]. The centre's proximity to the Tonle Sap provided all year access to rich fishing grounds due to a steeper shore in this region,[152] the seasonally flooded areas in the surrounding were the base for rice farming. Indravarman I's son Yasovarman however, only built Lolei temple close to the centre of the reservoir and moved the court to the northwest.[153] From this point in time the site of Roluos received no new constructions for several centuries. There is information about its occupation from stratigraphical pollen data in the moat of the Bakong. Penny et al. have shown that the amount of pollen related to urban use dropped significantly after the capital moved to the Bakheng, and stayed low until it rose shortly in the 12th century,[154] when, according to Jacques & Freeman, the Bakong underwent reconstruction.[155]

FIG. [5]: SATELLITE OVERVIEW OF THE ANGKOR REGION (IMAGE: NASA/LANDSAT7).

Yasodharapura

Between the 9th and 13th century the Angkorian rulers built their centres in the Angkor plain, successively constructing more monuments, always greater in size and splendour within the urban complex of Grater Angkor. Inscriptions reveal various reasons from power struggles that involved changes in the dynasty, a change in the state religion and conflicts with other regional powers that had influence on their decisions. The period of successive constructions in the centre of Angkor is here only briefly described.[156]

Phnom Bakheng Centre

While the move to create Yasodharapura and integrate Ak Yum and Hariharalaya as outliers seemed to have happened because of a major power struggle,[157] the choice of Phnom Bakheng as the centre of the new capital[158] might have had several reasons. First it was a natural hill, approximately halfway between Ak Yum and Hariharalaya, serving as the base for the new "mountain temple", an architectural style that had commenced with the Bakong and was to become a symbol of Khmer religion and statehood. Groslier considered that at the initial construction of Yasodharapura the earlier settlements[159] were still in use. To be the Hindu representation of the mythological Mount Meru as centre of the universe, the hill was artificially shaped and its top was covered with a temple pyramid.[160] The outline of the enclosure was marked by a rectangular moat of 650m length and about 440m width at the base of the hill. The new capital may have been connected to the two preceding centres by larges dykes. A causeway from Ak Yum supposedly led towards the east, later raised further as the southern embankment of the West Baray. Remains of this feature are visible in the area between the West Baray and Angkor Thom. Additionally, the Yasodharatataka, a giant reservoir was built to the northeast. With its construction, the water network of Yasodharapura exceeded the one of the old centre and connected the two, since the Roluos River served both as a water source. An inscription mentions that Yasovarman I founded a total of 100 *asrama,*[161] monasteries of different deities all over his kingdom, of which four were built south of this *baray*. A large causeway led from the Indratataka towards northwest, connecting the old and new centre. It meets the eastern causeway of Phnom Bakheng at an angle, while its virtual extension meets the crossing point of the north axis from Phnom Bakheng and the continuation of the southern embankment of the Yasodharatataka. Because it lies in the area where later the royal palace was constructed, this has kindled discussion about whether this causeway had continued straight to the northwest, perhaps indicating the importance of this area prior to the construction of the Royal Palace.[162]

Koh Ker Settlement

In the 10th century large constructions, including a large reservoir, commenced at *Lingapura*, a regional centre about 100km to the northwest of Angkor under Jayavarman IV, a descendent of Yasovarman. The region, today known as Koh Ker,[163] became the residence of this king in the year AD928 and at least part of the elite society from Angkor was moved to Koh Ker.[164] After Jayavarman IV's death in AD941 his son moved the royal court back to Angkor. An inscription, translated by Cœdès, says: Rajendravarman "*restored the sacred city of Yasodharapuri which had been abandoned for a long time.*"[165] According to Fletcher, the terms "abandonment" and "city" are however ambiguous, as it leaves in question who is leaving and what is abandoned, and could describe solely (part of) the royal court having left the area.[166] Evans[167] thinks it unlikely that the complete population was moved to Koh Ker and back, since the region was not able to sustain such a large population. While several stelae display Koh Ker as a secondary centre for a period of time and remains of a 12th century hospital chapel are evidence of later occupation, and the findings of Chinese ceramics of different periods suggest that there was continuing occupation,[168] its supremacy lasted only a short episode within the time of the Khmer empire.

Pre Rup, Ta Keo and Baphuon Centres

The new centre at Angkor was built south of the Yasodharatataka in the mid 10th century. Construction of the new state temple Pre Rup started in AD944,[169] duplicating the configuration of the earlier capital Hariharalaya, with the East Mebon, a temple of similar size centred in the *baray*. The following state temple Ta Keo was built half way between Pre Rup in AD968 and the area of the Royal Palace on the western end of the Yasodharatataka. Jacques sees the reservoir having served as a "*turntable*"[170] to ease the communication over the *baray* to the site of the old Royal Palace. The topography of the surrounding landscape indicates that the region was heavily transformed. Because of its vicinity to the 12th century Angkor Thom this could have also happened at a later stage, as the Ta Keo served only for a very short time as main religious centre of the capital.[171] The Baphuon temple was inaugurated just four kilometres to the west in about AD1000. Cœdès believed that Suryavarman I, who is acknowledged as the initiator of the new centre, was a usurper who emerged from a battle between three "kings" ruling simultaneously.[172] Jacques claimed that Suryavarman I, reigning for nearly half a century (AD 1002-1050), repaired the damages done in the 10 years of war that brought him to the throne, Phimeanakas was finished and work on Ta Keo was continued.[173] His successor Udayadityavarman constructed the Baphuon over the causeway which existed as a connection between the Phnom Bakheng and the Royal Palace.[174] Its enormous size would have had massive impact on the surrounding landscape. Cœdès linked him to the construction of the West Baray as well as *"a great number of canals."*[175]

Angkor Wat Centre

Suryavarman II (AD 1113-1150) initiated the construction of Angkor Wat in the 12th century. The excavation of the 200m wide moat and the sheer size of the construction must have concentrated a large number of workmen close to the construction site.[176] To the east of the enclosure, on both sides of the Siem Reap, strong topographic variations indicate dense former habitation. Groslier concluded from excavations at the Phimeanakas that the Royal Palace had also been relocated.

> *"[...] we concluded, from other evidence, that at this time (Angkor Wat period, first half of the XIIth century) the royal palace of Angkor's kings was established elsewhere, and this site momentarily abandoned. This is magnificently confirmed by the disappearance of all cultivated species and the expansion of the ferns and graminaceae, however, the forest itself did not have sufficient time to reappear."*[177]

After Suryavarman II, the empire experienced a period of threat, and large constructions were halted for some time in which the neighbouring Cham are said to have launched several attacks against Angkor. The claimed sack of Angkor by the Cham in AD1177, after which Jaya-Indravarman IV claimed the throne,[178] is however, disputed as the event is mentioned only in Chinese annals.[179]

iii. Jayavarman VII and the Configuration of the Centres

> *'No room! No room!' they cried out when they saw Alice coming. 'There's plenty of room!' said Alice indignantly, and she sat down in a large arm-chair at one end of the table. (AW, VII)*

Bayon - Angkor Thom Centre

Jayavarman VII took power in AD1181.[180] His reign provided stability after the struggle, and a construction boom started in the centre of Angkor. For the possibly 39 years he reigned in Angkor,[181] he is associated with some of the largest Buddhist monasteries, such as Preah Khan, Banteay Kdei[182] and Ta Prom, and ultimately the construction of the walled enclosure of Angkor Thom, with the Bayon temple in its centre.

> *"The sheer size of these foundations suggests a trend toward urbanization under Jayavarman VII, or at least a tendency to herd and collect large numbers of people from peripheral areas into the service of the state."*[183]

Most of the earlier state temples were placed into unutilized areas but in proximity of the already existing temples. Due to the vast space available early urban development could happen on largely unused space. In the mid Angkorian Period available space was limited due to preceding constructions which can be seen in the enormous extent of archaeological features. The plain was more densely populated and the earthworks related to the temples or the water management covered enormous areas. New space had to be created. The role of older state temples after a new state temple had been inaugurated is not well understood. Fletcher and Pottier estimate an approximate use of 400 years, with their importance declining over time.[184] There is epigraphic and architectural evidence that Jayavarman VII also remodelled and reused other former state temples, such as the Takeo[185] and the Bakong, showing an extensive use of Greater Angkor. Other buildings were integrated, destroyed or simply buried to make space for new constructions.

Angkor Thom, built for Jayavarman VII, was the last of the Angkorian ruling centres to be inserted into the region, and is for one reason unique at Angkor. The new centre was designed as a square of 3km x 3km, and surrounded by a massive enclosure wall and a moat. The interior character of Angkor Thom, a chess board-like street network in north-south and east-west direction, which integrated previous structures such as the remodelled Baphuon[186] and the area of the Royal Palace into its grid, was identified by an EFEO team under J. Gaucher.[187] Its configuration gives the impression of being developed from a drawing board. Regarding its enclosed square character it was unlike any previous political centre in Cambodia since the 7th century.

Preceding Centres

Preceding enclosed spaces, such as the pre-Angkorian circular sites, which consist of a number of rings of elevations and depressions, Groslier regarded as "*fortified settlements."*[188] M. Dega cautiously agrees with this analysis, that the moats and earthen walls surrounding the site have a *"defensive function."*[189] Undisputed is that the rectangular character of enclosed spaces had an importance to Angkor through its history; there are examples of earthen walls forming a rectangle around the pre-Angkorian centres of Óc Eo, Banteay Prei Nokor and Wat Phu. This tradition however was not continued at Angkor in the period before the 12th century.

Some preceding state temples at Angkor, such as the Bakong and Bakheng, had rectangular walls and/or moats that enclosed the sacred space. The large enclosures of Greater Angkor, e.g. Preah Khan, Ta Prom, Banteay Kdei and Ta Som, were according to the conventional view built also in the end of the 12th beginning of the 13th century. Claude Jacques argues that the enclosure walls of the Jayavarman VII monasteries at Angkor might have been constructed in the late part of Jayavarman VII's reign, or even by his successor, Indravarman II.[190] Secondary contemporary centres, such as Banteay Chhmar and Preah Khan of Kompong Svay had extensive rectangular enclosure walls,[191] but none match the walls of Angkor Thom. Possibly due to an initial dating to the 9-11th century,[192] the square outline of Angkor Thom was initially seen as the norm of a Khmer centre.[193]

Squares and Rectangles

Based on the assumption about walled medieval European towns, and the knowledge of historic Roman and Chinese cities designed from the drawing board, this “fortified city”, as an idealized interpretation of designed Angkorian capitals affected the understanding of the urban space at Angkor, dividing it into an inside and outside space. Even later, when Angkor Thom was dated to the late 12th to early 13th century, it stood as a stereotype of Khmer cities. This idea led to the search for confined limits of previous capitals. One example was proposed by B. P. Groslier, who mapped earthworks around the archaeological site of Ak Yum, which he interpreted as the limits of a pre-Angkorian centre he named Banteay Chhoeu.[194] The search for geometrical perfection went so far that Victor Goloubew proposed Phnom Bakheng[195] as the centre of a massive 4km x 4km square enclosure, consisting of a moat and double embankments which surrounded the 10th century capital of the earliest foundation of Yasodharapura,[196] named due to Goloubew’s uncompromising search for it: ‘Golou-pura’ meaning humorously ‘The city of Golou(bew).’[197] The idea arose from the interpretation of a broad double-embanked channel (Site ID: CP708) forming an L from the southwest corner of the West Baray running first south and then west, as displayed in Fig. [6].

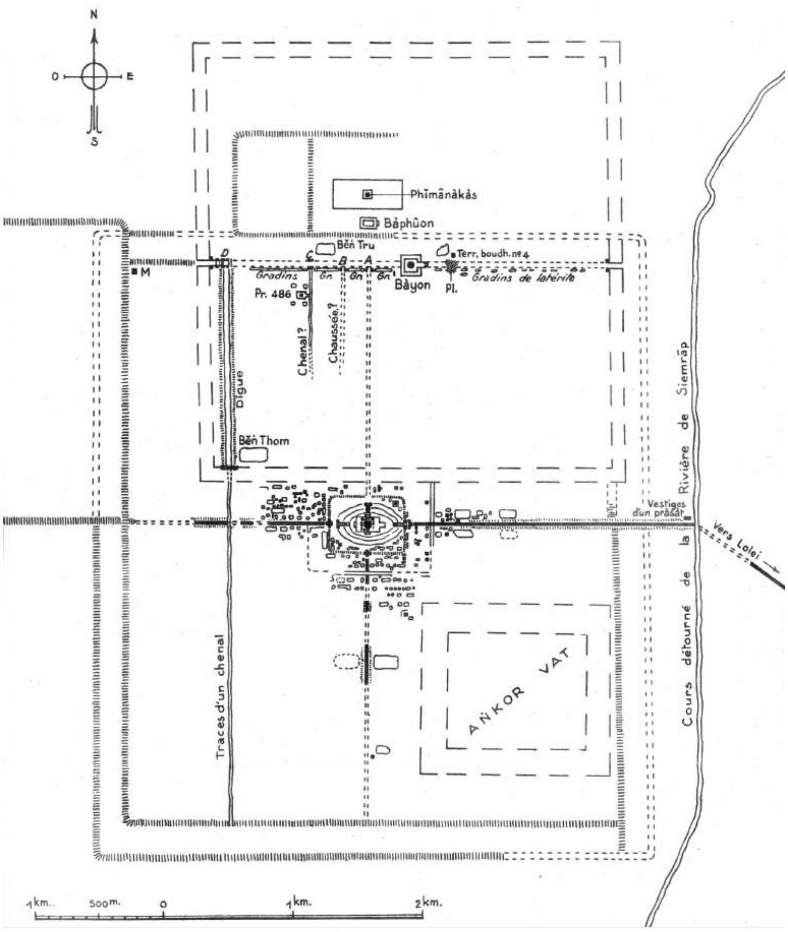


FIG. [6]: IDEA OF THE CONFIGURATION OF EARLY YASODHARAPURA (GOLOUBEW, 1934, PL.XII).

While the other sides were never found, for several generations the eastern and northern border of this hypothesized squared city was interpreted as being removed by the construction of Angkor Thom. Goloubew’s idea of a succession of enclosed Angkorian capitals was undisputed for more than half a century, undoubted by renowned scholars such as C. Jacques,[198] and leading to the search for any remains of the believed missing city limits of other centres. Jacques' description of the centre of Pre Rup shows the little evidence needed to assume the existence of a rectangular centre:

> *"[Pre Rup] city limits can no longer be discerned and its builders may well not have had time to surround it with moats. But its area can be reckoned on the basis that Pre Rup is about 500 metres south of the south dike of the baray which was clearly its northern boundary."*[199]

Influenced by the size and outline of Angkor Thom, Jacques and Lafond described Khmer cities as generally square,[200] and proposed the size of the city around Pre Rup as about 1 km square. He expected a royal palace north of the state temple within this enclosure, of which he admitted not having found any evidence but a small pond.[201] Jacques also proposed the existence of an unfinished defensive enclosure around the Ta Keo.[202] The "enclosed capital" theory was finally rejected, when C. Pottier provided evidence that the supposed part of the Yasodharapura moat was actually a later water control feature related to the West Baray. The nonexistent three other parts of this imagined "enclosure" were additional evidence that a "city" of this kind never existed at the Phnom Bakheng. He also identified the earthworks around Ak Yum as channels related to water management that was contemporary to the West Baray.[203]

That the centre of Angkor Thom was clearly unique and an amplification of the "traditional" Angkorian capital is today agreed on. The squared enclosure of Angkor Thom was a singularity in the city planning in the middle of the history of Angkor.[204] Designed and built after a crisis in the 1170s[205] Angkor Thom shows a change in Angkorian politics. Under threat from the neighbouring states and the fear of losing its supremacy in Southeast Asia, the enclosure walls display a need for protection. The new interpretation to see the enclosures of Angkor as successive centres that were built within an agrarian based urban matrix of undefined borders, helped to set an end to the search for evidence of enclosure walls around earlier capitals.[206] This also opens the discussion on how those centres would have looked like, how far they extended, and what urban Angkor actually was like. Regarding the missing structural features, and the extended landscape of rice fields, Cambodian architect Vann Molyvann raised the question, if it was *"[...] justified in calling these sites cities? Were they not rather a string of villages and irrigated farmlands with fortifications?"*[207] He concluded that*"[...] in this urban format, the royal inner city provided the vital nucleus and is strongly fortified. The real threshold is not between the countryside and the city, but between the inner and the outer city."*[208] According to Vann Molyvann the term "city" is however acceptable due to several reasons:

> *"The urban character of the Angkor cities emerges [...] from the presence of the royal inner citadel; from the larger number and size of sanctuaries, of monasteries and funerary temples dedicated to the ancestors; form the massive length and volume of the fortifications; and above all from the clear evidence that at each site there resided large numbers of non-food producers, pursuing specialized callings in hierarchic, well organized societies over many centuries."*[209]

Instead of a densely inhabited city with clearly defined natural (shores) or artificial (walls, moats) borders, as it was the case for medieval European cities, Fletcher *et al.* propose the idea that Angkor developed a type of low density urbanism.[210] This complex had no actual boundaries, similar to modern industrial cities and comparable to a *desakota*, an expression invented by T.G. McGee that describes the character of Southeast Asian cities, combining the

Indonesian terms for *"village- (desa) [and] city (kota)."*[211] *"The phenomenon can be centred but edgeless;"*[212] as Fletcher remarks, with a more populated centre that thins out towards its outskirts. He claims that *"low-density, agrarian-based urban communities have existed across a wide range of settlement sizes and that this is consistent with the behaviour of human beings who use and have used them in other major socio-economic ways of life."* [213]

Spatial Extent and Low Density Urbanism

Comparable cases of unfortified centres and low density urbanism[214] were identified in other forested (sub-) tropical environments with marked seasonal differences in rainfall, such as the Mayan centre of Caracol in Belize by Chase et al.[215] and Tikal in Guatemala, Bagan in Burma, as described recently by Hudson,[216] and the British-Sri Lankan excavations at Anuradhapura[217] in Sri Lanka. All those agrarian low-density centres grew food within their settlements which directly influenced the local environment. Those centres developed and existed over several hundred years, and Fletcher concludes that "*low-density urbanism cannot therefore be regarded as a transient anomaly [...]"*[218] of settlements.

This proposes a new idea of the development of Angkor, a change from conquest and development of new space, to a move of the political centre within a low density, but periodically urban, matrix, where only the elite moved, and large part of the population remained in its place. The size of the population and the extent of Angkor expanded with development of the centres and the construction of new monuments, as *"from an archaeological perspective, the extent of a settlement includes its expanding skirt as well as its core."*[219] This expansion stopped at some point in time. A possible reason is given by Fletcher, who states *"[...] that we might find evidence for low-density settlement patterns becoming increasingly transient and fragile the larger they become."*[220]

(c) WATER MANAGEMENT AND THE *BARAY*

The Network and its Components

The rulers of Angkor were also responsible for the construction of a network of earthworks and canals. Small rivers, which originated from the Kulen and had crossed the Angkor plain in prehistoric times in Northeast to Southwest direction, were redirected to channel the water into the network and the large reservoirs around the centre of Angkor, from where canals directed it in direction of the Tonle Sap. Once the extent of the system had been mapped, it was understood that its construction would have been a gigantic task, exceeding by far the amount of material moved for the construction of the temples and other structures.[221] This initiated a discussion on the functioning of the network with focus on the purpose of the *baray* from purely religious by keeping a stable water table for the *mebon*, to managing the seasonal differences in precipitation, to irrigation. The failure of the extensive water management system including the *baray* has been argued to have influenced the decline of Angkor in the 14th and 15th centuries.[222]

i. THE "HYDRAULIC CITY"

In the 1950s the archaeologist B.P. Groslier proposed a connection between water management practices and early state building in Southeast Asia as *"l'hydraulique agricole khmère,"*[223] after aerial images had revealed the vast outline of the water management system in Cambodia and the Mekong delta. His research in the pre-Angkorian state of Funan showed evidence of the rise of early sophisticated civilizations based on the control of water.[224]

In the same decade the historian Karl A. Wittfogel identified water management as the primary base for the evolution of societal control, including the development of politics and economy, using examples of early states in the Middle East, East Asia and South America. In the 1957 publication on *Oriental despotism* he described how the construction of large scale irrigation works led to a hierarchical society and to urbanism. This organization of water management led to a monopolized despotic political power, for which he proposed the term "*hydraulic society.*"[225] Those ideas might have been taken into Groslier's consideration in his later work, as he admires Wittfogel's approach in 1974, but carefully avoids the direct adoption of the simplistic theory for Angkor.[226] Since the mid 1970s, the Wittfogel's theory of state development has been widely criticized. Karl Butzer, who rejected the idea of large scale water governing, saw in the case of ancient Egypt: *"all the evidence converges to suggest that, at the social and administrative level, flood control and irrigation were and continued to be managed locally,"*[227] and *"no direct causal relationship between hydraulic agriculture and the development of Pharaonic political structure and society."*[228] The archaeologist Vernon Scarborough bases the rejection of Wittfogel's theory on two reasons: that "*cities and associated indicators of complexity and scale often predate canal systems of consequence"*[229] and that *"many ethnographically observed non-state groups have developed sophisticated water management schemes."*[230] Scarborough concludes that Wittfogel's theory could generally be rejected. Nevertheless he accepts water management as an important element in the development of a sophisticated society:

> *"Water management in the early state [is treated] as an economic and political force – an aspect of the production mode, the social relations organizing culture – to identify basic variables for assessing the adaptational effectiveness of cultural organization."*[231]

In the now famous article published in 1979, Groslier discussed the development of Angkor in the sense of a *"cité hydraulique."*[232] He proposed that the development of the water network was initiated by an already established central authority, the rulers of Angkor and their provincial lords, to create the large earthworks for the water management. While Wittfogel is not directly mentioned, de Bernon interpreted it as a modification to Wittfogel's "oriental despotism" hypothesis that included religion, besides politics and economy, as the third column for the development of an urban society, addressing with it the ceremonial importance of the monuments at Angkor.[233] This proposed that the massive construction tasks were achievable by a labour force which was not needed in the rice fields.

While multiple rice harvests per year were mentioned in the eye witness report by Zhou Daguan, a Chinese diplomat who visited Angkor in the years AD1296-1297,[234] in his 1979 paper Groslier did not rule out the possibility of only one harvest per year to provide enough food for the population,[235] implying a simple concept of the Khmer system to distribute water to the rice fields:

> *"The goal was clear: to ensure optimal water distribution to grow rice. By our observations the choice was having a storage capacity at the highest possible location, and then distributing the water by gravity over the largest area suitable to become permanent rice fields."*[236]

Groslier suggested that the distribution was made possible through sophisticated water management that was using the height difference between the northern and the southern part of Angkor. The *baray* were used as giant water tanks to regulate the irregular flow of water from the seasonal monsoon, to use it later in the year. In his model of the development of Angkor's water management, Groslier proposed also the existence of a reservoir between Hariharalaya and Yasodharapura,[237] only consisting of two embankments with large (and still existing) embankments that could have blocked a similar amount of water as the Yasodharatataka. As it was cited above, Groslier proposed that the water entered through the embankment at the highest point in the northwest and filled the *baray* by gravity.[238] The complete amount of water inside the reservoir could have been used as it gathered in the interior borrow pit running along the southern embankment. When needed it was sent through a breach of the dyke, and along the outer borrow pit of the embankment, from where it was distributed into the fields by plain gravity - no distribution network was necessary.[239] Groslier suggested that the water might also have seeped through the base of the dyke that surrounded the *baray* from where it ran into collector channels.[240] According to Groslier the concept throughout the extension period of Angkor was to extend the area of irrigable land from close to the lake further upstream, constructing more dams closer to the water source, to manage the water over longer periods and irrigate more and more land.[241] The food surplus produced by this strategy allowed more people to settle in the Angkor region, and freed part of the population from rice farming who were then employed for the monumental construction.[242] Groslier suspected that eventually the water management and the function of the *baray* failed. The population in the Angkor region declined which reduced the work force to serve the temples and might have led ultimately to a collapse of large scale organization.

ii. EXIT CHANNELS AND A DISTRIBUTION SYSTEM

And the moral of that is - The more there is of mine, the less there is of yours. (AW, IX)

Grolier's hypothesis was an innovative approach to explain the rise and decline of Angkor, as it was not based preliminary on information resulting from the well studied Angkorian iconography or epigraphy, but also included a geographical analysis of the landscape, produced by remote sensing surveys, archaeological excavations and restoration work.[243] His reasoning on Angkor's development focusing largely on environmental issues started a debate that is still going on.[244] The water engineer W.J. van Liere initiated the criticism in 1982. He observed that Groslier's hypothesis had neglected apparent problems concerning water distribution functions of the water network. The *baray* were missing necessary evidence, such as exit and distribution channels, and there was no information found in historic sources mentioning a sophisticated water management that was organized top down by the ruling class, which Groslier had proposed along with a simple approach of local rice farming. He therefore proposed that the *baray* had mainly religious purposes: *"To satisfy the need for year-round water supply for city moats and temple ponds, a system of theocratic hydraulics was developed [without any relationship] to the profane, down-to-earth agricultural hydraulics."*[245] Van Liere concluded that *"not a drop of water of these temple ponds was used for agriculture."*[246] Commenting and building up on his critique were namely P. Stott (1992), E. Moore (1989), J. Goodman & J. Sanday (1998) and R. Acker (1998). While they did not directly discard the whole idea of a hydraulic city that was governed by a central power supervising construction and regulating the water management, they mainly rejected the idea of the channel networks being used for irrigation purposes and highlighted a religious purpose for the *baray*. Since ground research concerning landscape archaeology at Angkor was impossible in the 1980s due to the ongoing political crisis in Cambodia, and could only slowly start again in the 1990s, early analysis was based predominantly on remote sensing data. Being aware of the gigantic and very evident water network at Angkor, the main criticism was based on two issues: the network lacked a distribution system to get the water from the *baray* into the field, and that the potential amount of water stored in the giant reservoirs would not suffice to irrigate large number of rice fields:

> *"The Hydraulics that did exist, such as the great baray at Angkor itself were just like the temple mountains, essentially a part of the urban scene, providing religious symbolism, beauty, water for bathing and drinking, a means of transport, and perhaps a supply of fish as well. Yet, not one drop of their water is likely to have fed the rice fields of Angkor."*[247]

Support for Groslier's theory in the following years came mainly from other French researchers, namely Jacques Dumarçay,[248] George Condominas,[249] and Olivier de Bernon,[250] displaying also a gulf between the francophone world, which had dominated the research on Angkor in the 20th century due to the importance of the EFEO in Indochina, and supporters of Van Liere coming mainly from Anglophone schools and cultural background.

Two international symposiums gave the opportunity to revive a dialogue between the two opposing groups, in the UNESCO conference *International Colloque Angkor et l'Eau* in Siem Reap in 1995, and *The Hydraulic City in Asia* [251] in Japan in the year 2000. Because the ground is well trodden, the aspects of discussion have been intensely thrashed out over the years, the discussion here is kept to a minimum, but will concentrate mainly on the main issues raised: (1) pre-existing examples of networks, (2) the historic sources, (3) geography and topography issues, and (4) what the characteristics of modern Cambodian irrigation could tell about Angkor. Since it was mainly van Liere's initial criticism that triggered the discussion, his arguments are here used for orientation. A summary of the water management by Ortloff has unfortunately not included any recent publications regarding the current discussion[252] and is therefore not further used in this thesis.

Pre-Angkorian Tradition

Regarding water management in pre-Angkorian societies, Malleret mapped a vast number of channels in the Mekong delta, including a 100 km long straight channel connecting the 4th/5th century centres of Angkor Borei and Óc Eo.[253] The work was recently continued by Bourdonneau.[254] The networks of canals indicate that there was already some kind of water management in mainland Southeast Asia that preceded Angkor.[255] E. Bourdonneau has emphasized on the multipurpose of canals:

> *"We know that some of the canals were used as waterways for transport, and it is equally certain that some others were used for agricultural purposes. These two functions could also have worked in conjunction."*[256]

He proposed a further study of the *"density and geographical distribution of the canals [and a] relationship to previously known archaeological sites."*[257] Mabbett and Chandler have played down the role of irrigation at Óc Eo, since *"what was needed was not irrigation but drainage."*[258] This was supported by Bishop et al. in the Angkor Borei region:

> *"Irrigation was an unlikely use for the canals in the delta, which remains well-watered after the rainy season by drainage from Cambodia's Great Lake. Indeed, large irrigation networks would probably have been unnecessary in the Mekong delta if recession-rice agriculture was sufficient to feed large populations in the delta."*[259]

The canals were therefore more likely needed to control the floods of the Mekong delta in the monsoon season. At Angkor Borei there are also remains of a large artificial pond, there is, however, no evidence that they were connected to the canal network. Although incomparable in size to Angkor, Sambor Prei Kuk, regarded as the 7th-8th century capital of Chenla, had rectangular water catchments as well as earthworks that were connected to the adjacent Stoeng Sen River.[260] Disregarding the temple ponds of historically preceding centres, Van Liere proposed that the water management at Angkor had evolved from a simpler system that had been in place before the large reservoirs:

> *"Some storage is achieved in the receding flood zones by means of simple earth works (called tnub in Cambodian). These tnubs, common in the Rolous [sic] plain, are rectangular, elongated east-west, with the northern side open (the general slope of the terrain is NNE-SSW). A wedge of water is retained in the tnub when the flood retreats, but the volume is not sufficient to irrigate downstream lands. Instead, crops are grown inside the tnub in accordance with water depth and in accordance with the speed of recession through evaporation and infiltration."*[261]

Pottier, who has challenged the main statements of the Van Liere (1982) paper concerning exit and distribution channels from the *baray* at the Japan conference, has pointed out, that, while certainly a simple construction, there is no evidence that those *tnub* were in use before the Angkor period and there is no evidence that they could have influenced the design of the *baray*.[262] Dumarçay associates the *baray* of Puoc,[263] also known as Kok Chan basin[264] roughly rectangular area enclosed by small earthen walls covering 2350m x 1190m with the pre-Angkorian circular settlement of Lovea to the northeast of Angkor.[265]

Historic Sources

Several researchers have mentioned that, starting from contemporary sources - such as inscriptions or the accounts of Zhou Daguan - to the arrival of the first Europeans in the 16th century, there is no mentioning of control of water or any form of irrigation. Stott remarks the absence of any reference to hydro-agriculture or disputes over water management in any historic sources starting with inscriptions:

> *"To my knowledge however there is no mention whatsoever of irrigation in the inscriptions, and especially none pertaining to the distribution of water to fields, although there are some records of reservoirs being constructed and dug.[…] The all-important stone inscriptions give no support at all for a hydraulic view of Angkorian society."*[266]

Y. Ishizawa points out that the Khmer terms on inscriptions[267] that describe the main features of the reservoir and the temple in its centre, refer to a sacred ensemble, but also mention the canals:

> *"Although the inscriptions were incomplete, they do contain words relating to waterways, ponds and water use. An examination of the historical inscriptions reveals that the baray, tatâka and añcun were religious facilities for purification purposes, and also symbolic purposes."*[268]

He interprets that "*the pond (taṭâka) acts figuratively as a mirror reflecting the glory of the king or the law (dharma).*"[269] He also points out that several Cambodian expressions on inscriptions relate to water management: *"In inscriptions (K.341), etc. we find words such as tnal ("embankment"), canhvar ("waterways for irrigation") chdiṅ ("river", stung in modern Cambodian), etc. The fact that these words relating to water are used so frequently, bear witness to the fact that these huge facilities were in fact used in the utilization of water regardless of scale, and did, in fact, function."*[270]

As with the inscriptions, Stott found no evidence for large scale irrigation in the contemporary firsthand accounts of Zhou Daguan. While the Chinese envoy describes *baray* as lakes,[271] the use of water in bathing scenes and rice farming, and mentions multiple harvests, he does not mention water management. *"Chou Ta-Kouan provides absolutely no support for any advanced system of irrigation at Angkor. In fact, the very opposite is the case, for the passage is a near perfect descriptions of flood-water retreat agriculture, the much simpler hydro-agricultural alternative."*[272] A comparable problem to the inscriptions is, however, the issue of translation. The Chinese sign for "lakes" Zhou Daguan used clearly meant the *baray*[273] and parts of the report might have similarly been misinterpreted, or there was just no appropriate sign describing what he saw. Van Liere was unable to find any description of water management by European visitors to Angkor in the 16th and 17th century:

> *"There are earlier descriptions [than from Mouhot], dating back as far as the 16th century and in none of them is ever mentioned the sophisticated agricultural techniques and intricate irrigation traditions that modern literature assigns to the Cambodian high civilizations[sic]."*[274]

Van Liere's conclusion is that firstly, if the irrigation was technically advanced, anybody would have noticed and mentioned it, and secondly *"if such organization had ever existed, then it would be inconceivable that these traditions had totally disappeared at the time when the early travellers wrote their meticulous reports."*[275] While it is still unknown when the network ceased to function, Fletcher et al. have shown that it had come under stress prior to the 14th century.[276] Once unused and overgrown, the function of the massive embankments of the *baray* remained unnoticed by Mouhot and contemporary explorers in the 19th century, who made no mention of any large reservoirs besides the Srah Srang. This is further discussed in Chapter (2).

The non-existent historic sources on the water network have been turned into a counter-argument for Groslier's hypothesis. While the significance of inscriptions is undisputed regarding the chronology of rulers and monuments, the number of inscriptions mentioning water management is comparable to the information extracted on many Khmer living or production patterns, which is extremely sparse or simply null, while their existence and importance are undisputed. Similarly Zhou Daguan's descriptions are incomplete and cover only aspects of Khmer society. Parallel to the discussion, it has been shown in other societies which had sophisticated water management and where the main population *"continued to live the traditional way of life in villages and small centres,"*[277] such as Egypt, that irrigation was organized locally.[278] Stephen Lansing has analysed the organization of traditional water management and irrigation in Bali, where however unlike Angkor *"no single kingdom controlled* *an entire river."*[279] To ensure the fair distribution of water *"delegations of farmers journeyed across the boundaries of kingdoms to perform rituals in chains of temples extending from the mountain lakes to the seacoast,"*[280] which *"articulate the hydro-logic of each irrigation system."*[281] Those temples *"define the institutional structure - the hierarchy of productive units - that manages the rice terraces as a productive system."*[282] Roland Fletcher proposes that below the organization of large scale water diversion, the numerous small temples distributed over the Angkorian floodplain might have had a similar function of organizing small scale water management for water distribution.[283]

Geographical Issues

The second important aspect in the discussion concerns the existence or absence of water management devices. Van Liere had not found any *"evidence of distribution channels to take the water to productive rice fields."*[284] The arrangement and distribution of Khmer rice fields around local temple sites supports the argument that rice production was generally organized by local authorities and not by a central power. This does not challenge, however, Groslier's idea which states that distribution channels were plainly not necessary, as the water would have run from the upslope rice fields to the lower lying ones by itself.[285]

In 1935 the West Baray was drained under the supervision of George Trouvé. [286] The drainage in the lower southeast corner was according to Pottier *"particularly located at one 'recess' of the dyke, a logical choice which could probably have been the one made by the ancient Khmer."*[287] He mapped several large earthen mounds alongside the southern embankment and identified them as potential blocked outlets, which could have been opened jointly, to reduce the pressure of the running water. From a checkerboard like distribution system south of the ramps two canals lead in southern and south-eastern direction. In between those canals, Pottier has shown that at least some part of the rice fields south of the West Baray are oriented in direction perpendicular to the canals and the local topography. He regards it as potential evidence of a distribution network.[288]

Van Liere argued that *"there is always a close relationship between settlement pattern and type of land use. In case of irrigation traditions the settlements are always aligned with the water supply system. [...] The present author does not know a single case where a temple pond was equipped with a distribution system to water the fields."*[289] Pottier has pointed out that rice field patterns changed from a radial orientation in pre-Angkorian times, to a rectangular and orientated in relation to temple enclosures.[290] Groslier proposed that the moats of Hariharalaya had been filled with water from the Indratataka, and served as additional water tanks. This has been questioned by Goodman & Sunday, who have argued that, since the moats and ponds were excavated into the ground and missed a connection to the channel network, without a device to get the water out, none of the moats of Hariharalaya could have been used for irrigation.[291] The amount of water inside would have provided only water to supply humans and livestock in the dry season. Van Liere also questioned the capability of the Khmer technology. *"The tributaries to the Great Lake that cross the belt of paddy fields do not have water for dry season irrigation unless one would build large storage dams upstream. The Khmer did not have the technology to build such dams."*[292] He also argued that *"All the dams [of the Kulen] are earthworks without gated outlet structures. Therefore these dams are flood retardation devices, not dams to store water for the dry season."*[293]

Groslier's ideas of how the *baray* functioned included gaps in the southern embankments or the water seeping through the embankment to distribute the water. Those ideas however were rejected by his critics as speculation, because no evidence of any of this had been found, therefore water distribution from the *baray* was seen as impossible. Hayao Fukui concluded in his contribution to the 2000 conference on water management at Angkor that *"anybody who supports the hydraulic theory of Angkor must explain how water was extracted from the baray."*[294] Not finding them implied they didn't exist, meaning an "evidence of absence." Pottier,[295] however, criticized this logic: The unsolved problem should be understood as "absence of evidence," meaning that similar to other yet to be answered questions concerning Angkor, living patterns, population size or reason for the abandonment, the sheer size of the water management and its reservoirs asked for more research; until then the question had simply to be left unanswered. And several researchers, including Pottier, have pointed out the existence of devices to retain, retard, spread or deflect water during the rainy season.[296] Made of earth and masonry, such as Krol Romeas, an inlet/outlet structure of the Yasodharatataka,[297] devices for directing water are now known from most giant reservoirs. This includes bridges, inlets and outlets, showing evidently the Angkorian capability to manage water. The known structures and new findings are discussed in detail in Chapter (7).

A Look at Modern Cambodian Irrigation Techniques

The existence of any sophisticated rice irrigation system in the Khmer empire was also questioned by pointing out the fact, that there is also no large scale organized rice irrigation in modern Cambodia for a variety of reasons.[298] The argument was raised, that if it was used initially, why had not at least part of the technique survived, and what could have been the alternatives? Cambodian farmers today use simple methods of water distribution, in a small scale comparable to Groslier's explanation to use gravity, where water is transferred from field to field by breaching and closing the side walls. Ebihara identified three techniques used to grow rice in a Cambodian village in the 1960s: *"(1) Rice grown during the rainy seasons that depends primarily on rainfall for water (2) 'Floating rice' cultivation in fields inundated by flood waters from rivers, streams etc. (3) Rice grown during the dry season. In some regions, two (or even three) of these methods of cultivation may be used to yield more than one crop per year."*[299] There is no mentioning of systematic or large scale irrigation. All of the techniques, however, are suitable for the floodplain landscape of Angkor, and could have also been used by farmers in different parts of the region. Stott favoured this concept of individual small scale rice farming for Angkor: *"It is now increasingly apparent that the perfection of flood-water retreat agriculture was the real economic basis of the Empire. The system was regional, small scale, farmer response to a unique set of circumstances created by the Great Lake of Cambodia."*[300] Stott based this on the accounts of Zhou Daguan, whose descriptions on Cambodian rice farming were interpreted as floating rice, a simple technique that depends on seasonal flooding. Therefore Stott concluded that:

> *"This floodplain, where receding flood agriculture was practiced in earnest had its fertility replenished annually. Receding flood agriculture was probably practiced in the Khmer Kingdom from a very early period and is a practice that is still evident in areas of Bangladesh which are flooded annually."*[301]

Irrigation for intensification may not have been necessary. While the requirement for the construction and particularly the maintenance of numerous masonry temples was a surplus of food, the bulk of rice growing was possibly already provided by the lake floods that seasonally covered the vast lake shore south of the centres.[302] The mentioned multiple harvests may have occurred in medieval Angkor, however, not by using the same area or method twice in the same year.

CONCLUSION

The development and decline of Angkor was influenced by regional environmental circumstances. Rice farming and fish from the seasonal alteration of the lake shore supplied Khmer settlements with food, its abundance freed the population part of the year for other work, such as quarrying and transporting stone material from the Kulen hills to construct the large monuments.

Major changes in the water supply due to the subtropical wet and dry seasons made water management necessary to sustain the growing population. The gently sloping topography from the base of the Kulen towards the Tonle Sap gave the possibility of redirecting slow running streams into artificial canals which over time resulted in the construction of a sophisticated water management system. While the discussion on the principle function of the network continues, it is now accepted that it altered large parts of the floodplain and heavily influenced the development of Khmer society.

The End of Angkor's Urban Complex

The construction process at Angkor does not seem to have ended abruptly after Jayavarman VII, the successor Indravarman II was, according to C. Jacques, possibly responsible for improvements of the axial roads that extended from Angkor, exchanging the older wooden bridges for stone bridges and completing some of the monuments. [303] The period of monumental foundations, however, ended with Jayavarman VII. There are a number of possible reasons for the demise of the Angkor. The adoption and rising importance of Theravada Buddhism might have ended the construction period of massive religious monuments,[304] but it did not in itself affect the dominance of the Khmer Empire at that time. Zhou Daguan visited Angkor over a century after the ultimate large construction period and did not mention any evidence of demise.[305] Jacques even argued that Angkor thrived until to the 16th century:

> *"[...] it was thought until very recently that the death of Jayavarman VII marked the beginning of the decline of Cambodia, supposedly 'exhausted' by wars and by the large number of building works ordered by this king. Therefore everything that was built more or less in the so-called Bayon style has been attributed to his reign, without admitting the fact, verifiable today that the Khmer continued to build and modify their monuments at Angkor and elsewhere at least until the 16th century."*[306]

The traditionally accepted year of "abandonment" - when Ayutthayan forces took Angkor in AD1431 - has been questioned as the fall of Angkor, since those attacks had been rather frequent by the Cham and later the state of the Chao Praya basin over centuries, and did not force large parts of the population to relocate. This is also supported by environmental research. Penny et al. (2007) have measured from AMS C^{14} dating of sediment cores, that *"large, even centrally organised work forces may have been present in Angkor as much as two centuries after the city was supposedly abandoned."*[307] It was therefore considered that other factors influenced the decision to relocate the royal court towards the Mekong. Recent interpretations consider the water management system as central for Angkor's demise, as it came under pressure from climatic change. Dendrochronological records of the 14th and 15th century show that strong monsoons were rapidly interchanging with long-lasting droughts.[308] The floodplain-culture of Angkor depended on relatively regular rainy seasons. Devastating floods would have seriously affected the strength of the earthen dykes and would have damaged the canals while the droughts must have destroyed the production of the main food source, rice.

In the 15th century the Khmer Empire lost supremacy to its neighbours. Cambodian authorities moved to the region near the Mekong-Tonle Sap mouth, where new possibilities of trade fuelled the rise of new capitals, such as Lovek, Udong and finally Phnom Penh. Central Angkor was probably at no time completely abandoned. Parts of the region of the so called "lost city" of Angkor, remained occupied, and in the 16th century there were intentions to reinstate Angkor as the Cambodian capital.[309] In the Post-Angkorian period a limited number of temples in the Angkor region kept their significance as Buddhist sanctuaries for the local Khmer population which even attracted pilgrims from other parts of Asia.[310] The natural decay of secular, mainly wooden, architecture in Angkor might have been sped up by fire due to accidents and warfare. Of the royal palaces little was left on the surface besides the massive walls inside Angkor Thom. The part abandonment of Angkor left a vast archaeological landscape. While sedimentary deposition filled the canals, the use of laterite and sandstone for construction purposes, embedded in the regional sand and clay matrix of the floodplain provided distinctive change in the subsurface and made it well suited for geophysical prospection.

CHAPTER (2) CHANGING PERCEPTIONS OF ANGKOR

And still as she listened, or seemed to listen, the whole place around her became alive [...]. (AW, XII)

The perception of Angkor as a multidimensional archaeological landscape kept changing over years of research, as the knowledge about the site increased and has accelerated considerably since 1990. From the 15th century onwards Angkor appeared in European travel reports but remained out of the spotlights until foreign visitors in the 19th century sparked interest with descriptions of ruins in the jungle, so forming the idea of a (re-)discovered "Lost City." New research methods provided ever-changing perspectives of Angkor; beginning with travel reports and translations of historic sources, then the study of the temples' architecture on site, iconography and inscriptions, moving on towards an understanding of landscape patterns by means of remote sensing. The subsurface was analysed by means of excavations and geophysical research.

(a) FIRST ACCOUNTS, OBLIVION AND RENAISSANCE

'It's a poor sort of memory that only works backwards,' the Queen remarked. (LG, V)

Practically no information was available in the European Middle Ages about continental Southeast Asia,[311] while Angkor was still thriving.[312] The desire to find the origin of the exotic eastern spices which had appeared in Europe and the myths about enormous treasures incited European interest in Southeast Asia. The discovery of the eastern and western sea passages around the globe to Asia[313] opened this part of the world to European adventurers, so from the early 16th century onwards the region was repeatedly contacted.[314]

i. EUROPEANS IN 16TH-17TH CENTURY CAMBODIA

The first mentioning of Cambodia in Europe is recorded from a contact between Cambodian and Portuguese envoys in Malacca in 1513,[315] after its conquest by Albuquerque in 1512. In the year 1515 the apothecary Tomé Pires gives a description of an independent state of Cambodia in the hinterland of Southeast Asia referring to secondary sources.[316]

European Sources on Angkor

The first Europeans visited Angkor in the late 16th century,[317] when Angkor still served as a capital of Cambodia. The Cambodian King Satha had relocated his court near to the old site in about 1570, "*though this apparently proved to be less ideal, as by 1593 the capital was again moved to Lovek.*"[318] Missionaries, treasure hunters and military expeditions arrived in continental Southeast Asia from the Portuguese colonies in India or the Malay Peninsula, or the Spanish settlement in the Philippines,[319] and visited the temples either over the Khmer royal court in Udong and Lovek, or later possibly through the Ayutthaya Empire (1351-1767) when it occupied the Angkor region. Angkor is first mentioned in the records of the Dominican monk Gaspar da Cruz, who failed to establish a mission in Cambodia in 1555-56.[320] Missionary Antonio de la Magdalena claimed to have visited the court of Angkor between 1585-1589,[321] which was recorded by Portuguese historian Diogo do Couto (~1542-1616), providing the most detailed description of Angkor at that time, describing e.g. Angkor Thom as a city with rectangular walls, and five gates and bridges, and mentioning canals, moats so large that boats could navigate, and stone cisterns as parts of the water management.[322] Other reports varied in accuracy and detail,[323] or mentioned Angkor out of curiosity and astonishment. Gabriele Quiroga de San Antonio described Angkor as a city that had been unknown before 1570, even by the locals.[324] Neglecting the Indian artistic influence and the local population who were seen having arrived later, Ribadeneira credited Alexander the Great or the Romans as the founders of Angkor.[325] Spanish and Portuguese colonial expeditions to colonize Cambodia were unsuccessful[326] and the growing pressure from the succeeding colonial powers, the Dutch and English, and a bit later the French, prevented further interest of the two early colonial powers.[327]

In the 17th century the Dutch dominated the spice trade. Their ships arrived in 1596 at Bantam on Java,[328] to establish trading posts in continental Southeast Asia. First contact was made with Siam in 1602 and the first trading post in Ayutthaya was established by the *Verenigde Oost-indische Compagnie* (VOC) early in the 17th century[329] to have access to local forest products, ivory and hides for the prime purpose to provide trade products for the copper and silver goods from Japan.[330] Dutch merchants arrived in Udong[331] in the year 1636. Political instability triggered attacks from the local population that enforced a conflict between the VOC and the Khmer. The hostility and sinking profit margins reduced the economic interest in the area and at the same time opened other opportunities for the Dutch.[332] Very few reports mentioning Angkor are found in Dutch records of that time.[333]

Afterwards Angkor was barely mentioned in reports from the other colonial powers, which had taken over the control from the Dutch in Southeast Asia in the late 17th century.[334] Louis Chevreuil, a French catholic priest based in Phnom Penh mentioned in his *Relatione* of 1677 a *"very ancient temple"* and "*place of pilgrimage"* he would have liked to visit, called "*Onco*" that is *"revered by gentiles throughout Southeast Asia like St. Peter's in Rome is by the Catholics of Europe."*[335] His compatriot Simon de la Loubère, envoy to the court of Siam in 1687-88, did not mention Cambodia in his accounts on Siam.[336] Nor are there any records by the British, who used the Dutch trading post in Udong in the 1650s.[337] Since actual visits to Angkor are not reported from any European after the Spanish and Portuguese, a Japanese inscription in Angkor Wat, dating to 1632 is so far the last recorded event of a foreigner visiting Angkor until the reappearance of the Europeans in the 19th century.[338]

Since the regional power and most of the population had moved from Angkor shortly after the first Europeans arrived in Southeast Asia, the area did not capture European interest, which at that time was either economic, in its search for trading partners, gold and spices, or missionary. The Thai capital at the time, Ayutthaya, was reached from Udong over new trading routes passing Battambang south of the Tonle Sap while the northern part of Cambodia was apparently little visited. While the European colonial powers fought for global dominance over the next 200 years, no foreigner was recorded in the region north of the Tonle Sap. Cambodia itself had, under the ill-fated rule of several monarchs, become a pawn between the two rising powers, Siam and Annam.[339] To summarize, there was no interest whatsoever by European countries in the temples of Angkor and the few *"[…] reports of the true grandeur of Angkor were not held as credible, […]"*[340] did not cross languages borders, were utterly ignored or simply not published.[341]

Maps Regarding Cambodia and Angkor

Based on Magellan's travel reports, which were available after members of his crew had returned to Spain in 1522, the Italian cartographer Giacomo Gastaldi in 1548 published the first map of Southeast Asia, marking a city named "Camboja," placed at the correct location but not associated to any country.[342] Six years later,[343] for G.B. Ramusios' edition of *Delle navigationi et viaggi* (transl. "Of Navigations and Travels") he accomplished a geographically more accurate version where close to the seashore the Mekong delta is displayed as a lake simply named "Lago" (Spanish for *lake*). The cities of "Camboya*",* on the shore of the Mekong, and "Langor" close to the Gulf of Siam, are displayed within the kingdom of Camboya (written: CAMBOYA 'R'). In 1561, Gastaldi delivered the first very detailed and geographically correct plan displaying mainly the Islands of Southeast Asia[344] with the "Lago di Camboia" in the hinterland and a city named "Camboia" on its northern shore. "Langor" is missing on this map. As the map is cut off just north of "Camboia", the lake could also refer to the broad delta of the Mekong, and the city to the Cambodian capital of Lovek. Since Angkor was not yet reinstalled as temporary capital of Cambodia, it is rather unlikely that the displayed lake and city represent Tonle Sap and Angkor.[345] With knowledge of Gastaldi's earlier maps, the 16th century cartographer Gerhard Mercator published a world map in Amsterdam in 1569. The map had a similar configuration, the city of Camboya now at the western shore of the Mekong, see. Fig. [7]. Interestingly this appears to be the last time the lake is displayed in European maps until the 19th century. While the maps were getting more detailed, the placement of "Langor" close to the shore can be traced through various publications in the 16th and 17th century, that were based on Mercator, namely the Dutch cartographers Ortelius 1570,[346] Joducus Hondius in 1606 and Willem Bleau in 1635.[347]

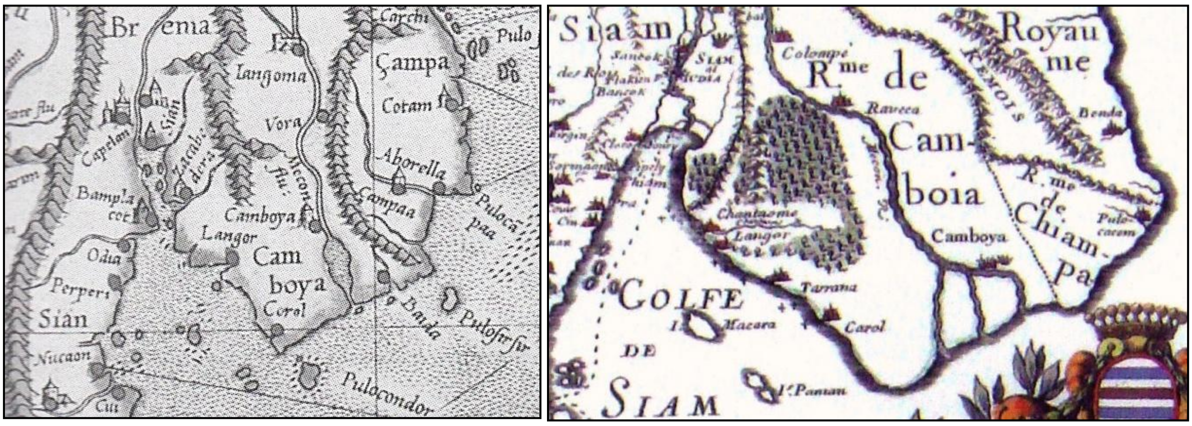


FIG. [7]: SECTIONS OF MAPS BY MERCATOR, 1569, AND R.P. PLACIDE, 1686 (SOURCE: SUÁREZ, 1999, P. 141 & HTTP://GALLICA.BNF.FR).

French cartography of the region must have had other sources, as those maps display other details. The *Carte du Royaume de Siam et des Pays Circunvoisin* of 1686, by R.P. Placide , see Fig. [7], is one of several French maps of that time,[348] which neither display Angkor nor the lake Tonle Sap but reduce the *Royaume du Camboia* and the region between Mekong - with the city of *Camboia* on its shore - and Chao Phraya, the river passing through Bangkok, to a large forest without any annotations.[349]

Then, for a period of time, Angkor received little attention and disappeared from the maps. When the ruins were re-discovered much later, there was no apparent record available of its origin and appeared as mysterious overgrown monuments of a "lost culture"; which meant that the research to understand Angkor started practically from zero.

ii. RENAISSANCE OF THE CAMBODIAN „ANTIQUE"

She saw an ancient city, and a quiet river winding near it along the plain, and up the stream went slowly gliding a boat. (AW, Original Ending)

The "Rediscovery" of Angkor by European Travellers

To name a fixed date or event on which European ignorance on Angkor changed into awareness is difficult, as there was a series of events that brought Angkor into the spotlight. The interest in oriental cultures and their history had risen in Europe together with its imperial interest in colonies in the Far East. Knowledge on the region was sparse; while the coast was well documented in maps, the interior was left blank.[350] Along with the colonial expansion in the middle of the 19th century, the French and British governments pushed for scientific and military expeditions to explore the Southeast Asian peninsula. Travels were difficult and hazardous. Cambodia in the 19th century was a war-torn country, subdued by its neighbours and in a situation that the historian David Chandler calls "*almost a failed state.*"[351] Most explorers started in Bangkok, since Siam had occupied the Cambodian provinces Battambang and Siem Reap in 1794,[352] reaching Angkor over the Lake Tonle Sap from Battambang, see Fig. [8]. Others arrived from Saigon, and travelled over the Mekong and Tonle Sap River by boat to Udong.

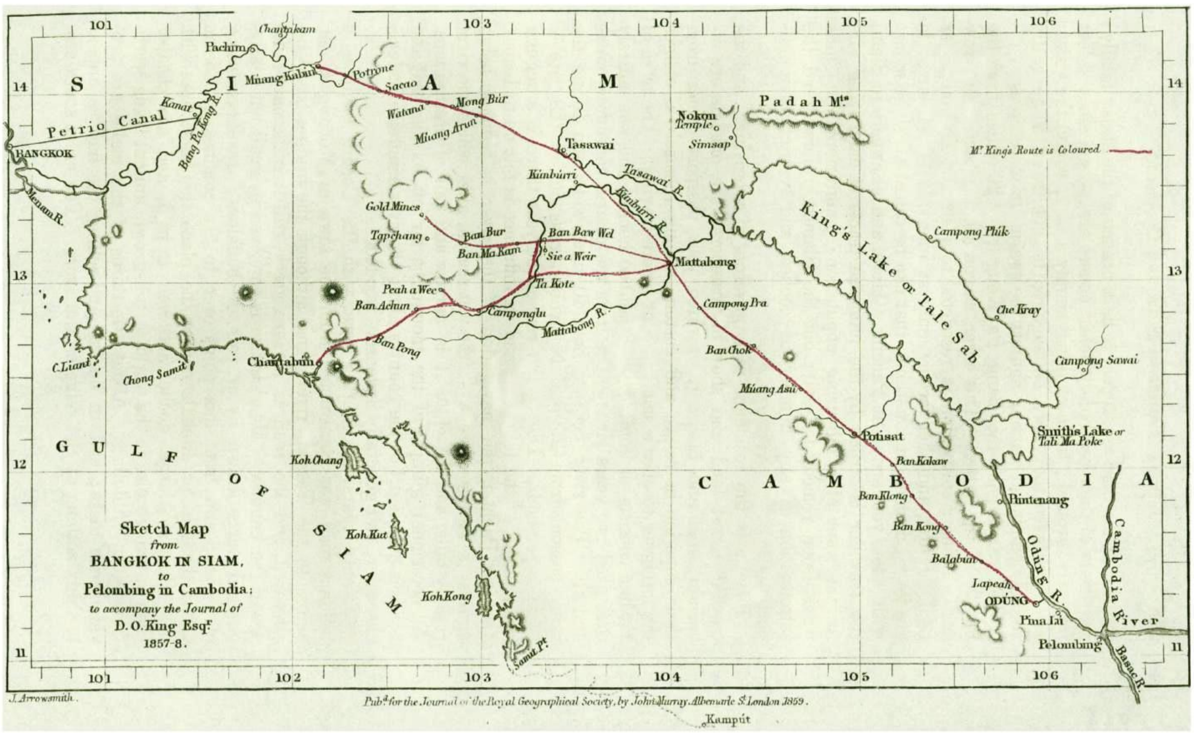


FIG. [8]: MAP DISPLAYING THE MAIN TRAVEL ROUTES FROM BANGKOK TO UDONG IN 1859 (SOURCE: KING, 1860).

Jean-Baptiste Pallegoix

The publication of 1854, *Description du Royaume Thai ou Siam,* by the French Catholic Bishop of Siam, Jean-Baptiste Pallegoix seemed to be the first European an account of Angkor in the 19th century. A map accompanying his descriptions and published in the same year, displays the only access route to a region named "*Nokhor Vat - Ancienne capital.*"[353] In the translated and reprinted publication of his report is a table of the successive inaugurations of French Catholic bishops in Thailand since 1662,[354] which would imply that knowledge about the region and Angkor would have been improved, documented and handed on over time. Pallegoix describes *"the wonderful ruins near the shoreline of the lake,"*[355] though from his description it is questionable if he personally visited the region.[356] Pallegoix mentions also the old Khmer empire, *"[a] great kingdom which stretched out from the 8th degree and 30 min to the 20th degree of latitude. Its domination stretched over several Lao states and even over Siam. It is only three hundred years since it lost its splendor."*[357]

1850s visitors

The first European in the 19th century who is counted for visiting and describing Angkor Wat as "*[...] l'a merveille de la péninsule indo-chinoise [...]*"[358] was a French cleric, Father Charles Emile Bouilleveaux in 1850.[359] The number of visitors from then on constantly increased.[360] The first descriptions are, however, full of speculations. A contemporary traveller, D. O. King, unaware of Bouillevaux's earlier publication,[361] presented his travel report from Bangkok to Udong in London and Rhode Island in 1859, describing Angkor as *"standing solitary and alone in the jungle"*[362] and *"no trace of which now remains, except in the Nokon Temple [...]" which was "taken by the Cochin Chinese about A.D. 200."*[363] At the same date in London, E. F. J. Forrest[364] gave an accurate travel account on the size of Angkor Thom and Angkor Wat.[365] He referred to the bas relief that displayed the churning of milk as *"probably to an event in buddhistical mythology"*[366] and mention additional cities in the jungle, while the chronological placement of Angkor is based on the accounts of the contemporary Cambodian king who is *"ascribing the erection of Nakon Wat and Nakon Hluang to a period antecedent to the Christian era."*[367]

Mouhot catches the Public Eye

While those reports of the 1850s remained relatively unnoticed, the botanist Henri Mouhot in the year 1860 brought Angkor back on stage for the European public as the mysterious ruined city in the jungle.[368] The posthumous publication of his travel reports in 1863 & 1864[369] fell in a time period that combined romanticism and the rising interest in re-discovered historical monuments and so called "lost" cultures anywhere in the world such as Sri Lankan and Mayan ruins.[370] Shortly afterwards the Scottish photographer John Thomson caught the public eye with the first photos from Angkor taken in 1866.

The explorers of the 1850s however still saw the temples as remains of a forgotten once sophisticated culture of long time ago, questioning the capability of the Cambodians to have built the imposing structures. Mouhot's perception was influenced by local stories. He gives no time frame when the civilization of Angkor had thrived. He compares it to ancient Europe and western Asia, describing it "*grander than anything left to us by Greece or Rome or Persepolis.*"[371] His information is based on local oral accounts and includes purely speculative numbers of Angkor having "*kept up an army of five or six million soldiers.*"[372] Those reports stimulated an impression in Europe of ruins in the jungle, referring to Angkor as a “lost civilization”, and later allowed the government of the French protectorate to claim the renaissance of the Khmer culture by restoring the monuments.

Angkor put into Historical Context

Mekong Exploration Commission

In a situation of reduced colonial options in Asia after the British dominance in India and China, the accounts from those solitary travellers passing the temples may have influenced the French government under Napoleon III to equip expeditions in the following years to map and comprehend Southeast Asia. The *Mekong Exploration Commission*[373] (1866-1868) passed by Angkor in 1866. It was led by Doudard de Lagrée and after his death by Louis Delaporte, who returned to Angkor in 1873 after his retirement from the military. Appointed by the French government to conduct further mapping campaigns in Indochina and with support of the *Société de Géographie* he created detailed maps of the temples and collected artefacts.[374] He returned to Paris with a number of drawings and archaeological specimens, bringing Khmer art to the attention of the public when the artefacts were displayed in the World Fair of 1878 in Paris. The success of the exhibition pushed the display of the Khmer art collection in the *Muśee Indochinois du Trocadéro*, of which Delaporte became the curator. The collection allowed constant display and research on old Khmer culture.

Adolph Bastian

It was Adolf Bastian, a German ethnologist, who started to put the ruins of Angkor into historical context. He visited the temples in 1863, only three years after Mouhot, and described the condition of the ruins in detail, had them drawn by an accompanying artist, and took rubbings of at inscriptions in Battambang[375] and Angkor Wat.[376] Frequently he searched through the archives of local monasteries for more information, started true scientific research concerning Cambodian history and archaeology. Bastian wrote his report with knowledge of Mouhot’s travel accounts and the measurements of the Scottish architectural historian James Fergusson[377] who had analysed John Thomson’s pictures.

Bastian is mainly credited with comprehending the artistic depictions in the sandstone reliefs as well as the Sanskrit inscriptions as of Indian influence, based on knowledge he had gathered in earlier voyages to India. He also tied the style of the terraced temple structures to the ones in Java.[378] In 1866, based on a combination of mainly two types of sources, Bastian published the first version of a historic account of Cambodia.[379] To his knowledge “*the history of Cambodia had not been written*”[380] so far. He did not stick to plain descriptions but presented ideas about the temples’ diachronic construction history, placing the Ta Prom younger than Angkor Wat.[381] The temples of Angkor Wat and Angkor Thom as well as Ta Prohm and Ta Keo he saw as “*royal and priestly residences*”[382] of the same time period being not aware of the fact that the wooden royal palaces had disappeared. In his publication Bastian included the already translated reports of Chinese envoys about the pre-Angkorian periods of Funan, Chenla, as well as some Spanish & Portuguese travel report.[383]

In his book Bastian combined local legends and myths with royal legacy lists that he had found in the royal courts of Bangkok and Udong. Of these, so Bastian was told, only recent historic sources had outlasted the destruction of the royal palace of Udong in the 18th century. He seemed to have favoured "*listening to the stories of the people*" anyway, and confided in folkloric tales and their association to actual places.[384]

He correctly claimed that the sandstone of Angkor Wat were not of the region,[385] yet had no knowledge on actual construction dates: His dating of Angkor Wat was based entirely on local legends.[386] The art styles inspired Bastian to wildly mingle the regional tales and comparing them with other founding myths around the globe (i.e. finding a connection between Alexander and Angkor, Java and Denmark).[387] While he did not mention his sources on that account, the names agree with reports from Marcelo de Ribadeneira.[388]

Concerning Bastian's description of the landscape, for him the temples remain solitary and disconnected monuments in a jungle. He mentions that the moats and earthen embankments of enclosures were used as roads,[389] and describes masonry bridges. The only features of the water management besides the masonry bridges, he mentions, is Sra Srang. He comments on the remains of a "*military road*" which passed Angkor from "*Korat to Cochinchina*", [390] and associates the temple of Phimai with Angkor.[391] On his return to Europe, he described, as did several other scholars,[392] his discoveries to the *Royal Geographical Society*,[393] providing a quite a detailed map of the area based on the temples he visited.

Angkor as it was seen by the Local Population

The early reports about the people living around the ruins show that the Cambodians were well aware of the temples and their historic importance. Bastian's travel accounts display a routine in which his local guides showed him various temples, several of which he described as being used as sanctuaries, which is a clear indication that, while not a topic of interest for Europeans at that time, the Khmer still used them. Bastian described the occupation of the temples he visited in several accounts. While the temple called Ta Keo was uninhabited, he "*[...] passed two other remains of antiquity, Lailan and Bakong, both of them now converted into convents; that is to say, the priests have built their low and tottering cells between these splendid ruins, which they were not able to repair.*"[394]

Bastian guessed, however, that the reoccupation was rather recent. "*Following the destruction of the country, [the ruins] had been even forgotten by the natives, and their rediscovery was celebrated by the making of a coin.*"[395] Possibly Bastian was referring to an event of 1853, when Udong had minted new coins with European dies and machinery,[396] which display a triple tower on one side that could perhaps be Angkor Wat; see Fig. [9]. The currency could be an indication that Cambodian authorities were aware of their history before Europeans visited Angkor. As Angkor was under Siamese rule, the Cambodian ruler would have claimed back its national heritage which later would become a defining icon of the countries' identity.[397]

It is clear that the Thai were well aware of the existence of the temples. In a collection of Thai maps from the late 18th to mid 19th century, rediscovered in 1996, Angkor Wat and Angkor Thom were displayed as two of several pagodas north of the town of Siem Reap.[398] The importance and influence of the ruins within Southeast Asia can be seen by Bastian's visit to the Thai King, who "*[...] had not visited Nakhon Vat himself, as there prevails a mysterious fear throughout Siam and Cambodia to approach this hallowed spot.*"[399] This is supported by Bouilleveaux who described "*[...] une statue médiocre de Bouddha, donnée, dit-on, par le roi de Siam [...],*"showing the Thai interest in the temples and its significance as a place of worship.

Mouhot encountered the viceroy of Battambang in Angkor, taking one of the "monuments" to bring them to Siam.[400]

FIG. [9]: CAMBODIAN COINS DISPLAYING BUDDHIST DATES OF THE YEAR 1847/48, MINTED IN 1853/6. (SOURCE: HTTP://WWW.COINCOIN.COM)

While the knowledge of the ruins existed, as well as historic documents describing the post-Angkorian history,[401] the construction history of the temples was not part of the Cambodian identity. The *Kah Luang,* the Siamese governor of Siem Reap, describes to Bastian "*the mighty stones of which Nakhon Vat was built as too heavy to be moved by human force.*"[402] Several historic accounts besides Bastian, e.g. Henri Mouhot[403] or J. G.G. d'Abain, quoted the locals to express their astonishment for Angkor Wat when visiting the temples several years later, described it as being the "*work of angels.*", or the "*work of giants.*"[404] Many of the stories reported from local sources have to be regarded as foundation myths, not uncommon for historic monuments of a preceding and disconnected time period. Their construction was mystified by referring to supernatural powers as builders,[405] or associated to an incredible number of people, as d'Abain reports:

> *"Nokhor, or Angkor, was the capital of the ancient kingdom of Cambodia, or Kmer, formerly so famous among the great states of Indo-China, that almost the only tradition preserved in the country mentions that empire as having had twenty kings who paid tribute to it, as having kept up an army of five or six million soldiers, and that the buildings of the royal treasury occupied a space of more than 300 miles."*[406]

At the beginning of research in the period of "rediscovery" was the astonishment about the splendour of Angkor. At this point in time it was not yet clear which of the European powers was going to dominate the region and the few travel reports were equally recognized disregarding the language used. For the French, British and German visitors the accounts from the local population were as much a source for information as the historic documents and were often reported without being questioned. Those initial reports and the following discussions however show the beginning of intra scientific discourse concerning the history of Angkor; and paved the way for more scientific and institutional research.

(b) TOWARDS CHRONOLOGY

Well then, the books are something like our books, only the words go the wrong way… (LG, I)

i. EPIGRAPHY AND HISTORIC SOURCES

While Bastian had correctly identified the Angkorian inscriptions as related to Sanskrit,[407] the first were translated about a decade later, which also marks the first attempt to date the temples. Before the 19th century the translation of documents in Chinese or Sanskrit was mainly cultivated by individual pioneers,[408] often Dominican or Jesuit missionaries living in China or India.[409] The first translation of the Chinese envoy Zhou Daguan's report on Cambodia in 1295-1296, displaying detailed descriptions on society and life in the Khmer Empire, is often associated with Jean-Pierre Abel-Rémusat in 1819,[410] while it had already been translated by French Jesuits living in Beijing, which was published in 1789 in Paris.[411] With the founding of research societies such as the *Asiatic Society of Bengal* (1784) in Calcutta,[412] *Societé Asiatique* (1822) in Paris, *Royal Asiatic Society of Great Britain and Ireland* (1824) in London and the *Deutsche Morgenländische Gesellschaft* (1845) in Berlin, scientific research on Asian studies became more systematic. The nationalization of oriental studies enhanced the number and quality of scientific research expeditions and also influenced the studies in and about Cambodia.

Epigraphic sources brought back to Europe

The discovery of Sanskrit and Khmer inscriptions in French Indochina demanded for an analysis by Sanskrit epigraphists. As a member of the French Cambodia surveying expedition lead by Louis Delaporte in 1873, F. J. Harmand brought back samples of *estampages*, rubbings of Sanskrit inscriptions from Angkor, to France. Their publication caught the attention of a professor at Leiden University, Johan Hendrik Caspar Kern.[413] His translations of those inscriptions in 1879[414] provided the first exact dates in relation to the temples, and the work became a starting point for the research on Angkorian chronology. Auguste Barth and Abel Bergaigne were the exceptional Sanskrit linguists in France at a time when Étienne Aymonier returned with more rubbings from Cambodia. Together they published the translations in 1882,[415] later with Barth in 1885, and after his death with Bergaigne in 1893, providing the first detailed translations and interpretation of inscriptions. Bergaigne published a first chronology of Khmer kings in 1884,[416] which gathered the knowledge about Khmer medieval history, as well as a Cambodian-French dictionary. This was followed by Aymonier's work in the years 1901-1904, when he described the known Khmer temples from all over Cambodia.[417]

L'École Française d'Extrême Orient

'Speak in French when you can't think of English for a thing.' (LG, II)

The founding of the *École Française d'Extrême Orient (EFEO)* in 1898 in the wake of the establishment of French colonies and protectorates promoted the study of historical monuments in the region, as it was "*immediately given the onerous task of managing the archaeological heritage of French Indochina, covering a territory a third larger than that of France.*"[418] It provided more research staff, financed more expeditions and led to the discovery of a large additional number of historic monuments with Sanskrit and Khmer inscriptions.

The systematic translation of inscriptions by the epigraphists Louis Finot[419] and George Cœdès[420] in the early 20th century opened a completely new view on the medieval Khmer culture. The resulting chronological framework combined the inauguration dates of kings and ruling dynasties with historic events such as wars and the construction of a number of temples. For the first time the Angkor period and its monuments were understood in a chronological order. Cœdès later focused on the inscriptions composed in Khmer, mainly consisting of lists of people and material, realising their value to understand the economy of Angkor and Khmer everyday life.[421]

The increasing number of discovered and translated inscriptions improved the knowledge about Angkor significantly. As sole source of information epigraphy was the dominant authority for Cambodian history. While trying to disentangle myth and actual history, however, epigraphy also supported the legendary part of chronicles and inscriptions by taking the sources sometimes too literally.[422]

ii. ICONOGRAPHY

The Bayon Anachronism

Nevertheless, in 1927 the construction chronology established from the inscriptions was challenged by the art historian Philippe Stern.[423] The Bayon and its believed mediocre architectural style had been placed in the 10th century as the probable centre of Yasodharapura, the capital of King Yasovarman (889-915). Without even having set foot into Cambodia at that time, Stern noticed inconsistent architectural and art styles of some temples at Angkor which would not fit into the accepted construction chronology.[424]

Stern's opinion was that the style of the Bayon was too evolved for this time.[425] In a thorough investigation of photographs and the sculptures at the Museé Guimet, where he worked as a curator, Stern created a register of decorative motifs which he arranged in their diachronic appearance based on evolution of construction techniques. From very early aerial photos he also reinterpreted the central position of the Bayon and Angkor Thom as a later addition, a very radical notion. Based on this outcome he placed the Bayon into the reign of Suryavarman I (AD1001-1049), and his successor Udayadityavarman II (AD1050-1066), both of whom he affiliated with Buddhism.[426] This structural and simplistic approach, presuming continuous development in masonry techniques, was not without critique, questioned at the time by Henri Marchal,[427] and later by Jean Boisselier,[428] though its importance has always been acknowledged as a breakthrough discovery.

Changes in the Chronology

Stern's work led Cœdès to reinterpret some of his earlier translations of the corner stelae of Angkor Thom, and he detected a connection between Jayavarman VII and the city walls. Constructed in the same style as the entry gates of the wall and therefore presumably in the same period, the construction history of the Bayon and a whole group of other temples of that style, e.g. Preah Khan, Ta Prohm, Banteay Kdei and Banteay Chhmar had to be reconsidered. They were moved one and a half centuries, into the reign of Jayavarman VII, which Parmentier in 1927 had already associated with the Bayon.[429] This placed that construction in the turbulent period when Mahayana Buddhism replaced Hindu-Brahmanism as the state religion. It was later supported by the translations of stelae from similar style temples, such as Preah Khan at Angkor.[430] Based on Stern's and Cœdès' work and following the combined effort of several other epigraphists and art historians, Gilberte de Coral-Rémusat finally produced a revised chronology in 1939.

This episode is a good example of the way the evolution of research techniques tackled conventional beliefs, and displays how two very different techniques, iconography and epigraphy, worked to support and challenge each other. Philippe Stern's publication in 1927 had ploughed through the conventional principles on the historic accounts of the monuments and turned the construction history upside down. As George Cœdès remarked: "*Depuis 1927, date de la publication de la thèse de M. Philippe Stern, les études d'archéologie khmère sont entrées dans une voie nouvelle*."[431] The revised chronology has been accepted with minor changes since. The following research was concentrating more on the *why* and less on the *when* and offered the opportunity to revise established relations between structures. Considering the information resulting from the limited epigraphy, B.P. Groslier summed up the status of knowledge about Angkor's chronology in 1960:

> *"it is only the religious and official life of the country which is described, and even they are rather sketchy.[...] As for other possible literary sources – mostly Chinese histories – they are practically all tapped, and, although important, are too laconic to offer more than a cross-check or eventually fill up a gap in the chronological framework."*[432]

He listed potential evidence that has vanished: palm leaf manuscripts, the oldest structures, statues and secular buildings that were made of wood, and the most important cult accessories which were made of metal, so that the temples today are *"no more than empty shells."*[433] Considering the vast gap of knowledge concerning the evolution of Khmer art and society, Groslier concluded that "*It is, in any case, obvious that only archaeology will be able to reveal this past, for there is little hope of obtaining more texts, which will always be only lapidary ones.*"[434]

(c) SURVEYING OF A LANDSCAPE

> *'I should see the garden far better,' said Alice to herself, 'if I could get to the top of that hill.' (LG, II)*

Despite the work by Étienne Aymonier and Étienne Lunet de Lajonquière[435] in the beginning of the 19th century to establish a complete monumental inventory, the vast forested landscape combined with the immense quantity of historical structures at Angkor were still not completely identified and mapped in the early 1920s. This situation demanded a new technique to map the area. Aymonier's description and Sorin's accompanying map of 1904 display a fundamental understanding of the arrangement of Angkor, as they show the royal road network and the major *baray,* but lacked the connecting earthworks and their relation. In 1908 the collaboration of the French geodesist Buat and topographer Ducret produced a more detailed map, displaying a concept of the existence of a water management system.[436]

i. MAPPING CAMPAIGNS AND REMOTE SENSING

First, there's the room you can see through the glass - that's just the same as our drawing-room only the things go the other way. I can see all of it when I get upon a chair - all but the bit just behind the fireplace. (LG, I)

The Early days of Aeronautics

Since the French government was in need of accurate topographic and geographic maps of its protectorate, initial study of aerial photos of archaeological features started in conjunction with the geographical mapping campaigns in Southeast Asia. World War I had pushed the development of airplanes and aerial photography, and their use for archaeology in Southeast Asia was not much later applied there, than at other large historic sites worldwide.[437]

Louis Finot was able to gather images from mapping campaigns as early as 1921 to investigate archaeological remains in the Mekong Delta. As mentioned before, Philippe Stern used aerial photos from Angkor to establish the connection of the Bayon to Angkor Thom. Initiated by Victor Goloubew, a joint venture with the French Navy's aeronautic division was established 1932 to work regularly with EFEO for an understanding of the archaeological landscape, in later years continued by B.P. Groslier, who was so impressed by the results, that he named aerial surveys the "*radiography of archaeology*".[438] While in the beginning the focus was on the discovery of temple structures, the huge amount of new data collected enhanced the established archaeological maps and displayed for the first time disconnected earthworks as roads between the centres and as canal and *baray* embankments. This allowed Pierre Paris[439] and Louis Malleret[440] to identify and map the remains of the canal network in the Mekong delta.

The ongoing conflict in Indochina from 1946 to 1954 prevented the archaeologists from working in the Mekong delta and redirected the research focus to Cambodia. Nevertheless, from 1951 to 1954, EFEO in collaboration with the French Air Force took aerial photographs of every suspected archaeological site.[441] The aerial surveys were supported by a ground team under the supervision of George Trouvé to establish a precise topographical plan of the monuments and their surroundings. B.P. Groslier summarized the experience:

> *"Southern Indochina is a paradise for archaeology from the air. It is easy to spot the ancient field grid, the irrigation works and so forth. These works are relatively recent, and they have seldom been erased by more recent human activities. Or, if man is still living in the same area, he is often re-using the old arrangements. The forest is often a handicap, and very few other natural phenomena have altered the face of the earth."*[442]

The new technique not only helped to discover around four hundred "*hitherto unknown [sites], connected by several hundred of canals or roads [...],"*[443] but provided a new innovative interpretation of Angkor, from disconnected historic ruins towards temples embedded in an archaeological landscape; see Fig. [10]. Aerial photos directed the focus onto the earthworks, acknowledging them as part of the development of Angkor. The collected data became a major pool of information to consider the actual size of Angkor, its outline and the relationship between its different features. With the mapping of the former overland roads the Khmer's infrastructure and transport system for construction material was exposed.

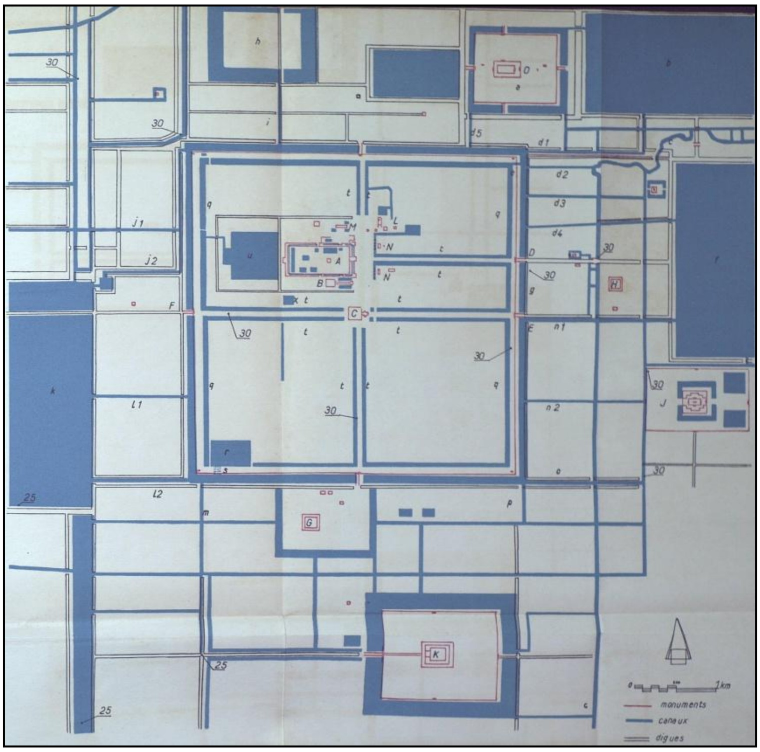


FIG. [10]: CANALS AND DIKES OF CENTRAL YASODHARAPURA BY GROSLIER (SOURCE: GROSLIER, 1958, PL. VII).

Modern Remote Sensing

Since the early days of basic aerial photography, remote sensing at Angkor has come a long way. The global coverage and availability of high-resolution satellite imagery helped to map zones which had not been reached before. Due to the insecure situation in Cambodia in the 1980s, satellite and aerial remote sensing became for a while the dominant research methods, and a large part of analysis was done by interpretation of remote sensing data only.[444] In the 1990s various remote sensing missions, especially by ZEMP[445] and JICA[446] completely mapped the area and integrated the data into a GIS environment.[447] The aerial campaign by Finnmap[448] in 1992-93 provided high resolution stereo images of the Angkor area. This gave Christophe Pottier the needed material to analyse the topography, identify and map earthworks constructed in pre-modern times within the central and southern zone of the archaeological park.[449] To the visual remote sensing, several campaigns provided additional radar imagery.[450] The data of remote sensing techniques that was used within the research of this thesis is discussed in detail in Chapter (4).

ii. TOPOGRAPHY

> *'When you say "hill," ' the Queen interrupted, 'I could show you hills, in comparison with which you'd call that a valley.' (LG, II)*

Once the construction chronology of the monuments was relatively well arranged, and the ordered complex of the configuration of Angkorian monuments and their east-west orientation had been diachronically recorded in precise architectural plans, the temples' construction dates and locations provided the possibility to link formerly unrelated structures with each other. This work was followed by topographic mapping of the anthropogenic landscape of Angkor. The aerial surveys revealed artificial linear earthworks such as roads and canals, their geometrical outline clearly distinguishing them from natural landscape elements such as rivers and hills. Modern remote sensing campaigns have concentrated on mapping the exact locations of those features by geo-referencing them into digital GIS environments and mapping the earthworks, revealing the giant network of channels and embankments created by the Khmer between the 7th and 13th century. The visible overlap of archaeological features due to sequences of building and destruction could help to separate and also classify earthworks chronologically.

Rectangular and Linear Landscape Features

Similar to the monuments, the artificial landscape also displays to some degree, geometric patterns. Earthworks such as the large rectangular enclosures, linear canals, or even rice field patterns can be seen. Limited to ground survey, those features had been known locally from the beginning of research, e.g. Adolf Bastian mentioned the straight Angkorian roads;[451] the rectangular *baray* embankments were mapped to some extent by Aymonier[452] and then fully by Lunet de Lajonquière.[453] The full extent of the network was discovered only when the study of aerial images revealed a so far unmatched scale of archaeological features. The results have been presented in increasing detail in archaeological landscape plans since the 1930s.[454]

In Search of a Master Plan

Similar to the interpretation of the centres, the linear earthworks displayed on maps enhanced the idea of the existence of geometrical perfection in Angkorian structures and led to over-interpretation of the earthworks as well as a misjudgement of the architectural abilities of Angkor's builders, trying to fit every structure into a bigger plan.[455] The vast extent of artificial earthworks related to the monuments led some to believe in a Khmer advanced cosmological understanding of the world. P. Paris[456] brought up the argument of a master plan, by trying to find evidence of an importance of the north-east direction. He connected Angkorian temples of very different construction periods and religion using angles; see Fig. [11]. He superimposed triangles on the Angkorian landscape, e. g. between the temples of Bakheng, Preah Khan and Banteay Kdei or Pre Rup, Ta Prom and Ta Som. This proposal lacked context and contravened historic evidence, as the monuments he connected are not contemporaneous. In this sense, besides their overall broad orientation on an East-West axis, the direction of the features and their relation to each other had to be interpreted in a different context.[457]

The idea of an initial master plan to urbanize the Angkorian landscape was however not followed up.[458] Recently, Pottier has argued strongly against it: *"Nobody really thought that a "master plan" ever existed for Angkor, a site occupied at least during 6 centuries."*[459] To the contrary, Angkor is more properly to be seen as a palimpsest, a landscape that has developed over centuries in which architectural features had been built and then demolished if the space was needed for other purposes. The arguments against a "master plan" however should not prevent a discussion on the geometrical relations of historic monuments and earthworks. Completely rejecting a reading of the landscape in its entirety risks putting too much emphasis on individual structures at the expense of the overall picture. The palimpsest landscape has to be untangled, by (digitally) removing monuments from following construction periods to gain information on changes in the configuration. There are actually several temples associated with each other, and linear earthworks connecting them support this interpretation. Relation and influence of monuments has become an important part to map so far unknown buried features, and examples are given in Chapters (5-8).

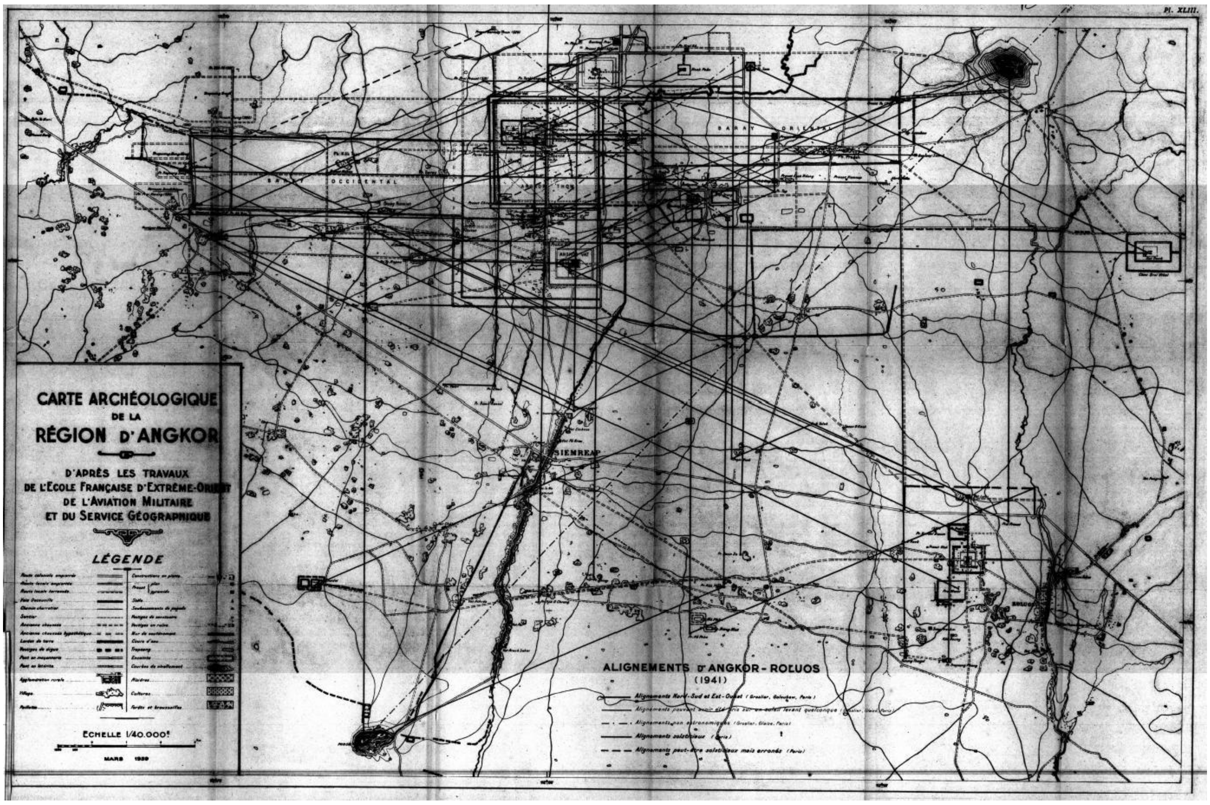


FIG. [11]: PRESUMED CONNECTION OF MONUMENTS BY P. PARIS (SOURCE: PARIS, 1941, PLAN XLIII)

A Palimpsest Landscape

Cataloguing and mapping the variety of archaeological features at Angkor was one task, understanding their relationships was another. The initial maps either displayed the known number of historic structures of Angkor, or were architectural plans of temples. The vastness of the floodplain region with its numerous monuments might have mislead investigators to conclude Angkor was a once continuously and evenly spread populated area. The impression of an urbanised landscape, depicted in modern archaeological maps[460] could be misleading as it only shows the millennium of construction on one level. Clearly separated from the rest of the system at Angkor is Hariharalaya, while most of the network was entangled over centuries of development. Those maps had to be separated into layers to untangle the landscape diachronically and display the development graphically. Henri Parmentier in 1916 sorted the Angkorian temples in Indochina into successive maps based on their association to rulers or dates mentioned on inscriptions.[461]

Victor Goloubew

Already in 1935 Victor Goloubew[462] presented ideas of the chronological development of Angkor in maps and how the construction of monuments influenced landscape and preceding structures, disentangling the palimpsest landscape of archaeological features at Angkor. His intention was though impaired by the search for "Goloupura," the imagined 4km x 4km square enclosure around Phnom Bakheng, whose display dominated the plans of the development of central Angkor, displayed in Fig. [6] in Chapter (1).

Lawrence Palmer Briggs

Lawrence Palmer Briggs, United States consul to Indochina, based his work on the historians of EFEO, especially of George Cœdès and George Groslier, and displayed within *The Ancient Khmer Empire* a series of chronological maps on the geographical distribution of inscriptions, displayed in Fig. [12], very possibly based on Victor Goloubew. He however included several avoidable flaws, as they had already been solved at that time, such as the construction of the Bayon preceding Angkor Wat.[463] Nevertheless there is a reason for the successive densification of the Angkorian floodplain.

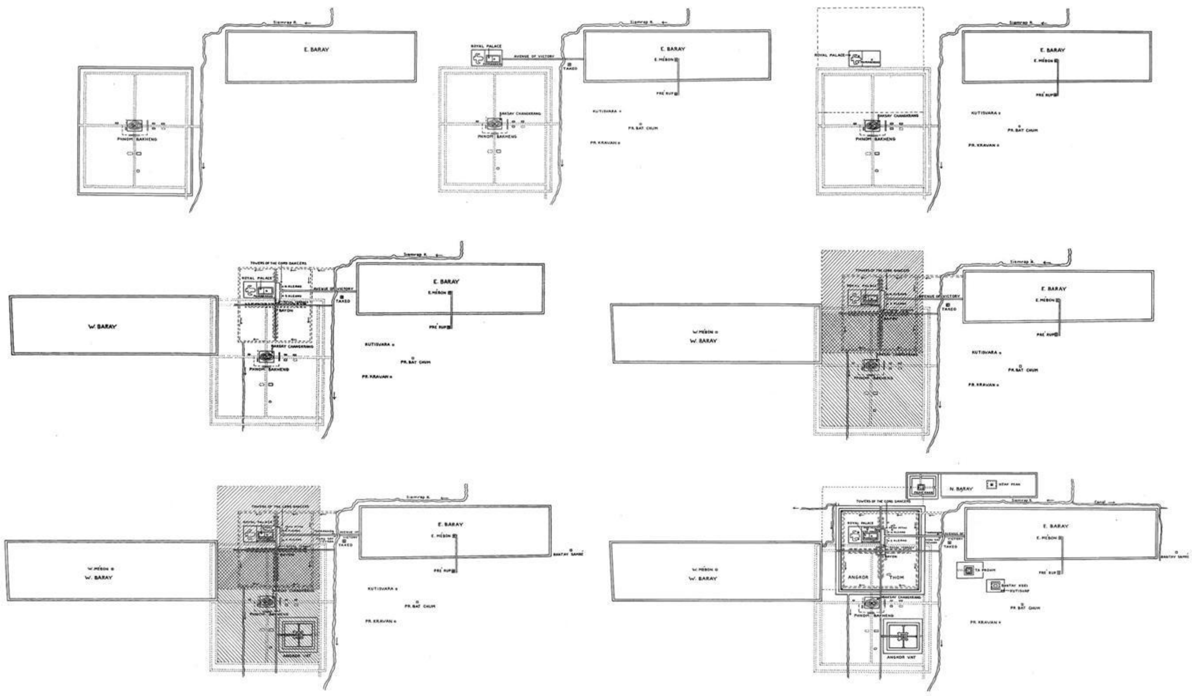


FIG. [12]: DEVELOPMENT OF YASODHARAPURA BY L.P. BRIGGS (1951).

Bernard Philippe Groslier

Groslier then summarized his interpretation of the development of the landscape in 1979, introducing the expression *hydraulic city* to explain the impact of the water management at Angkor.[464] With the aerial discovery of the extended channel system, B.P. Groslier intended to present the so far most ambitious interpretation of the development of Angkor, to create a chronological overview of the development of Angkor:

> *"With this data [the results from the aerial images], and the known facts about this problem, we built up a preliminary interpretation of the space organization at Angkor, and formulated some working hypothesis on its possible implication for the evolution of Khmer society."*[465]

The results were finally published in 1979 within the discussed *Cité Hydraulique*,[466] a set of five maps displaying the area from pre-Angkorian times to the final foundations and constructions; see Fig. [13].

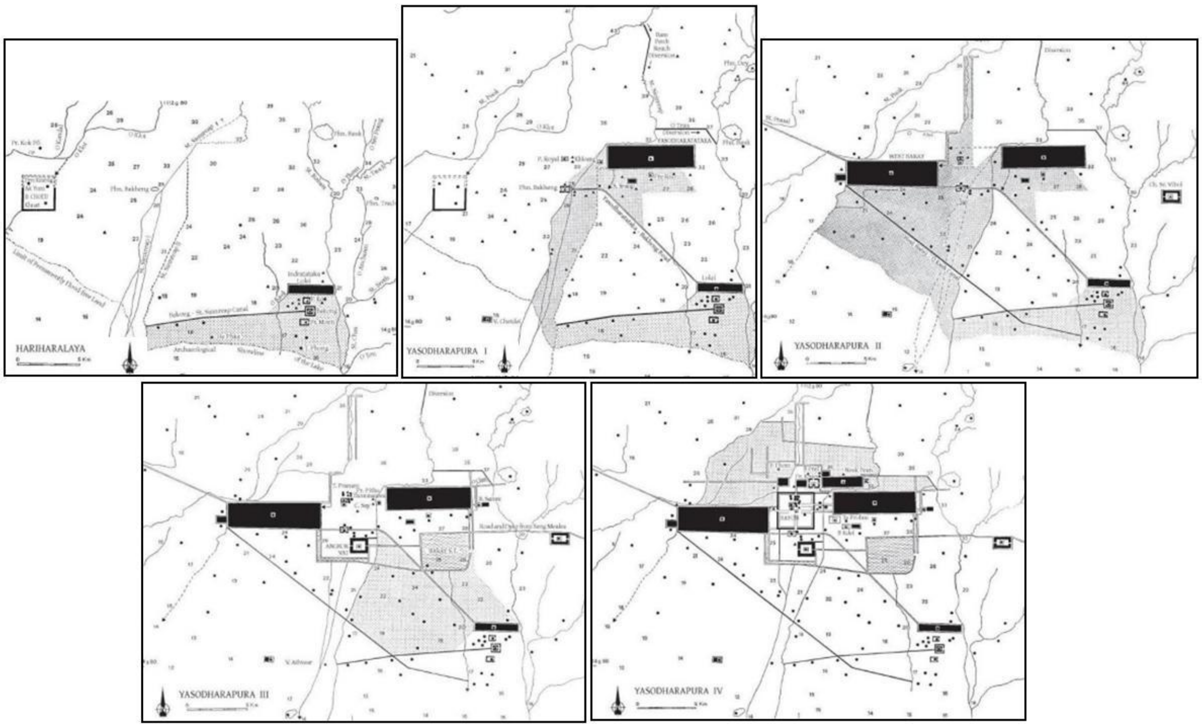


FIG. [13]: DEVELOPMENT OF ANGKOR BY B. P. GROSLIER (1997).

Since Groslier, few graphical interpretations mainly based on Groslier have been published to visualize the centres' successive periods of construction and relocation, to mention is Jacques and Freeman's attempt, to visualize the modifications of the landscape with the development of new centres, and the extent of settlements.[467]

FIG. [14]: DEVELOPMENT OF THE WATER NETWORK OF ANGKOR AFTER FLETCHER ET AL. (2008).

Fletcher *et al*. have analysed and displayed the development of the water management network in a larger scale, which included the later mapped features, see Fig [14].[468] Today the landscape is interpreted as a palimpsest, which, if new space was needed, was 'scraped clean' and 'overwritten.' Due to Angkor's nonlinear development the landscape reveals a history of alternating construction and decay. The relocation of the centres within Angkor influenced the landscape significantly: while activity increased in one region, the preceding centre displayed a reduced activity.[469]

(d) INTO THE SUBSURFACE

'First, she tried to look down and make out what she was coming to, but it was too dark to see anything.' (AW, I)

Until to the 1950s the subsurface had been mainly ignored before, and interest in the issue developed very late as compared to other regions in the world. Excavations so far had only been carried out to free a structure from spoil and remove debris together with the overgrowth that had accumulated over the centuries. The improvement of techniques, such as the use of stratigraphical excavations and the discovery of radiocarbon dating shortly before, offered new possibilities to receive actual chronological information and to understand the everyday life of the medieval Khmer. Additional scientific techniques were needed to analysis the newly gathered data.

i. ARCHAEOLOGY - BREAKING GROUND

'What impertinence!' said the Pudding. 'I wonder how you'd like it if I were to cut a slice out of you, you creature.' (LG, IX)

Stratigraphical Excavations

While it is disputed who invented the now commonly used stratigraphical method in archaeology, it is believed to have been applied by individuals at various archaeological sites worldwide over the turn of the 19th to the 20th century.[470] The advanced technique was used in Southeast Asia already in the 1930s, e.g. by Olov Jansé in Tonkin 1934-1939. First stratigraphical excavations were carried out in the Angkor region in the early 1950s. This included the uncovering of buried features, sampling and interpreting the findings such as ceramics, tools and bones and art historic analysis of archaeologically relevant items.

While work at the temples was interrupted by the Japanese occupation of Indochina in World War II in the 1940s,[471] the EFEO as the academic branch of the French protectorate government still concentrated mainly on clearing and restoration of monuments as well as the ongoing aerial campaign to map additional structures and earthworks. Work on the temples conducted in the beginning of the 20th century, such as in the enclosure of Angkor Wat by Henri Marchal and Henri Parmentier,[472] was intended to clear the structures of undergrowth and to remove soil that had accumulated over several hundreds of years at its base. The unearthing of valuable items such as stone, bronze statues or ceramics occurred mainly by chance or was deliberately collected to improve museum inventory.[473] The objects were mostly found in direct vicinity to the temples or in field surveys with the help of local guides to search for art works, while the "*identification and dating of the monuments remained essentially in the hands of the* *epigraphists.*"[474] Archaeological excavations were conducted to improve the knowledge on the construction history. Marchal excavated within Angkor Thom, at the Elephant Terrace as well as at the Bayon,[475] to investigate if Philippe Stern was wrong with his new chronology. Goloubew did several excavations near the Phnom Bakheng trying to prove the existence of a four kilometres squared outline of the 10th century Indrapura.[476] Nevertheless Bernard Philippe Groslier claimed that *"not a single excavation was carried out at Angkor until 1953,"*[477] when the excavation at the Royal Palace of Angkor Thom were carried out,[478] and criticized the simple clearing of archaeological sites as the right scientific approach to understand Angkorian and especially the even lesser known Pre-Angkorian culture, promoting stratigraphic excavations: "*In the first place, the prehistory of Cambodia [...] is still waiting the spade.*"[479]

With the beginning of the 1950s though, the science of modern archaeology had arrived in the region. George Trouvé is credited as being the first to systematically excavate at Angkor.[480] The synthesis of a variety of scientific methods applied to a problem concerning archaeology is attributed to B. P Groslier. His extensive unearthing of the subsurface revealed the construction technique of Khmer monuments formerly not known, as it became visible at the royal palace, the stratigraphic method used at temple sites was intended to find connections between different religious sites. *"The excavations I conducted were essentially intended to determine the relative positions of the temples and their urban layouts"*, explained Groslier.[481] They also provided first hand information on the construction stages.[482]

Excavations of an Angkorian cemetery at Sra Srang in 1964 opened a view on funeral rites.[483] The objects unearthed provided information about everyday life and death at Angkor, which before had only been drawn from the few depictions in reliefs, mainly of the Bayon.

Analysis of Imported and Khmer Ceramics

With the excavations the research on ceramics also changed, drawing a line between the conventional art historic approach and scientific research. The excavation by B. P. Groslier at the palace of Angkor Thom in the campaigns of 1952-53 and in 1957,[484] as well as at Sra Srang in 1963 unearthed a large number of Khmer and imported ceramics from the neighbouring states Vietnam and Thailand as well as from China. Groslier commented on it in 1960:

> *"One of the most significant discoveries was the enormous bulk of ceramics. Part of it was Khmer, and it was completely unknown till then. We were able to draft a first tentative chronology of this material, which was of the greatest help for our next research, as will be seen later. But the largest quantity consisted of Chinese export ware. There is very little known about this item for it was made for export only and is not found in China itself, where its kiln-sites have not been studied, not even located."*[485]

The well-developed understanding of precisely dated alterations in Chinese ceramics due to the high variety of material used, its form, decoration and glazes, made it a an important relative dating method for stratigraphic layers. B.P Groslier describes the immense improvement regarding the dating of excavated material using Chinese ceramics:

> *"The other data of Angkor excavations were sufficient to establish a chronology of this material between the IXth and the XIVth centuries, with an accuracy of within half a century. This may seem perhaps too loose, but one must realize that previously the range was about two centuries."*[486]

The imported ceramic revealed dimensions of trade and interaction between Angkor and contemporary states. Large quantities of imported ceramics are often related to a ceremonial and administrative centre, temples or palace site. According to Fletcher the abundance of finds throughout Angkor however displays that not only the elite but a greater part of the society must have had access to porcelain and stoneware.[487]

Although the Chinese imported porcelain and stone ware improved the relative dating of some types of Khmer ceramic, it was over a long period of time that the latter was discarded as inferior for chronostratigraphy. Aymonier had already discovered a production site for Khmer ceramic in the late 19th century, the kilns at Anlong Thom in the Kulen,[488] and George Groslier[489] wrote as early as 1921 an overview on Khmer ceramics on the basis of complete vessels. Aymonier and G. Groslier both interpreted the potters for Khmer ceramics to be Chinese.[490] Excavated shards though, while abundant over the complete period of Angkorian occupation, received little research attention until the late 20th century.[491] This was especially true for unglazed ceramics, which again was given even less attention than glazed stone ware.[492]

> *"A variety of unglazed utilitarian earthenwares and stonewares were produced in Kamputchea between the sixth and fourteenth centuries. Archaeological evidence is lacking because unglazed shards were discarded during excavations"*[493]

The reason for this was quite simply the dominance and abundance of easier to date Chinese ceramics compared to the less sophisticated Khmer stone and earthen ware. "*It was the very excellence of the Chinese wares and their expanding availability in the Angkorian period which seems to have inhibited the full flowering of the Khmer ceramic tradition. This is partly to be seen in the limited repertoire type [...]*"[494] B.P Groslier argues *"if the archaeologist had to judge Khmer art entirely by the ceramics, he would not place it first among the arts of Southeast Asia."*[495] The crude Khmer ceramic did not make a big impression; due to its simplicity it was more difficult to use for relative dating, as it covered broader period of times. "*Due to the absence of systematic studies, identification and dating are frequently done 'negatively' by 'impressionist' comparison,*"[496] even in surrounding Southeast Asia, if a vessel did not have the Chinese or Vietnamese superior impression, it must have been Khmer. Groslier though pointed out that most vessels produced in Angkorian kilns would not have been for export, but simply for local use.

While whole pieces of stoneware received earlier attention mainly from collectors, they preferred "*unusual objects and limit[-ed] their choice to undamaged vessels of good quality.*"[497] A study of those though did not provide an overview and understanding of the usual cooking pots. As late as 1981 Bernard Philippe Groslier described that Khmer ceramics had "*attracted scant attention until now and this silence is due to many reasons [one of it is that] the Khmer did not develop a great ceramic art. One could hardly say they mastered it.*"[498] Another reason is that *"the Khmer seemed to have made little use of ceramics. [...and they…] seemed to have been reserved for functions to which their own physical quality and low price assigned them."*[499]

> *"With the exception of roof tiles, it is not evident that the evolution of the ceramic art followed the architectural or sculptural styles or the historical rhythms (essentially the reigns of the great kings) which we used to delineate the evolution of Khmer civilization."*[500]

The issue is whether it actually shows the domestic life of ordinary people. Groslier argues that the Cambodian farmers and peasants would have used the abundant organic material as the main everyday craft material;[501] therefore ceramics did not provide a large quantity of information on the daily life in medieval Angkor. While research on Chinese ceramic as an indicator for the higher class has remained, and has advanced to a very accurate relative dating method,[502] the dominance of research on imported ceramics over local products was broken in the 1980s, when excavation started at historical Khmer production sites in Thailand[503] and has thrived since. Extending and focusing the new research on Khmer kiln sites notably Sophia University and the local APSARA Authority[504] provided new information on production processes and enhanced the knowledge on the chronological development of Khmer ceramics,[505] and with it also the development of Khmer society. The research on Khmer kilns has changed considerably with the use of modern scientific techniques, involving also geophysical methods such as Magnetometry and GPR[506] that provided knowledge on the extent and structure of the kilns, or the study of production techniques of ceramics and element composition of the material. Excavations of Khmer kilns provided the quantity of material from some time periods to produce consecutive ceramic sequences also from Khmer ceramics.

ii. The Natural Sciences

While the broad chronology of ceramics was established to analyse the construction history of the monuments, more precise dating of material depended on more sophisticated natural sciences, such as radio carbon dating and trace element analysis. The excavations also provided information for a new field of research, the statistics; research up to then can be characterized as qualitative. A statistical approach to investigate ceramics and pollen gave information on production and living processes. The number, spread and density of ceramics gave an idea of the degree and type of occupation over a period of time and helped to identify areas of settlement. The use of many scientific methods was delayed in Angkor by nearly 20 years, due to the civil war, but the more recent combination of different techniques has pushed scientific research and the historical understanding forward. While several international teams had started to work at Angkor in the 1980s,[507] the inauguration of Angkor as World Cultural Heritage in 1992 and the establishment of APSARA as control agency provided opportunities to other research groups for the application of scientific techniques.

Radiocarbon-Dating: Defining Periods of Urban Occupation

The discovery in 1949 by Willard F. Libby[508] and his team of the radioactive isotopes ^{14}C in carbon rich material, and resulting from that the development of the radiocarbon dating technique revolutionized the study of archaeology.[509] With the ability to compare the stratigraphical data from excavations with actual dates from inscriptions, first measurements had been conducted by Louis Malleret on old Southeast Asian wood that was unearthed in excavations at Óc Eo in the Mekong delta, which were carried out in 1944.[510] The technique was later applied in Angkor by B. P. Groslier,[511] putting a new factor on the Angkorian archaeological map. Chronology before that had mainly been interpreted from inscriptions. The discovered production sites and durable remnants of goods indicated the living space and gave an indirect time span of occupation in connection with the inscription dates. But now the precise dating of layers of occupation, fire places and production sites such as furnaces and kiln sites would provide knowledge on exact dates of use. With the new dates the relation between the chronology of construction and the actual time of use of a temple could be questioned. The lifespan of an administrative centre was not reduced to a single date of inauguration - and depending on the belief that the ruler had marked the correct date - but now provided a time period from the beginning of occupation to abandonment or at least a date of when it was in use. What had been "written in stone" was suddenly questionable.[512]

Pollen Analysis & Statistics

Palynological or pollen sequence analysis had been initially used in Angkor by EFEO researchers in the 1950s, providing information about the existence of plant species over a period of time, to identify whether the land had been cultivated or left unused. For Groslier the information retrieved by palynological data was the "*most important results of [the royal palace] excavations.*"[513] By counting occurrence and dominance of a number of plant species in excavation layers or drill cores, pollen analysis provides information on the occupation of an area and the intensity of its use, as it changes from primary forest to agricultural landscape and secondary forest. Those changes of the landscape can be dated. For a successful measurement in the modern pollen analysis a continuously existing water body is needed which has preserved the organic material deposits. According to Penny *et al*. *"vegetation is sensitive to the activities of people and the composition of the flora will often indicate the nature of land use at any given point in time."*[514] The high potential of the method for Angkor was shown by Penny *et al.* in a core from Hariharalaya, from which it was possible to reappraise and date anew several historic events known only from inscriptions: The resulting information put the excavation of the inner moat to the beginning of the eighth century, prior to the inscription dates stating the construction of the temple.[515] A section of less cultivated material and more water plants in the 10th century fitted to the relocation of the court to Yasodharapura, or the excavation of the outer moat leading to a decrease of cultivated plants.. Another construction period in the 11th century was not evident in the data, neither was a decrease in the time of the so called sack of Angkor in 1431. The continuous demise until the 16th century however is evident. Additionally, palynological data from a sediment core taken from the pond in the West Mebon gave information *"[…] on the changing composition of the aquatic flora"*[516] and *the* fluctuating water level in the reservoir over a period of time.

Magnetic Susceptibility

A rather simple, rapid, cheap and non-destructive geophysical survey method has made a great impact on the knowledge of the construction history of monuments at Angkor. First used in an archaeological survey in 1993,[517] magnetic susceptibility *"[...] is a measure of the extent to which magnetism can be induced in materials*"[518] which depends "*on the amount of ferrimagnetic minerals present in a rock*"[519] The technique was adopted in 1998 for the relative dating of Angkorian monuments first on carved sandstone,[520] then on the laterite bases.[521] While sedimentary rocks have low susceptibilities[522] due to the lower magnetite content, it is enough to distinguish between different sedimentary formations. Measuring magnetic susceptibility has simplified the work on chronological construction periods of a single structure and in relation to others by way of identifying different parts of buildings to the same rock type and quarry. The immense amount of sandstone and laterite needed for construction purposes came from different quarries and for this reason the technique has been especially effective at Angkor. The results not only confirmed the art historic and architectural analysis of several construction states of temples such as the Bayon,[523] Preah Khan at Angkor and other temples associated with Jayavarman VII, but allowed to establish a whole construction chronology of monuments, by relating small adjacent parts to the central temple structures,[524] showing the consecutive additions to enlarge the temples.

iii. Archaeological Prospection

Geophysical applications provide a link between archaeology and the natural sciences. Their use in Angkor can be traced to the early 1990s. Geophysical prospection techniques used during and often preceding archaeological surveys have been promoted as cost-effective and time-efficient,[525] as they provide quick results in comparison to excavations. K. Kvamme proposes that especially a *"survey of large contiguous areas is [...] essential for making sense of patterns in cultural landscapes using geophysical (or any other) data sets."*[526] They are also non-destructive: the soil can remain undisturbed if no excavation follows, especially important on "*cultural sensitive burial, sacred or ceremonial sites.*"[527] Kvamme describes the evolution of an instrument only suited for "*discovery purposes into entirely new domains such as the wide-area mapping of settlement structure, inter-settlement comparisons of form or the examination of individual house sizes, shapes, orientation, and arrangements of interior components.*"[528] Dahlin and Loke[529] have shown the 3D possibilities of resistivity measurements in near-surface geology, which since then has evolved to a method for rapid data collection.[530]

Ground Penetrating Radar

Compared to other geophysical methods GPR is a rather young technique. Nevertheless the history of its development demonstrates that it was a long process before the physics behind the method could turned into a reliable surveying instrument. Electromagnetic sounding as a means for ground penetration has been known for over half a century, yet its application has boomed only over the last two decades. Radar as a ground penetrating survey technique started with research into glacier depths measurements.[531] First attempts to measure ground water table depth in deserts were made in the 1950s in Egypt.[532] Early efforts to map archaeological features were accomplished in the 1970s.[533] It was the advances in computing and digital recording techniques that made GPR a widely used survey method in the early 1990s, as it was now possible to process the vast amount of 3-dimensional data. The greater sensitivity of instrumentation *"[...] allowed the detection of deeper, smaller and more subtle buried features."*[534] Since then GPR instrumentation has become more robust and the software more stable for rough field surveys. The improved storing capacity and the increase of computer processing speed as well as advances in imaging techniques have provided the base for its growing acceptance as a geophysical prospection method, and the variety of its applications has risen since. The ability of GPR to view and discuss results on site has replaced magnetometry as the most diverse and valuable tool in archaeological prospection. The development of software for GPR as a 3-dimensional subsurface prospection method[535] has boosted its use in archaeology and has made GPR the most diverse of all geophysical methods in this field of study.[536]

While these near-surface geophysical surveys have been around for several decades now, little has been published on the use of geophysical prospection methods in Angkor so far. Possibly the first use of archaeological prospection methods at Angkor is described in an internal report by Exaltus and Orbons[537] of the *Regionaal Archeologisch Archiverings Project* (RAAP, University of Amsterdam) in collaboration with the EFEO in Siem Reap, which used electro-magnetic measurements, surface resistivity and magnetometry surveys around the centre of Angkor

Thom to evaluate the applicability of those methods. The focus was on the detection of soil changes to map walls and water saturated ditches referring to natural or artificial channels. The initial surveys inside the royal palace area around the Phimeanakas and in the southeast of the Bayon[538] were not continued, possibly partly because *"the application of magnetic measurements and electro-magnetic measurements did not prove to be a very effective technique."*[539] The authors however describe resistivity as a *"very effective technique,"* which *"revealed the presence of numerous stone alignments, some of which form structures."*[540]

The earliest GPR survey was presumably conducted by Dean Goodman and Yasushi Nishimura in 1997, to investigate a part of the area between Banteay Kdei and Sra Srang.[541] They rediscovered a buried enclosure wall, which had been excavated by B.P. Groslier in the 1960s, but whose location was lost during the civil war.[542] Also in the 1990s the *Cambodian Authority for the Protection of Angkor and the Region of Siem Reap un*der supervision of Nishimura conducted several GPR as well as magnetometry surveys at the Tani Kiln site to the northeast of Angkor,[543] marking the extent of the kilns as well as the orientation and depth of the fire chamber. The *Archaeological Survey of India* used GPR to conduct several transects in Ta Prohm temple as an initial investigation for the reconstruction of the temple complex. The results published in 2001 though show a very limited use in a number of transects, displaying the detection of roots in the subsurface.[544] In 2008 *Atkinson-Noland & Associates*, a US based heritage consultant hired by the *World Monument Fund* (WMF) investigated the possibility of high frequency GPR for detecting and measuring cracks, high moisture and salt concentrations in the Angkor Wat sandstone walls and roofs. Intended as an initial attempt the project was not continued. In 2005 the *Greater Angkor Project* worked in collaboration with Paul Brugman (Geospatial Information Unit, Australian National University) to investigate features of the water management. GPR surveys were conducted at an Angkorian bridge north of Banteay Sra.[545] The *Japanese Government Team for Safeguarding Angkor (JASA)* applied resistivity, frequency domain electromagnetic (FDEM)[546] and GPR[547] at the Bayon complex in June 2007. Using a set of 200-150MHz antennas for the GPR survey, mainly single transects were conducted to interpret structural features on the monument and its surrounding, a subsurface velocity analysis was performed and the signal identified several layers of laterite blocks. A GPR transect displayed a correlation to an excavation here. The 200MHz antenna averaged a depth of 3m; the deepest reflection was measured at 5m. The *Banteay Srei Conservation Project* has shown the usefulness of a variety of methods in their 2007-2008 archaeological prospection campaign. The surveys, using magnetometry and resistivity,[548] were accommodated by archaeological excavations and preceded the construction of the local museum and car park.[549] Also in 2007, Maksim Bano and Philippe Duringer of the *Université Louis Pasteur* Strasbourg applied GPR in a collaboration with the *École Française d'Extrême Orient* at Prei Monti for the MAFKATA project.[550]

CONCLUSION

Perception of Angkor

The methods described and applied in this thesis provide information on different aspects of the archaeological research that were addressed in this chapter, concerning (1) structure, (2) chronology, (3) landscape and (4) living patterns. Working with GIS maps may have imposed a different idea of describing the archaeological landscape of Angkor as multi-dimensional. GIS displays features on a map exclusively as dots, lines and areas, for presentation purposes also a 3-dimensional display exists. Additionally to the combined geometrical features enters the time factor, in physics associated with the 4th dimension ("space-time"), when displayed features appear on maps or disappear through time. This multi-dimensional display of a map is here used to describe the changing perception and expanding understanding of Angkor, see Fig. [15].

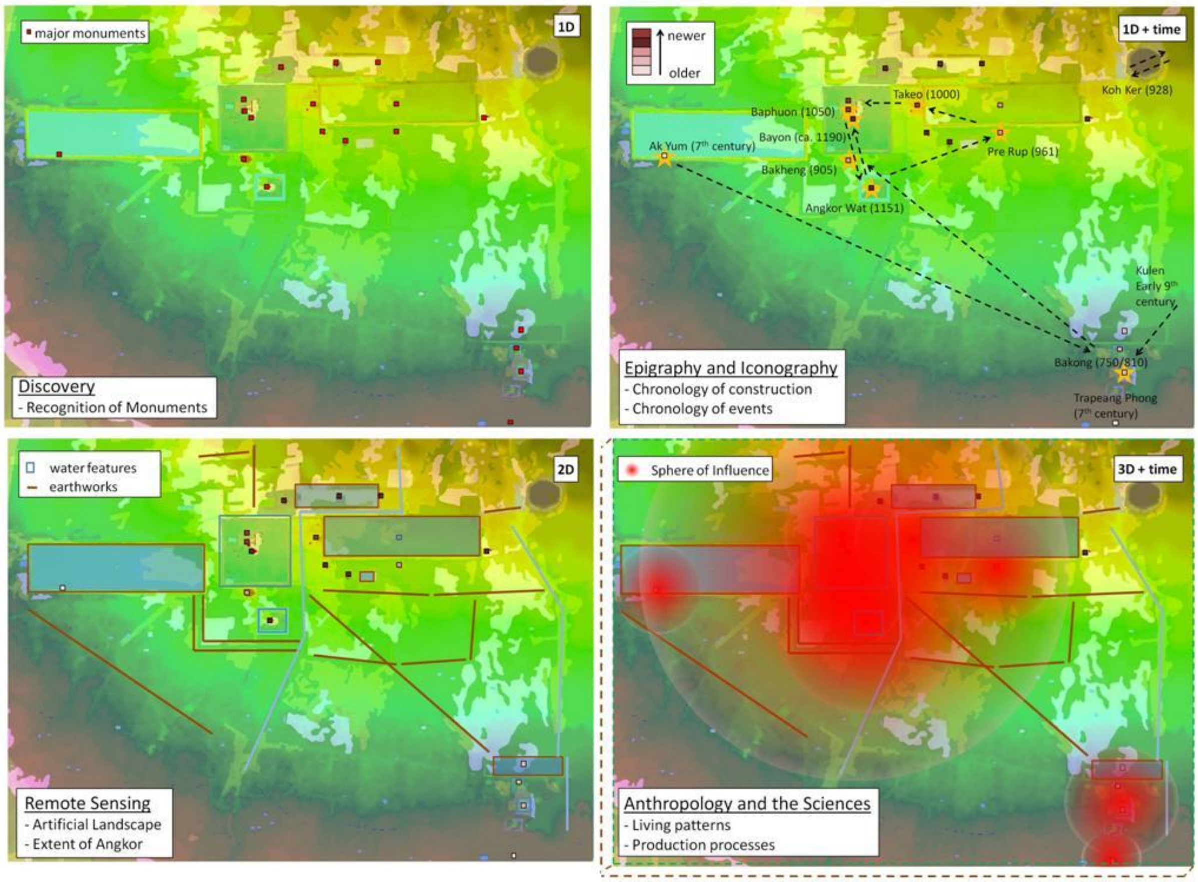


FIG. [15]: THE SUCCESSIVE USE OF NEW RESEARCH METHODS BROADENING THE KNOWLEDGE ON ANGKOR.

The early explorers recognized the temples as individual structures, separated by the vast jungle and as remains of an "ancient" period, here interpreted as disconnected dots; (1D). When epigraphists started to translate the stone inscriptions in 1879 and art historians interpreted the different architectural styles, the temples and the associated rulers were put into a chronological context to each other (1D + time). One of the first impressions that early explorers noted was the supposed perfect geometrical outline of the temples and the symmetry within the structures. With the implementation of aerial photography in the 1930s, the focus widened onto the large network of linear features consisting of earthen roads, canals and embankments of reservoirs and displayed the relations between them (2D). Since the 1990s, ystematic mapping filled the gaps between the linear features with ponds, mounts and rice fields creating a topographic surface that embedded not only the temples and earthworks into the archaeological landscape but brought life of the common people of Angkor into the picture.

The pyramidal monuments and topography provide already partly a 3-dimensional image by displaying a surface relief. The interest in the diachronic development of Angkor was intensified with the first stratigraphical excavations, which, according to B.P. Groslier, was initiated in 1951. With the interpretation of excavation results and the increasing use of scientific methods such as ^{14}C dating the focus broadened from the inaugural dates of kings and temples to living patterns of settlement and has called into question the strict inscription dates. Magnetic susceptibility challenged the construction chronology, while GPR as one of the non-invasive geophysical methods inks the studies of archaeological landscapes with excavations and extends the research focus in the 3rd dimension (3D + time).

Studying Angkor

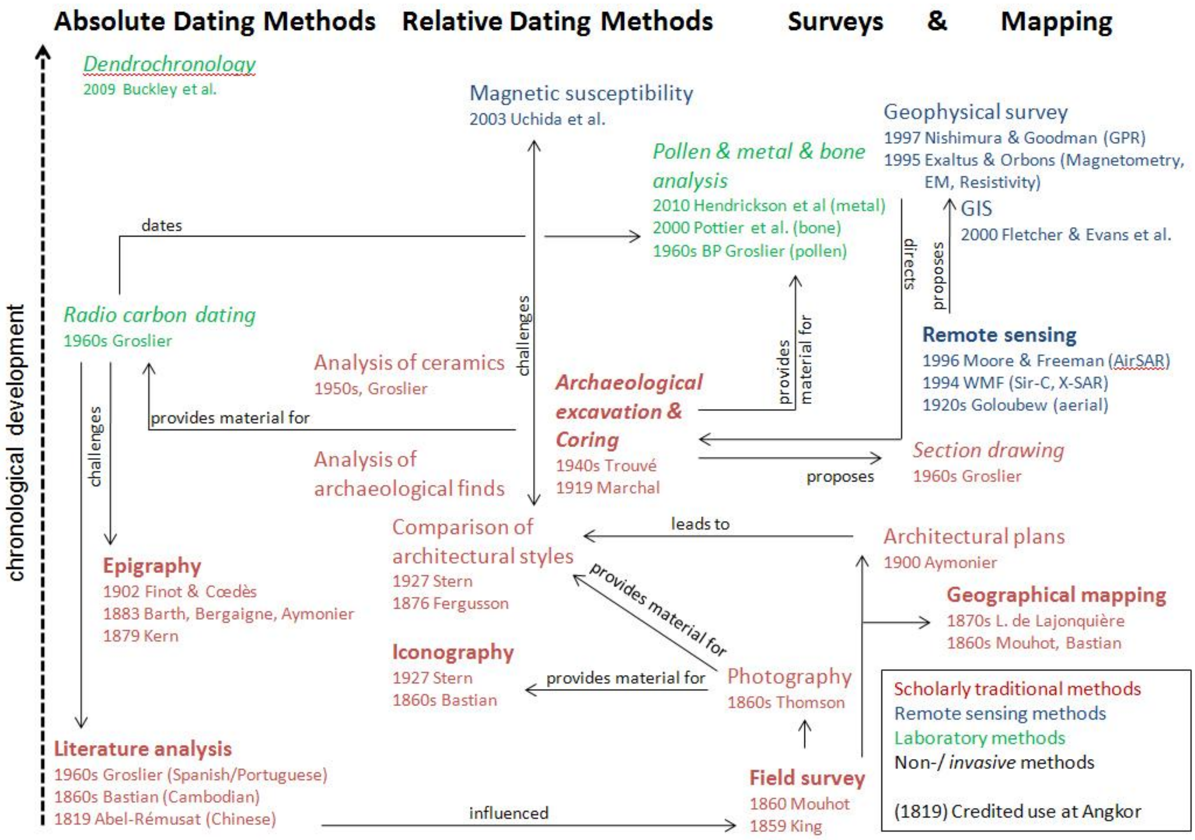


FIG. [16]: CONCEPTUAL MODEL ON THE SUCCESSIVE USE OF NEW RESEARCH METHODS IN ANGKOR.

Today Angkor is no longer lost and mysterious. New scientific research methods that have been developed and tested elsewhere were successfully introduced to the archaeological site and their results reported in scientific journals, see Fig. [16]. ^{14}C dating challenged the research on written documents and epigraphy which had provided data for a chronology of temple inauguration dates. New data also questioned important events such as the rulers' succession and wars with neighbouring states that embedded Angkor and the Khmer Empire into the history of Southeast Asia. Comparative studies of the iconography and architecture of the monuments have solved questions regarding their construction history, while the use of magnetic susceptibility differentiated stages of construction. By entering the subsurface, archaeological excavations have revealed masonry foundations and short lived wooden architecture, graves and their interior as well as ceramics, improving our knowledge on Khmer material culture and society, such as funeral rites and trade organization. The use of remote sensing increased the knowledge on the horizontal configuration of the Angkorian landscape, revealing the extent of the settlement and the enormous water management system.

We know now that Angkor was more than a group of great ruins. The major temples were in the middle of political centres whose successive relocation urbanized the surrounding landscape, creating a network of channels, banks and vast extended residential occupation. Structures had been demolished, overbuilt, reused and reconstructed. Subsurface analysis using geophysical methods could here test on the one hand the outcome of remote sensing techniques that target the broader landscape and prepare or expand on the other hand archaeological excavations, which in themselves only provide information about locally restricted areas.

CHAPTER (3) GPR, PROCESSES AND PROCEDURES

'Impenetrability! That's what I say!' (LG, VI)

Ground-penetrating radar (GPR) is the primary prospection method used in this study to detect and analyse subsurface features in and around Angkor. The research methodology was developed around this technique and was modified according to the local conditions. The chapter starts with an overview of the theory and the development of GPR as an archaeological prospection technique. The operating sequence for data acquisition in the field and the following processing steps are explained; this includes the insertion of data into GIS, and the analysis and interpretation of the results in conjunction with other data. To show the diversity of archaeological questions that can be addressed at Angkor, and to illustrate the effectiveness and limits of the technique, several examples of 'small scale' GPR surveys are given that preceded and accompanied archaeological excavations at habitation, production and burial sites.

(a) SENSING A LANDSCAPE BELOW THE SURFACE

'Now here you see, it takes all the running you can do, to keep in the same place. If you want to get somewhere else, you must run at least twice as fast as that.' (LG, II)

GPR is widely used in archaeological prospection to locate and measure the extent and depth of subsurface features, and due to the 3-dimensional results it is regarded as one of the most complex as well as versatile of the geophysical methods used in archaeology.[551] Advances in GPR processing, the digital recording techniques, data storage capacity and faster analysis, have made this geophysical method a true landscape survey investigation method, not only used as a support for aerial surveys and excavation. Compared to the extensive use in archaeological surveys worldwide, only a few mainly unpublished GPR surveys within Angkor are known.

i. INTENT OF THE SURVEYS

The individual GPR surveys at Angkor were initiated by questions based on the historical background, previous archaeological work, an analysis of remote sensing data, and potential geometrical/symmetrical relation of visible archaeological features. Assuming that the local ground composition provided reasonable potential for a positive detection of underground features by GPR, a target area was defined for the survey. The surveys can be sorted according to the degree of prior archaeological knowledge about the area in terms of the expected outcome, starting with the highest potential:

- **Appraisal**: to find natural or archaeological features on the basis of previous well-founded assumptions; to further clarify, correct or extend the knowledge
- **Identification**: to find natural or archaeological features on the basis of rather vague assumptions; to contribute to a more precise hypothesis

- **Discovery**: to find unknown archaeological features on the basis of a configurational pattern; to form a hypothesis for further investigation

Principally GPR means measuring and processing the reflected energy and travel time of an electro-magnetic wave sent into the subsurface. The most basic information collected consists of single signals. The successive return signals are combined in a GPR profile (or –transect) which provides, with the use of special software, a vertical cross-section of the subsurface. The stored raw data from the GPR measurements that are processed and displayed as radargrams can be seen as a primary result from the survey. The use of more sophisticated software, which combines a set of parallel profiles, provides subsurface information of an area in a 3-dimensional grid. This allows the determination of location, dimension, depth, and form of a detected object. To describe the local variation in the GPR signal response within a radargram, depending on wavelength, reflection angle and ground composition, the term anomaly is used. It signifies a surface or object with different electro-magnetic characteristic (dielectric and conductivity) that triggers a stronger reflection or varies in its reflection angle and is therefore distinguishable from its surrounding. From now on the term anomaly is used for interpretable features or objects detected in 2-dimensional GPR profiles and 3-dimensional grids. The analysis of those anomalies in the context of the ground composition leads to primary results in a broader sense. With additional information from historic sources, related archaeological excavations, and other survey methods, conclusions can be drawn about the material, and its archaeological the purpose and previous and possibly changing use of the measured anomalies.

ii. GPR Theory and Application

'The question is,' said Alice, 'whether you can make words mean different things.' 'The question is,' said Humpty Dumpty, 'which is to be master - that's all.' (LG, VI)

Theory and Terminology

GPR is a non-destructive geophysical survey method to evaluate the stratigraphical complexity of the near-surface underground. With knowledge of the ground composition and the signal velocity, the resulting data provides precise information on the location of the feature. GPR exploits the wave character of electromagnetic fields. The basic physical principles behind radar physics are described with the Maxwell equations, which explain the properties of electromagnetic fields and their relationship to each other. Planar layers or boundaries provide the most basic examples of wave propagation, as here the wave arrives at a specific angle of incidence defined by the height of its source, which here is represented by the antenna, and the lateral distance of the layer from the source. The linear wave propagation and the refraction, reflection and transmission of waves at interfaces are described by Snell's law and the Fresnel coefficients.[552] The GPR waves are also subject to attenuation, which is controlled by conductive dissipation of the ground that it transmits through. Radar wave reflection must be correlated directly to subsurface features in order to make accurate correlations of their depth. The two-way travel time (TWTT) of the signal measured in a GPR survey must be converted to distance, e. g. depth below the ground surface or elevations above datum. However, this can be complicated when the ground composition changes. For inclined or dipping reflectors, wave propagation is more complicated, as the distance to the reflector and with it the travel time of the signal changes with depth. By applying a migration process, it is possible to determine a dipping layer, to improve a "*distorted image subsurface stratigraphy and features in the ground.*"[553] The scattered radar diffraction signal is calculated back to its point of origin and the dipping reflector can be geometrically re-located to its true subsurface position. To apply migration, some knowledge about the layers' velocities is needed, which can be obtained by measuring the travel time to a buried reflector of whose depth is known. Alternatively the velocity can be determined by hyperbolic matching of point source targets contained in the raw radargrams. This provides higher accuracy in determining the depth and vertical extent of archaeological targets.[554]

The resolution of a GPR survey consists, as Annan states, "*of two components, namely the longitudinal resolution length [concerning the range of depth] and the lateral resolution length [concerning the angular or sideways displacement].*"[555] Longitudinal resolution of the signal is directly dependent on its distance from the source: The further the source, the lower the resolution. Lateral resolution additionally depends on the signal's pulse width and its velocity in the soil. Therefore ground penetrating radar antennae are set up to be focused in downward direction to provide the least scattering.

Resolution and penetration depths are directly related to the frequency that is used by the system. A higher Frequency provides more accuracy and therefore better resolution. However, amplitude loss due to attenuation and scattering of the signal are less in low frequencies, which provide better penetration. For archaeological prospection a frequency range of 200-800 MHz antenna is usual, depending on the aim of the study and especially on the size and depth of the feature being searched for.

Ground Properties and GPR Signal Velocity

The velocity of the radar signal, based on the ground composition, is the primary factor to differentiate features in the subsurface. Several geological factors limit the results achieved by the GPR. Depth and resolution of the survey are heavily dependent on the physical ground properties. For example high clay content and salt water can trigger a weak response signal or influence the signal-to-noise ratio. There are several key factors that influence the outcome of signal penetration depth in ground penetrating radar. The issues have been widely discussed in publications concerning the use of GPR.[556]

Variations in *electrical conductivity* ε and *dielectric permittivity* σ especially influence the survey, and so does to a lesser extent *magnetic susceptibility* μ. Keary *et al*. explain that reflection of the radar pulse occurs when there is a strong contrast in dielectric properties across an interface, resulting in a diminution of energy.[557] Since dielectric permittivity is relatively constant in natural soils and does not vary more than factor 10, the more variable conductivity has strong influence on the depth.[558] If $\sigma=0$ which means the ground has high resistivity and electrical loss is low, GPR could penetrate to great depth, while a high σ as it is in a conductor like saline soils, or saltwater, the signal would disperse rapidly. Depending on antenna type and soil properties, Kearey et al. picture a possible depth of 20m or even 50m. Especially the presence or absence of water in rocks is a dominant factor for their electrical properties. As water is present in all natural material, filling the pore spaces, dissolving the salt and containing conductive ions, the electrical conductivity of the water is the major factor in the conductivity of the soil. This influences the velocity of the radar signal, which is the important measureable factor to define the depth of an object. Velocity can vary widely from 1-1000 m/µS (equals 0.001-1ns/m).[559] Conyers states that GPR "*is especially effective in certain sediments and soils between about twenty centimetres and five meters below the ground surface, where the targets to be imaged are fairly large, hollow, linear, or have significant physical and chemical properties that contrast with surrounding medium.*"[560] Conyers & Lucius describe the main impacts on the signal velocity:

> *"In most settings, the water content of soil and sediment will increase with depth and the average radar wave velocity of the material will correspondingly decrease. The degree of residual water content in the vadose [lat: shallow, also called unsaturated (ed.)] zone and the depth to a water table can fluctuate because of topography, stratigraphy and drainage features. In archaeological context, anthropogenic activities can often create layers which contrast in velocity of those that surround them, complicating velocity measurements."*[561]

An overview of radar signal velocity in soils is displayed in Tab. [1]. Some characteristics of Cambodian soils in regards to the use of GPR have been discussed in Chapter (1).

	Goodman (1994)	*Conyers & Lucius (1995)*	*Kayen (2003)*	*Mala Easy 3D (2007)*
Standard (unknown)				0.1
Air				0.3
Water				0.033
Limestone (wet)				0.09
Limestone (dry)	.106			0.12
Concrete (dry)				0.15
Clay (wet)				0.074
Clay (dry)				0.15
Silt (wet)				0.063
Silt (dry)				0.1
Sand (wet)	0.055		0.06	0.055
Sand (partly saturated)	0.075			
Sand (dry)	0.11	0.1499	0.15	0.15
Fine grained soil			0.05	
Soft cohesive soil	.1		0.05	

TAB. [1]: SOIL VELOCITIES ACCORDING TO DIFFERENT SOURCES[562] (VELOCITY IN [M/NS].

Setting up the Instrument

A standard GPR system for archaeological purposes consists of a transmitting and receiving radar antenna integrated in a single case, which is shielded to prevent background noise. The antennas are connected to a control unit, which produces and regulates the radar pulse. The data is recorded either on an integrated hard drive or linked to a notebook. The system is powered by a rechargeable battery. GPR software allows some initial processing and data check in the field. The data collection is done by moving the equipment over the ground, while either periodically or every few cm (measured by an attached survey wheel) it sends an electromagnetic pulse into the subsurface. Whenever the signal hits a layer with a different electromagnetic property than the layer above it, part of the signal is reflected and sent back. The rest of the signal progresses as explained in Snell's law and is reflected from every subsequent layer. The signal diminishes when noise, as a result of the signal's dispersion in the ground, overpowers the signal response. The remaining signal energy is received by the second antenna and the time elapsed (travel time) is measured in nanoseconds [ns], while the velocity for electromagnetic signals is displayed in meters/ nanoseconds [m/ns]. The subsequently transmitted signals from one survey line are combined in a radargram. With knowledge about the composition of the subsurface from coring or a GPR velocity analysis using hyperbolic matching from point source reflections[563] the travel time can be converted to depth, allowing the creation of an electromagnetic image of the subsurface.

Regional Soil Composition and Signal Penetration Depth

The soil composition and the varying groundwater table have a major impact on the signal response and the penetration depth of the GPR, as the combination of minerals and water content enhance or reduce the radar signal propagation significantly. The topsoil at Angkor mainly consists of clayey sand that is several meters deep.[564] When excavated and dry, it can become very hard and impenetrable to water,[565] as found on the earthen embankments and so called "occupation mounds," and in the base of clay beds in canals.

The calculation of the *two-way travel time* (TWTT) GPR signal and its conversion to actual depth in meters was compared to the measured depth of structural foundations in associated excavations, mainly laterite in hardened clayey sand.[566] At those sites the approximated standard ground velocity of 0.1m/ns[567] was reasonably close to the results measured, especially if the depth of the features was rather shallow. This average is close to the velocity of loamy soil of 0.09m/ns[568] and dry sand 0.11m/ns.[569]

To have approximate depths for water management features the standard ground velocity of 0.1m/ns were then applied. The fluvial plains provide similar near surface ground composition all over Angkor; the standard ground velocity was adopted to display approximate depth for all archaeological sites in the region. Since the surveys mainly concentrated on gathering information to ascertain if something existed and not how deep it was located, the exact depth of a feature was not of crucial importance for the outcome of the survey. As the surveys were generally conducted in the dry season, the seasonal weather condition would have influenced the signal velocity only to some extent.

The signal depth or TWTT range was set up according to the survey focus in Cambodia as the penetration depth varied significantly. The maximum depth depended on the antenna type used, which required for the landscape surveys the use of the larger 250MHz antenna. The principal factor for penetration depth was the local ground composition. Measurements ranged from less than one meter depth to approximately four to five meters, considering the limited knowledge about the soil velocity in the area to calculate the travel time to depth conversion.[570]

The worst signal penetration was recorded over the compact clay of roads, large embankments and some habitation mounds where the signal depth sometimes reached less than one meter. This contravenes Angkorian archaeology: as the main construction took place on raised mounds they provide the highest probability to discover buried features. The subsequent construction and destruction periods are detectable in several areas where archaeological evidence was found several meters under the ground, such as the areas of the royal palaces at Angkor Thom[571] and Prei Monti.[572] For most archaeological places of interest at Angkor though, signal penetration depth of one or two meters was usually sufficient to detect structural remains, such as buried walls or foundations. Smaller features below this depth would be difficult to interpret anyway, since the resolution of the radar signal degrades with depth. For grids, a depth of about

50ns TWTT was set up, as the survey was mainly done on dry ground and concentrated on masonry remains close to the surface; this travel time corresponds to a depth of about 250cm when assuming the average velocity.

The best GPR penetration depth was achieved mapping channel features on sandy soil in saturated but not flooded areas, for example in the plain around Hariharalaya with its vast rice fields, which were reachable in the late dry season (see Chapter 8). A signal depth of 400-500cm[573] was measured in the desiccated ponds and saturated ground of former river beds. The increased penetration depth from dry to saturated sand has been known as *"radar lensing."*[574] Nobes *et al.* explain this effect: "*the lower velocity (due to high dielectric permittivity) causes the radar signal to be more focussed into the subsurface, and more energy goes into the area beneath the stream.*"[575] Therefore: *"The apparent increased depth of penetration is partly due to the increased time required for echoes to return at the slower velocity, but the larger two-way travel time does yield a greater depth of penetration."*[576] For this reason a depth of 80ns-100ns TTWT (corresponding to about 450-500cm) was set up for the long GPR surveys.

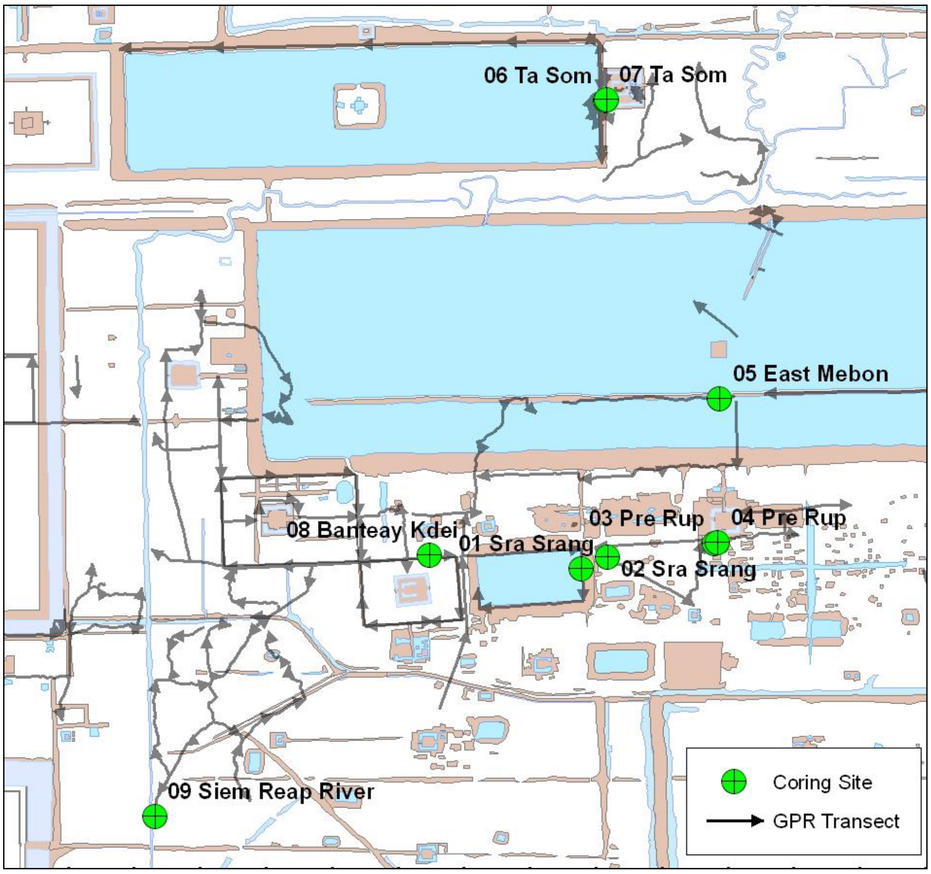


FIG. [17]: CORING AT SELECTED SITES FOR GPR ANALYSIS (BACKGROUND: POTTIER).

Coring was applied to several sites in order to understand the nature of the clay where the GPR was not able to penetrate the surface, in comparison to deep penetration, see Fig. [17]. The results from the hand coring and probing showed that penetration depth was directly related to the density of the earth, the tougher the ground the higher the resistance toward signal and corer. Once extracted from the ground the hard clay turned into very fine grained loose soil.

The ground composition of mainly fluvial deposits in the Angkor plain differed significantly from other Cambodian archaeological sites. Comparing the surveys with results from the Kulen Hills, Koh Ker, Banteay Chhmar and Preah Khan of Kompong Svay was helpful to correlate the reflection of the GPR signal with different types of surface geology and environmental properties in Cambodia.

Koh Ker

Lateritic ground was covered by a thin layer of soil and there were no fluvial deposits close to the temple site. Using the 250MHz Antenna, the GPR did not get a reading below one meter in rice fields. It was not clear if the non-detection of canals was based on the ground composition, or if canals that were suspected to run on the west side of Prasat Thom simply did not exist.

Preah Khan of Kompong Svay

Similar to Koh Ker, laterite was detected very close to the surface, covered by approximately 30-40cm of soil.[577] Penetration depth of the GPR survey was thus shallow and the noise factor very high. The mapping of the canal, running through the centre of the *baray*, showed however that for a number of purposes GPR proved useful at PKKS.

Banteay Chhmar

The region provided less penetration depth than the floodplain of Angkor, but it was significantly better than in the previously described areas. GPR results from within the reservoir did not provide sufficient information to support or negate a proposed natural laterite layer close to the surface.[578]

Kulen

A survey in the Kulen Hills, that was initiated to investigate the interior of a recently discovered enclosure, did not produce readily interpretable results. Although information was missing from excavation about the consistency of the subsurface, preliminary results showed the soil was soft and signal penetration depth reasonably deep to about two meters.

Setting up a Grid

Selecting the right antenna for archaeological purposes depends on the "*correct operating frequency for the depth necessary and the resolution of the feature of interest*".[579] Generally it can be said that a higher frequency provides higher resolution but less penetration depth. The surveys in Angkor were carried out with 250MHz and a 500MHz shielded antennae exclusively on a Malå GPR system. The antennae are shielded with the objective to enhance the signals response, reduce influences from other radio sources over the ground, such as power lines, radio towers or cell phone. Besides the close proximity to the ground the shielding minimizes leakage of the signal into the air as well.

The small temple site of Prasat Phtu (see Chapter 5) served as a test case to assess the capability of the 250MHz and the 500MHz antenna, and to identify the most suitable antenna for the following tasks, see Fig. [18]. Both antennas were used for the same profiles and grids. The results were that the 250MHz antenna was the more stable one, with a signal penetration depth that was considerably better and the resulting resolution using 50cm spacing was comparable to the 500MHz antenna regarding the size of masonry to be detected. This is the reason for the use of the 250MHz antenna in most of the following surveys.

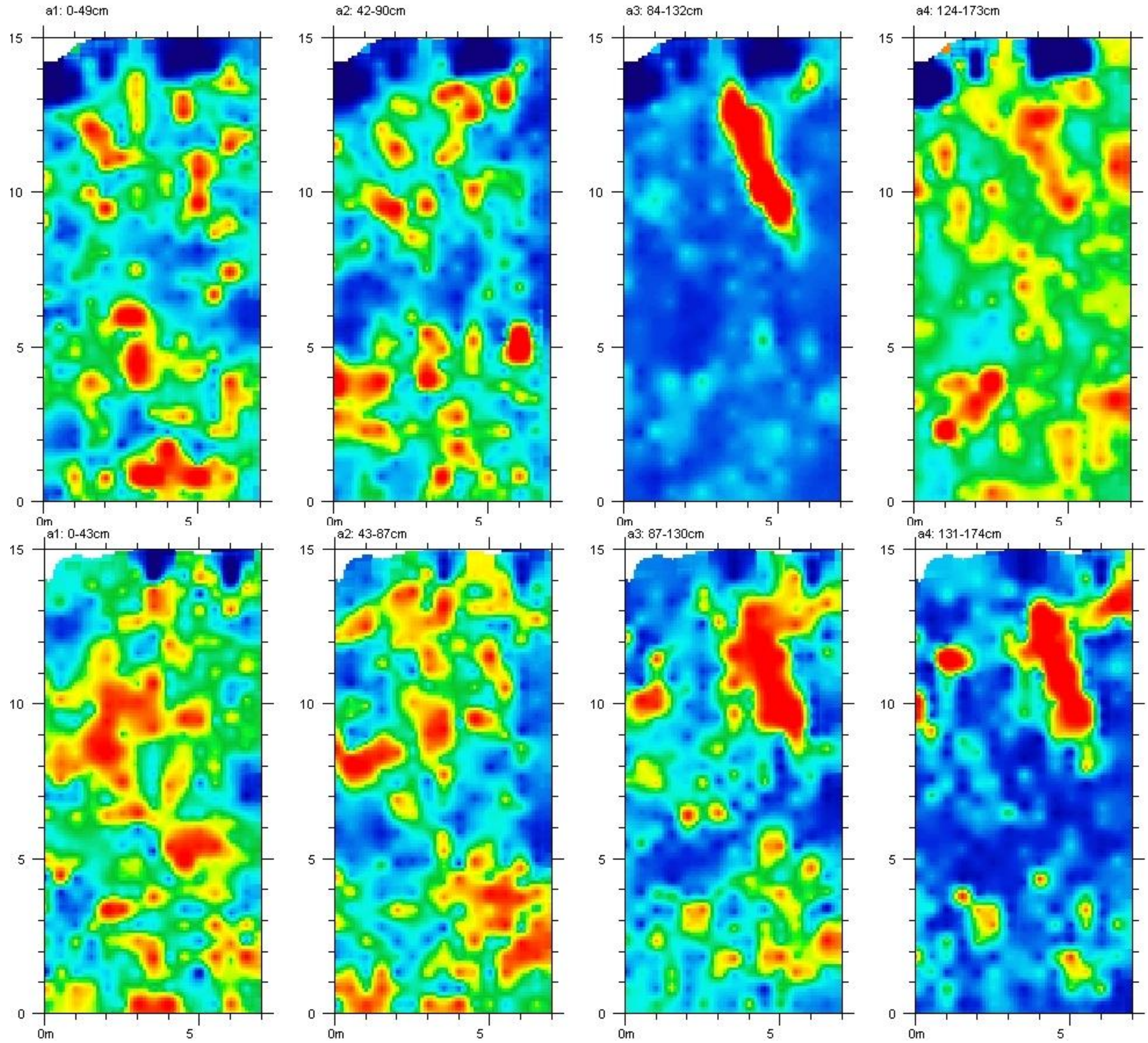


FIG. [18]: IMAGE COMPARISON OF THE SAME GRID SPACE WITH LATERITE WALL; 500MHZ (ABOVE) AND 250MHZ ANTENNAE.

Regarding the interpretation of water management features, the choice of antenna was simplified, as here the depth of canals and river basins clearly had priority compared to the resolution of near surface features. The standard equipment to investigate sediments are low frequency antennas, ranging from 25-200MHz.[580] Since only two millennia of fluvial deposits at Angkor are of importance to differentiate natural and human made stratigraphy, the 250MHz antenna was sufficient.

iii. Processing and Interpretation of the Data

'May I give you a slice?' she said, taking up the knife and fork. (LG, IX)

While a number of features, such as canals, were already detectable in the field, further interpretation and classification was only possible in conjunction with additional data processing.

Filtering Single Profiles

To interpret first results directly in the field, the Malå monitor provided basic filters to enhance the signal. The profiles however were then downloaded as raw data. A set of three filters was applied to each individual transect, to improve the data's characteristics, remove noise and enhance the signal vertically.

- ***DC-Removal*** – Mala equipment sometimes produced a constant electrical DC-(direct current)-offset, which created a shift in the mean amplitude of the waveform. The DC-removal eliminated the offset of the signal amplitude from each individual "*trace*", or one single return signal.
- ***Band Pass Filter*** – Although named 250MHz or 500MHz antenna, the signal emitted consists of a wide band of frequencies comparable to a bell shape. The band pass filter allows only a defined bandwidth to pass. For this a Fourier transformation was applied to convert the signal into the frequency domain and the filter was applied. For the 250MHz antenna, a band pass filter between approximately 100-500MHz was implemented; frequencies above and below this were suppressed.
- ***Time Varying Gain*** – worked as an amplifier of the signal. It compensated the amplitude loss of the signal from spread and attenuation and enhanced the lower reflections. The application affected the interpretation strongly, as the amplifier was individually applied on profiles using linear or exponential enhancement, and the best possible outcome was chosen.

Processing Grid Data

To survey an area with GPR, a rectangular grid was set up. The instrument was run over the total outlined area in parallel lines in either east-west (EW) and west-east (WE) or north-south (NS) and south-north (SN direction. Obstacles hindering the survey such as trees, termite mounds or buildings, were marked in the plan. The decision for the spacing between the survey lines had to be a compromise between the velocity of the survey and the resolution of the results. Narrowing of the grid lines made the survey take a considerably longer time to complete, while the resolution could be improved only to some extent.[581] Considering the size of some survey areas as well as the expected extent of the subsurface features, 0.5m spacing was the line spacing for all grids. In several smaller grids the survey was done in all directions, and the data later combined to improve the resolution; the results however did not improve much. Concerning the size of grids, the rule was 'the larger the better,' with minimum obstacles in the path of the GPR to make the results interpretable. If possible the GPR was always run to the end of the stacked tape. If this was not possible due to an irregular area, a baseline was set out from where the GPR wheel measured. Before a profile or grid was begun, the antenna offset was set to 0. Special GPR software[582] that integrated knowledge about ground velocity and the *travel time to depth* relation (and was initially developed exclusively for archaeological prospection purposes) was used to integrate the data from each line in the anticipated grid and produce a depth-dependent three-dimensional map of the surveyed area. The map can be viewed as horizontal slices, layer by layer defined by the depth, known as time-slices.

Several steps of processing had to be followed to produce a 3-dimensional image of the subsurface:

a) Setting up the data frame:

- Setup of a virtual information grid file that provided x, y-location of every radargram.
- Since the GPR was run in both y, and minus-y direction for data collection, the direction of the radargram had to be corrected.

b) Processing of the data:

- **0-offset repair** - 0-offset is the measured time of the first return signal. An error that occurred because of sudden jumps in the recording process due to equipment failure. This happened mainly in rough terrain.
- **Gain** - Linear and exponential enhancement of the signal amplitude by depth is needed to strengthen the weakening of the return signal from dispersion over time, and to equalize the signal to depth ratio.
- **Filtering** - There was no need for manual additional filtering since automatic filters were applied and it was shown over time that the data did not appreciably improved (using methods such as migration and deconvolution).
- **Resampling** - processing vertically downwards, starting from the newly calculated 0-offset, where each radargram is cut into equally spaced time divisions of signal return.

c) Developing a 3D image

- **Slicing** – Using the data from the complete set of radargrams, the slicing process averages "*over the squared amplitude of the reflected radar signal over a horizontal spatial window and a vertical time (depth window)*"[583]
- **Automatic kriging interpolation** – a process (using a least squares estimation algorithm) used to calculate a mean value between the data points and a central point.
- **Gridding** – using the information provided, with a search radius including information of at least 3 radargrams (at 50 cm spacing an interpolation search radius of 75 centimetres was used), horizontal time slices are produced; with knowledge about the ground composition time can be converted into actual depth.
- **Topographic correction** – In special occasions and if the topography was an important factor and had been measured on site, the results could be recalculated with a topographic correction.

This resulted in horizontal slices to detect and measure size, depth and form of the anomalies, from which 3D images were created and presented here in the thesis.

iv. GPR AND THE REGIONAL ENVIRONMENT

Alice laughed. 'You must hit the trees pretty often, I should think,' she said. (LG, IV)

Survey limitations due to Geographical Aspects

Field research in the Cambodian countryside was limited by a number of variables. Challenges included natural obstacles, such as dense vegetation or seasonal flooding, or human made obstacles, such as private property and the ongoing threat from landmines in some outlying enclosures.

The Size of Angkor

One major constraint for a detailed GPR survey was the sheer size of the archaeological landscape of Angkor. The Angkor flood plain covers over 3000 km^2 and includes hundreds of archaeological sites and many kilometres of Angkorian canals and roads,[584] making it the largest integrated archaeological landscape in the world. The area that was possible to cover by GPR for this thesis was in consequence limited to locations that had the highest potential for interpretable results. Whilst GPR is used in long 2-dimensional surveys for engineering purposes (e.g. road analysis[585]) or geological mapping, as well as in large scale archaeological investigations,[586] covering the archaeological park of Angkor would be difficult even for fast recording techniques (e.g. the antenna mounted on a quad bike). The landscape survey that covered the water management system (see Chapter 8) is very similar to a road analysis, but the target features (e.g. silted up canals and river beds) are much larger, more in the category of tens of meters, and therefore are more easily detectable. The distance interval between recordings was consequently extended to 5cm spacing. The combination of this GPR data with aerial image data brought the results close to a 3-dimensional survey of a large scale area. The relatively simple ground composition of the near surface geology of the Angkor floodplain provided the base to extend the mapped GPR anomalies into the landscape using the remote sensing data.

Dense Vegetation

The Cambodian countryside is in the main, either covered by woodland or rice fields; in particular the inner part of the archaeological park, surrounding Angkor Wat and Angkor Thom, is covered by dense forest. The thick underbrush in these forests prevented the instrument from being used anywhere other than on paths. The forests provide an immense number of trails hacked by local people for travel and to collect firewood. In the area around Angkor, JICA[587] has mapped a large number of those forest trails. The JICA maps (more information in Chapter 4) were crucial to the data collection for orientation in the field, as the GPS often did not receive any satellite signals in the forest and the collected GPR data was useless if not locatable on a map. Where ever possible GPS locations were recorded and later complemented with the map.

It was also possible that the path was overgrown and no longer detectable since the last mapping (1999-2005).

Flooding and Groundwater

The Cambodian climate influenced the GPR surveys critically. While the best weather for fieldwork is in early December till the end of March, when heat and humidity are reasonably low, at the beginning of the dry season most rice fields are still flooded and harvesting of rice starts around that time. The annual monsoon not only produces a seasonal flooding of the area but also raises the level of the groundwater table. Between January and March of 2005, R. Acker measured the ground water table of wells around Angkor, recording depths predominantly of less than 1.5m or 2.5m in the region around Bakong and Phnom Bakheng,[588] which was the highest level measured in the region. When the water had receded and harvesting had cleared the fields, the wet ground was best for conducting surveys, as the GPR signal penetrated wet clayey sand much better than when it was dry. Later the ground became very difficult to survey with the GPR, as the rough surface of the ploughed field and the dry clayey sand made useful data recording technically impossible. Other areas remained under water most of the year and hence acted as a natural boundary for data collection. Due to the seasonal flooding the survey was limited to raised paths and small roads.

Roads and Paths

Angkorian country roads were generally not paved. The exceptions are causeways in temple enclosures and the major bridges, associated with the period of Jayavarman VII.[589] Built purely from clayey sand, after more than 800 years of existence, many of the roads are still detectable and defy the weather conditions and annual flooding. Considering this, it is apparent how resistant the clayey sand is when once hardened. The radar signal barely penetrated those features. Some of the original Angkorian roads, such as the embankments from the large reservoirs, Yasodharatataka and the West Baray as well as Sra Srang, had occasionally a penetration depth of not more than one meter depth. Many of the major modern roads around Siem Reap are raised substantially above the ground level on causeways/ embankments and have recently been paved with tarmac. They were found to be impenetrable for the GPR, as the asphalt covers a thick gravel foundation. Although even for the unpaved roads reasonable depth penetration was often prevented due to the ground composition, that was usually hardened clay and to their height in relation to the natural surface.

Landmines

Due to Cambodia's recent past, there is still a limited danger of mines. Although potential minefields have been cleared within the Angkor Archaeological Park and Siem Reap, the common rule was to stay on paths in forested and unoccupied areas. This was especially necessary in the outlying centres where GPR surveys were conducted, Chau Srei Vibol, Preah Khan of Kompong Svay, Koh Ker, Banteay Chhmar and on the Kulen.[590]

Terrain and Property

The growing population of Siem Reap province and the resulting extensive construction complicated the data recording especially concerning long GPR profiles. New and larger buildings as well as fences that marked private property in the Angkor Park limited the length of profiles. If possible, private property was left aside in transects and grids and large surveys were conducted on unoccupied ground.

To summarize: the perfect location for long profiles consisted of paths in a forest free area of even topography, which was slightly raised over the natural surface and still undeveloped.

V. ANOMALIES IN GRIDS

*'Found what?' said the Duck. 'Found **it**, the Mouse replied rather crossly: 'of course you know what 'it' means. (AW, III)*

Due to their 3-dimensional nature, anomalies in grids have a very different appearance and can be detected and identified best when combining the information from the GPR profile in the processed time slice showing the data from the top view and in the 3-dimensional view. Anomalies in grids can be made to stand out by using different shading or colours. In the analysis of grids in the thesis, a colour chart was provided for the software:[591] from blue, representing little reflection or a dispersed signal meaning no ground disturbance, over green and yellow, to red, symbolizing a strong reflection meaning an abrupt change between two soil layers. Consequently a void under a layer of soil would display a colour similar to dense material in the graphical presentation, here displayed as bright red.

Construction Material

Only durable construction material (e.g. laterite, sandstone and sand) was expected to be detected by GPR. Wooden beams, for example, were part of most roof constructions but generally have deteriorated over time.[592]

Masonry (brick, laterite and sandstone)

Masonry subsurface features were the main target in surveys using the grid method. Due to their density, stone structures under a cover of sand or soil appeared in grids in a bright red colour. The return signal from any of the three main construction materials - bricks, laterite or sandstone - despite the fact that that they consisted of very different components - could not be distinguished from each other; e.g. see Chapter (5).

Sand

When sand was used as filling material for foundations (in combination with layers of small rocks) the extent of the foundation trenches was often detectable as it provided a clear boundary towards the overlying and surrounding soil. However, in several occasions the remaining sand foundations, or potentially the small rock layers within them - see construction techniques in Chapter (5) - were at first misinterpreted as masonry, as they provide a similar abrupt change in reflection from the soil matrix; e.g. Angkor Wat in Chapter (5).

Obstacles and their Potential Misinterpretation

Earlier in this chapter major obstacles were mentioned that prohibited GPR surveys on a large scale, such as landmine zones, dense vegetation or infrastructure. Grids were therefore laid out in areas that had been cleared of dense vegetation. Within the grid, smaller obstacles had to be identified and marked to disqualify them as potential archaeological features. These types of obstacles are discussed below:

Natural Rocks

Being similar to masonry, the irregular outline of the feature makes the distinction between masonry foundation and natural stone. Small rock formations however can be misinterpreted as destroyed and buried foundations. Due to the massive alluvial deposits in the Angkor plain natural rock layers were only an issue in direct vicinity to natural hills of volcanic origin; e.g. see Chau Srei Vibol in Chapter (6).

Trees

Tree roots and covered tree trunks display a sharp hyperbola on the corresponding 2-dimensional GPR profiles, and those anomalies could usually be ruled out as such. The location of large trees as well as visible stumps were measured and marked within the grid plan after the GPR survey, so that in time slices straight roots of large trees were not mistaken as masonry; e.g. see Banteay Srei in Appendix.

Termite Mounds

The outer shell of termite mounds consists of very tough, hardened clay while the inner is soft and sponge-like. Even when destroyed the remains on the ground left an impenetrable mark in the GPR results, displayed in the time slices as a blue spot. Their frequency of appearance as well as the horizontal extension (five meters or more), were especially problematic for the radar signal; e.g. see *asrama* in Chapter (6).

Modern structures

Buildings, sheds, small structures and fences were clearly marked out on the field record map covering the GPR time slice. To ensure the correct distance of the measurement wheel regarding the profile, the instrument was moved to the side of the obstacle with secured wheel, moved along the obstacle, and put back on the right path at the other side; e.g. see *asrama* in Chapter (6).

(b) Sample Sites - Testing the Technique

> *Then she began to looking about and noticed that what could be seen from the old room was quite common and uninteresting, but that all the rest was as different as possible. (LG, I)*

Several 'small scale' GPR surveys were conducted at different archaeological sites. Most surveys were initiated in conjunction with other researchers as to investigate a specific task concerning living patterns at Angkor. The GPR surveys focussed on habitation patterns, work places, and cemeteries. Each of the categories is represented by several sample sites. The research question was, if and how each of the different occupation types (e. g. dwellings, burial sites, and production locales) could be investigated and made visible by GPR. Besides site specific questions, the research was conducted to apply the elements of the technique and to test the limits of GPR at Angkor, as was as furthering our understanding of how people used these locations in the past.

i. Habitation Patterns

Before archaeological research turned to Khmer habitation patterns, knowledge about the daily life of the Khmer in medieval times was very limited and mainly based on inscriptions, on the iconographic reliefs of the Bayon[593] (various images are devoted to the depiction of everyday life) and on the eye witness reports recorded by Zhou Daguan.[594] The reason for this was that structural evidence of medieval Khmer habitation, constructed of perishable material, such as wood and bamboo, had generally disappeared above the surface due to the weather extremes of the tropical climate, and it was of interest if any remains below the surface would be recognizable by GPR. Yet there is evidence of habitation everywhere in the landscape.

Due to the annual flooding which inundated most of the region, large parts of the population at Angkor had to live on any locations that were slightly elevated and provided firm ground in the wet season. Patchworks of habitation have been identified around local temple sites, associated with rice fields and earthworks. Additionally small mounds of varying size, form and height made of clayey sand and distributed all over the floodplain of Angkor were recognized by Pottier in aerial photos as potential habitation mounds[595] - living space of the Khmer commoners. This extensive living area of the main population at Angkor was detected by aerial and remote sensing methods by associating them to rice field patterns presumably from the Angkor period.[596]

A higher ceramic density also provides evidence of previous living areas. However, even the absence of surface scatter of ceramics on many earthen mounds does not discount them as having been used for occupation. The use of ceramics might not have been widely spread within the rural population - still today coconuts vessels and wooden dishes are frequently used. The space around the buildings is kept very clean; trash is swept to the side and accumulates beside the mounds. Also, the mounds might have had other purposes for the people besides habitation, for example they may have been elevated areas for animals to be safe from floods during the rainy season; or possibly used for vegetable and fruit gardens. These functions for mounds are common today.

Archaeological excavations concerning occupation remained for a long time secondary to the work on monuments. B. P. Groslier, who directed the first large scale excavations at the Royal Palace of Angkor Thom in 1952-1953, mentioned that they

> *"[...] unearthed foundation deposits, consisting of bronze plate jars, gold ingots and silver foil. The excavation of the domestic quarters and kitchen of one palace furnished us with a vast amount of kitchen waste (bones, etc.), important evidence as to the food of the period as well as to its fauna."*[597]

He was, however, aware of the limited knowledge the results produced, when concerning the common Khmer:

> *"These excavations were necessarily limited to a small area: and because we were obliged to choose the site of the Royal Palaces, our results cannot be uncritically extended to the whole of Khmer life; they express only a very special aspect of it."*[598]

In recent years, living patterns of common people were revealed e.g. by M. Stark[599] concerning pre-Angkorian life in the Mekong delta, at Angkor in the excavation at the Siem Reap Airport[600]and Prei Khmeng.[601] Trenches through canal embankments at Tumnup Barang by the Greater Angkor Project (GAP) unearthed stratified deposits of occupation debris. Accompanying surveys on the embankments of canals by GAP found a spread of ceramics and occupation debris.[602]

GPR Anomalies and Living Space

There is no record for successful geophysical investigations concerning Khmer habitation in Cambodia. Since masonry remains are absent, and any wooden structural features would have deteriorated since their instalment in the now empty and unoccupied spaces, it would be difficult to indentify traces of non-elite habitation using GPR.

Literature about GPR surveys on prehistoric living sites world-wide, which are similar to Khmer earthen mounds in the sense that there are no large structural or masonry remains, give information on possible targets. Whiting & Orvald[603] name soil moisture variation that occurred due to a difference in land-use as a potential result regarding the detection of living patterns. K. Kvamme named several features related to the general search for habitation by GPR, some of them could also have existed in a Khmer village, such as dumping grounds, storage and borrow pits and gardens.[604] In addition the remains of fire places, wells and latrines might be recognizable. Traditionally constructed huts in the Angkor region are generally built on stilts to withstand flooding. Remaining postholes from historic stilt houses could work as indicators for occupation, but because of their size are unlikely to be recognized by the GPR.[605] Regarding the life in modern Khmer stilt houses, most of the time is spent under the building in protection from the sun. A similar situation could be expected from a traditional population; therefore a strong occupation layer is not expected on the mound. Long term occupation hardened the soil surface under the building from the continuous pressure of people and farm animals.

Taking those accounts into consideration, the GPR survey targeted differences in soil density which should be recognizable comparable to uninhabited mounds. For analysis and presentation purposes, the GPR processing software is used to enhance strong signal return and to associate the measured energy to the colour table accordingly: from strong (red) to little (blue). In an environment of very little soil variation anomalies that are displayed red in the results might just represent a minimal soil difference, which could lead to misinterpretation and speculation without additional information - such as wall remains or geometrically arranged postholes.

Surveys were conducted at six sites that showed potential for habitation: on mounds (1) to the east of Banteay Srei to evaluate the data from other geophysical methods, (2) at Doun Kaev northwest of the West Baray, (3) at Run-Ta Ek east of Phnom Bok, and (4) to the east of Prei Monti. Additionally, surveys were conducted over linear earthworks: over the (5) northern embankment of the Indratataka and (6) to the north of Angkor Thom at Nokor Krau I. Some surveys were conducted with the knowledge of previous archaeological excavations and to cross-check their results.

Habitation Mounds

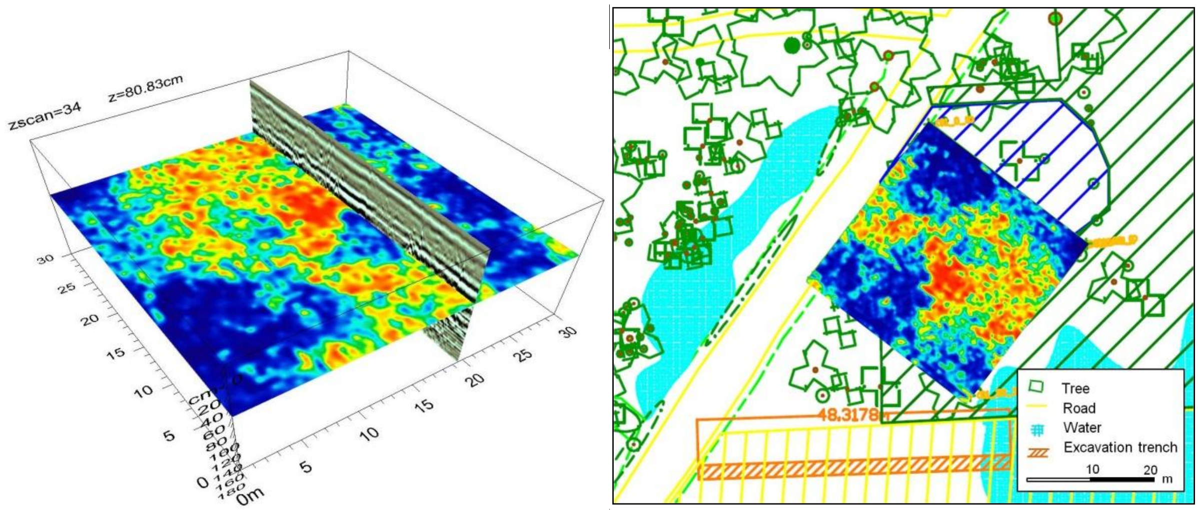


FIG. [19]: GPR FOOTPRINT OF A POTENTIAL HABITATION MOUND BANTEAY SREI (BACKGROUND: BSCP).

The GPR survey at Banteay Srei was conducted to crosscheck the results of magnetometry and resistivity measurements which had not detected any interpretable pattern regarding habitation in this area.[606] A 30m x 30m grid (BS_G1) was laid out over a slightly elevated habitation mound to the northeast of the temple, see Fig. [19]. The results show a roughly 20m x 20m square of less penetrable material that is oriented in east-west, north-south direction, from 60cm depth downwards traceable in varying strength and seems to be connected to another rectangular area further south. A second 30m x 30m grid (BS_G2) over a mound south of the central causeway of Banteay Srei revealed only an irregular distribution of small anomalies. A comparison survey over the rice field beside the mound (BS_G4) provided much deeper signal penetration than the mound but displayed also only a chaotic pattern of small anomalies.

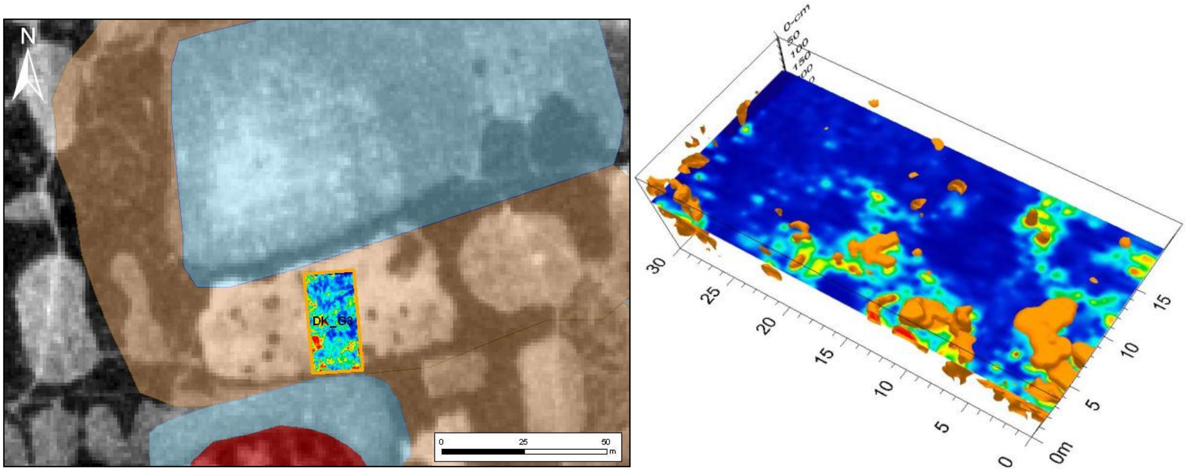


FIG. [20]: LANDSCAPE AND GRID DK_G3 AT DOUN KAEV INDICATE PATTERNS OF HABITATION (BACKGROUND, FINNMAP & EVANS).

A 30m x 15m GPR grid (DK_G3) was laid out to the north of two small temple sites of Doun Kaev - described in Chapter (5) - over a large mound which was located on the southern side of a *trapeang*. The nearby shrines as well as the pond to the north were indicators of potential habitation in the area, however very few ceramics were found in the area. The GPR results displayed an area nearly void of anomalies in the eastern part of the grid, and several stronger features to the west at 100cm depth, as it can be seen in Fig. [20]. While those anomalies display no geometric pattern, they display a clear signal difference to the surrounding and indicate a previous use of the mound. Analysis of the profiles ruled out the possibility of those anomalies representing tree roots.

A small grid (RT_G1) was laid out over a mound at Run-Ta Ek to the northeast of Phnom Bok, to compare the GPR results with the findings from a preceding archaeological excavation that had revealed a very limited ceramic distribution[607] - it did not show any clear patterns of habitation. Neither did profiles crossing the mound, however strong anomalies were measured besides the mound, see Fig. [21].

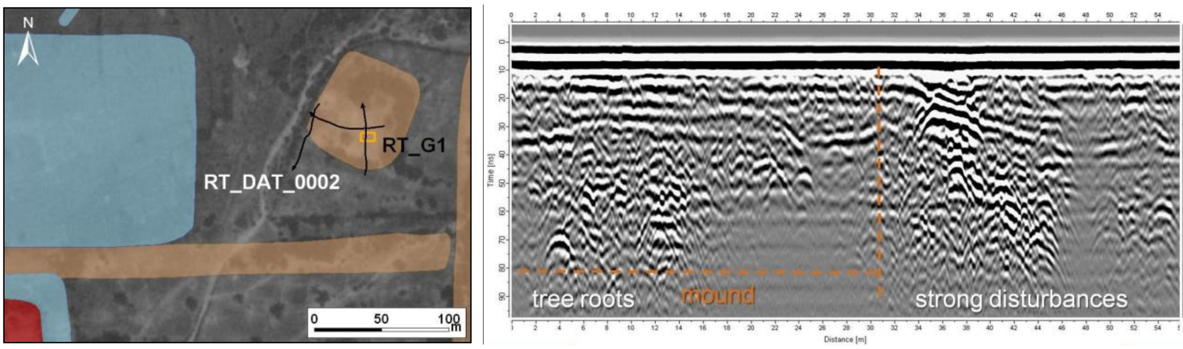


FIG. [21]: PROFILE RT_DAT_0002 INDICATES MAIN DISTURBANCES BESIDES THE MOUND (BACKGROUND: EVANS/ FINNMAP)

A special case of potential habitation patterns was investigated with long profiles over a large rectangular mound east of Prei Monti of approximately 100m width and 270m length. Since Prei Monti had been identified as the royal palace of Hariharalaya,[608] the mound was seen as significant due to its position in front of the former eastern entrance to the palace and because it was situated within the outer large moat that connected the Bakong and Prei Monti. The question was raised by C. Pottier[609] if the mound had served as an addition or had any connection to the palace.

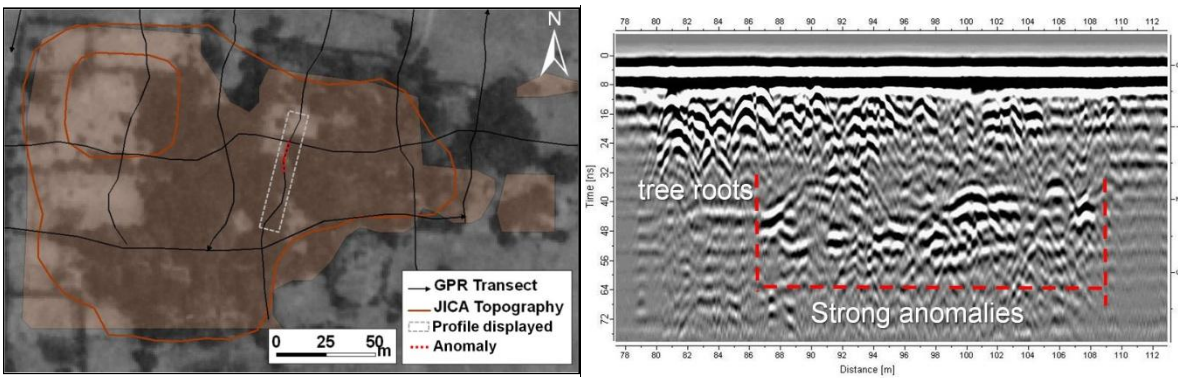


FIG. [22]: GPR RESULTS FROM THE MOUND AT PREI MONTI (BACKGROUND: POTTIER/ FINNMAP).

The mound displayed only few traces of ceramics or other evidence of living patterns. The sides of a large pit on top of the mound used as a sand quarry by the villagers did not display any clear stratigraphy, but showed there was pure sand down to about two meters depth. The GPR profiles over the mound showed ambiguous results. Several small but strong anomalies could have referred to structural remains, see Fig. [22]. Further survey work using grids to cover parts of the mound would be favourable, but the area is too densely settled to conduct large scale investigations.

Occupation on Embankments

Today settlements alongside linear earthworks are a common sight in the Angkor area as the linear communities of stilt houses provide connectivity to the road system. This would also have been the case in the Angkorian period, where the settling alongside canal and reservoir embankments provided direct access to the transport system, which was part of the multifunctional role of the linear earthworks; see Chapter (8). However, most embankments that now serve as living space have lost their original function as water directing devices. Fletcher *et al.* describe the potential breaching of embankments for the water management as having possibly prevented any denser habitation on some earthworks.[610] Hendrickson reports an abundance of ceramics from several centuries from an excavation trench through an Angkorian road, but points out not to not having found a distinct cultural layer associated with potential occupation, as the ceramics could be fill material of different stages of repair.[611] Since most Angkorian roads have suffered severe erosion, evidence may have been washed away from the surface. The analysis of long GPR profiles conducted over the northern Indratataka embankment showed that the penetration depth of the signal was generally in correlation with modern habitation patterns. Less penetration referred to areas of modern occupation, possibly due to a difference in soil density. However, there were also unoccupied areas on the embankment which displayed similarly low penetration depth, which could be an indicator for preceding occupation in the Angkorian period, see Fig. [23].

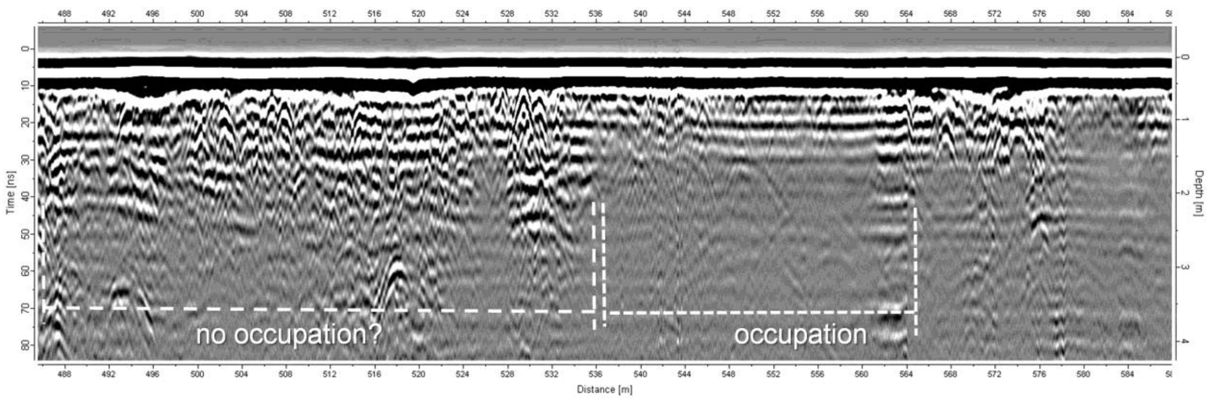


FIG. (23): GPR RESULTS FROM THE NORTHERN INDRATATAKA EMBANKMENT.

An excavation at Nokor Krau I by L. Benbow on the embankment of the moat of Angkor Thom in the search for living patterns,[612] revealed a thin lateritic layer at approximately one meter depth. The corresponding GPR survey (a combined E-W and N-S grid conducted by the author), to the east of the open trench, detected this feature and marked the extent. Due to the strong response, the laterite dominated the GPR result and displayed the difficulty to find living patterns along potential structural remains, see Fig. [24]. Despite this feature, the two areas surveyed at Nokor Krau I displayed only patches of small irregular anomalies, similar to Doun Kaev, and were not interpretable without additional information. Several GPR transects were conducted in the surrounding passing the excavations, to possibly relate the archaeological site with its environment.

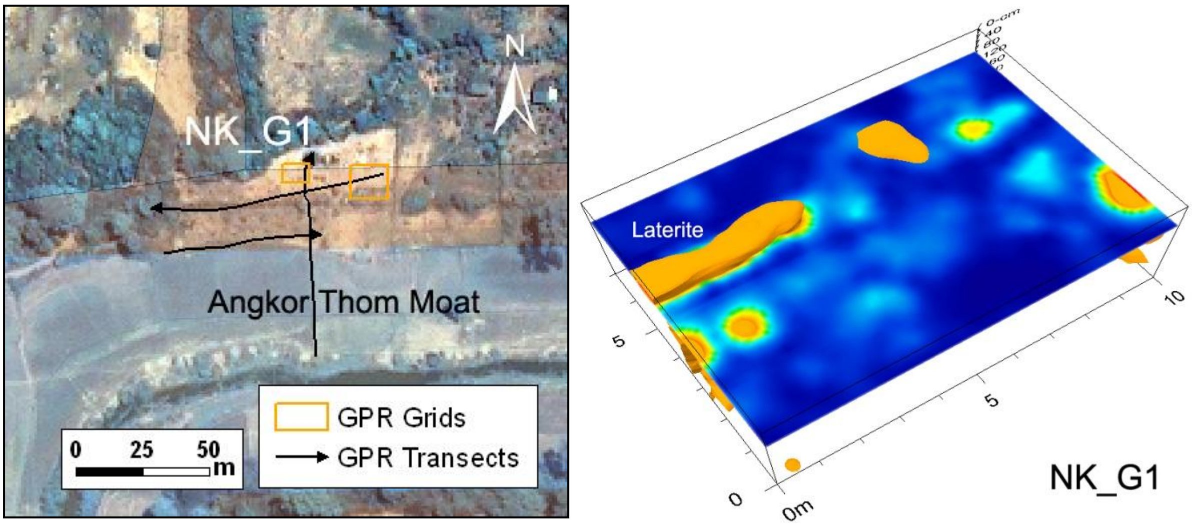


FIG. (24): NOKOR KRAU I AREA (BACKGROUND: POTTIER/IKONOS) AND GRID NK_G1 RESULTS.

Other Patterns of Habitation

The GPR survey detected potential habitation patterns which did not directly display areas of habitation, but anomalies that certainly indicate human intervention. At two archaeological sites, Chau Srei Vibol (CS_G11) and the *asrama* of Prasat Komnap (AS_G1), located south of the Yasodharatataka, analogous anomalies were detected in areas outside the enclosure walls. The anomalies detected have a rectangular form and enclose areas of less signal response about 20m wide and 40m long. The borders are about 1m wide and were detected rather deep under the ground (about 150cm).

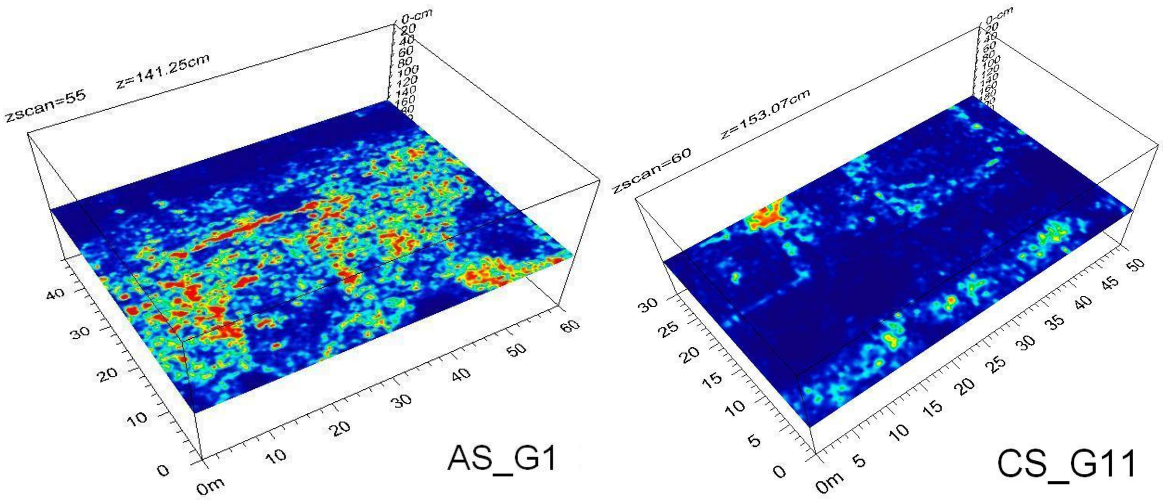


FIG [25]: DEEP LINEAR ANOMALIES AT PRASAT KOMNAP AND CHAU SREI VIBOL, POTENTIALLY REFERRING TO LIVING PATTERNS.

At both archaeological sites they were located close to the embankments in lower lying areas which might have been prone to flooding part time of the year. The features were too long to be walls of buildings, and the reflection too weak to be regarded masonry, but also too straight to be of natural origin; see Fig. [25]. The dimension of the features however seemed too small to refer to rice fields. Fields of nursery rice however have about the same size, and while it is rather speculative, they might have been the limits of a fenced animal barn, of which the hardened clay sides remained. Summing up the surveys on habitation, it has to be distinguished between the detection of living space and its analysis. The GPR results show that there is a limited possibility on detecting habitation due to differences in soil density. Hardened impenetrable clayey sand reduces the penetration depth. Large rectangular anomalies of hardened soil on mounds, first and foremost detected at Banteay Srei, could indicate a formerly inhabited area comparable to modern rural occupation. If this is taken as indirect evidence of long term occupation, the long profiles taken at the Indratataka embankment would display a possible method to measure the spatial extent of settlement features.

Concerning the analysis of potential occupation, the soil matrix provides only little penetrability that is needed for a further interpretation of the radar signal. Besides a stronger and weaker response from the top soil, no detailed pattern was distinguishable from transects or grid results. Smaller grid spacing of GPR profiles (e.g. 0.25m instead of 0.5m) would only improve the outcome if the GPR anomalies that have been mapped can be better defined. For that, more GPR studies in conjunction with other methods could improve knowledge on the detected features. This is questionable however, as even archaeological excavations at some potential habitation sites did not provide sufficient information to declare a mound as having once been occupied.[613]

ii. PRODUCTION SITES

Angkorian production sites integrate locations of archaeological finds that indicate an occupation by manufacturers and artisans, e.g. the making of pottery,[614] metal work such as iron smelting sites,[615] and the cutting and working of construction material, such as sandstone and laterite quarries[616] and sandstone workshops.[617] The latter two have not been investigated by GPR so far.

Kilns

In recent years the Bangkong Kiln site, situated north of the Indratataka, has come under pressure from development. A GPR survey on several kilns to study structural elements was proposed preceding excavations, which were to salvage some of the ceramic material. Previous work on kilns had revealed information on their structure. Geophysical surveys conducted by Y. Nishimura in 1994 before the excavation of Angkorian kilns at Tani,[618] situated northeast of Phnom Bok, revealed the extent and structure of the fire chamber under the mound of a kiln. Following the surveys, the structural elements were verified by excavation. Similar structural features were unearthed when a kiln at Thnal Mrech on the Kulen was excavated.[619] At Bangkong the kilns differ in appearance, as they are only slightly raised mounds, and therefore more difficult to distinguish from the surrounding landscape.[620] Bangkong represented an archaeological site under threat of destruction, since several kilns had been bulldozed by the time the survey was conducted. A previous field survey by APSARA personnel had discovered several unknown potential kilns in the area.[621] Four sites were chosen for investigation,[622] representing five categories of the kilns' status: (BN_G1) intact for testing of results, see Fig. [26], (BN_G2) partly bulldozed to detect the fire chamber, (BN_G3) completely destroyed to measure the remaining features, (BN_G4) as well as one site where a kiln was expected regarding the change of soil properties and ceramic distribution. While constructed of the same material as its surrounding soil context, the burned and hardened clay structure of the kiln was expected to return a different signal.

The flat ground surface of the area made topographic correction for the interpretation unnecessary. The survey revealed sizes and structures of several kilns. Strong reflections were associated with the hardened walls of the original kiln mound, visible in the grids as an oval of 15-20 meters, as well as a fire chamber of about 6-7m length, with the lowest part at about 1500-200 cm depth, similar to what has been shown by the Japanese survey at Tani.[623] The longitudinal appearance of Angkorian kilns, as it had been revealed in the excavation at Tani, was detected at Bangkong as well. At Kiln BKK13[624] evidence for the fire chamber, as a strong parabola shaped reflection on the time slices, was detected on the long side of the mound walls. The slope of the fire chamber was to some extent visible and appeared to be of a smaller gradient than at the Tani kilns, but difficult to measure. More results are discussed in the Appendix.

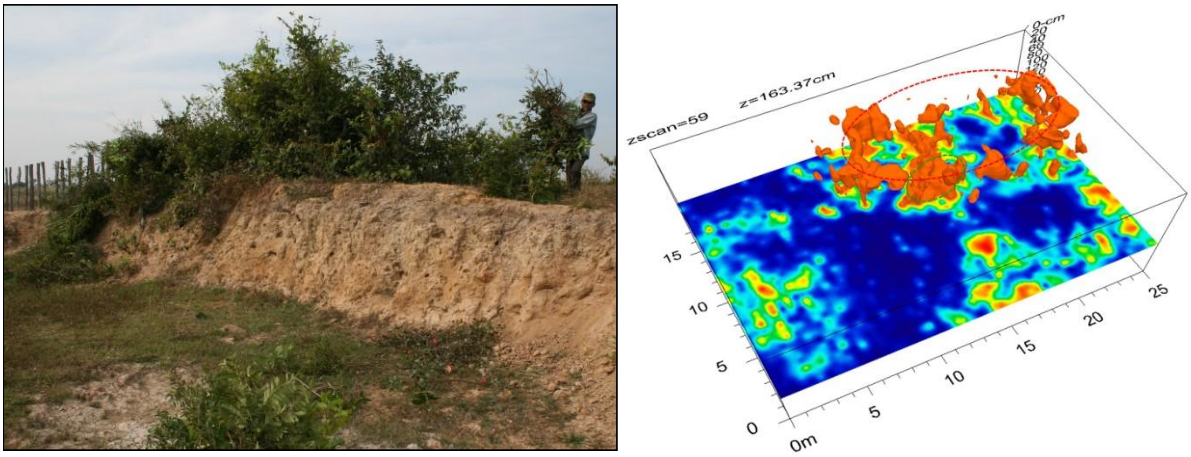


FIG. [26]: SECTION OF KILN SIDE (COURTESY: CHHAY). TO THE RIGHT THE OVAL SHAPED KILN BKK13. TO THE LEFT BN_G1 DISPLAYED AS ISO-SURFACES (ORANGE), MARKED ARE THE OUTER WALLS (RED LINE) AND FIRE CHAMBER (GREEN LINE).

Furnaces

Preah Khan of Kompong Svay has been classified as an important iron production site[625] close to Phnom Dek, the Iron Mountain. Features related to iron smelting have been identified and mapped recently by the Industries of Angkor Project (INDAP).[626] The iron smelting furnaces are located mainly on the embankments of several ponds within the outer enclosure wall. This led to the proposal to survey the potential iron furnaces.

Several transects were run over locations where furnaces were expected, being small mounds on reservoir and pond embankments. The soil at Preah Khan is very lateritic; embankments consist of very hard and impenetrable soil, not only for the GPR signal but also for coring which was done at the same time as the geophysical survey. The resulting low penetration depth complicated the verification of furnaces, see Fig. [27]. A furnace however was identifiable due to changes in the topsoil, predominantly since the reflection from the uppermost layer of the furnace was stronger than from the surrounding embankment material. An interior structure, as it was revealed in the following excavation[627] was not recognizable in the GPR profile. For this reason the laying out of a grid to collect more accurate measurements was abandoned.

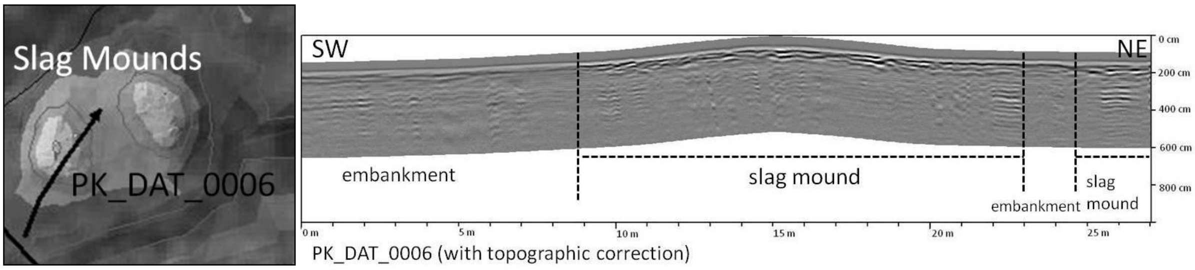


FIG. [27]: GPR-PROFILE PK_DAT_0006 OVER SLAG MOUND AT PREAH KHAN OF KOMPONG SVAY (DTM: HENDRICKSON).

iii. BURIAL SITES

GPR has been actively used to identify graves in historic and modern European[628] as well as native North-American[629] cemeteries, and a large number of publications on the use of GPR concern grave detection. Recently GPR was used on colonial graveyards in Australia also by the author, showing the possibility to map the location of graves.[630] One of the pioneers of GPR in archaeology, Bruce Bevan, named a main soil attribute to detect graves using GPR: "*Should the natural soil have a rather planar stratification, then the chaotic soil which fills the grave shaft could be detectable.*"[631] While the basic attributes are the same, the search for very old graves where neither a coffin was used nor a strong soil change is measurable was expected to be more complicated.

Due to the Hindu and Buddhist crematory rituals applied in the Khmer culture, very few skeletons of the Angkorian period exist.[632] The only Angkorian cemetery so far detected was unearthed by Groslier at the excavation of Sra Srang where bodies had been cremated. This is a different case with graveyards from the Pre-Angkorian period, where the dead were not cremated but buried. Some of the cemeteries were in use over centuries and extended over several hectares, such as in the case of the burial mound of Phum Sophi north of Sisophon in north-western Cambodia.[633] The elevated areas are today used for habitation. In recent years, the identification of undisturbed graves in Cambodia has become an important issue for archaeologists due to excessive and ongoing looting of burial sites.[634] GPR used in forensic analysis[635] has shown that the disturbed area when recently unearthed has a different signal reflection than undisturbed areas, and is therefore detectable by GPR.[636]

Pre-Angkorian: Phum Sophi

Phum Sophi is a settlement on top of a pre-Angkorian burial mound that extends over 15 hectares while elevated not more than 1.5m above the natural ground surface.[637] The extent of the looting that occurred in the last few decades was displayed in a shrine in the pagoda of the village, which presented hundreds of unearthed skulls and bones. In the GPR survey the initial motivation was to learn more about the detection of graves, and the prospection for looting-free areas. Three grids were laid out at the modern shrine and in unused areas between buildings inside the village. In pre-Angkorian funeral rites the dead were buried without coffins. Finding solitary graves exhumed over a millennium ago and covered by the same soil that had been unearthed to excavate the grave, was a complicated task. None of the grids showed that the soil variation between the natural earth and the untouched graves was strong enough to be detected by the GPR. Any evidence that could produce an anomaly detectable with the GPR survey had probably deteriorated over time, and therefore definite burial features have not been readily detected with the GPR so far.

The technique however proved to be useful for identifying looted areas, see Fig. [28]. While the softer fill of a recently looted grave was already partially detectable on the ground surface, the GPR results provided clear information on disturbed ground that had suffered looting versus areas that had been left untouched. Looting pits differed strongly from their surrounding soil context and provided valuable evidence for choosing an undisturbed area for excavation. Because the three survey grids were laid out either in areas of dense soil (as the case in the courtyard of the local monastery) or in already partly looted areas, it represented a case similar to the search for occupation patterns: recent disturbances dominated the GPR results, possibly overshadowing more subtle signal returns created by undisturbed graves.

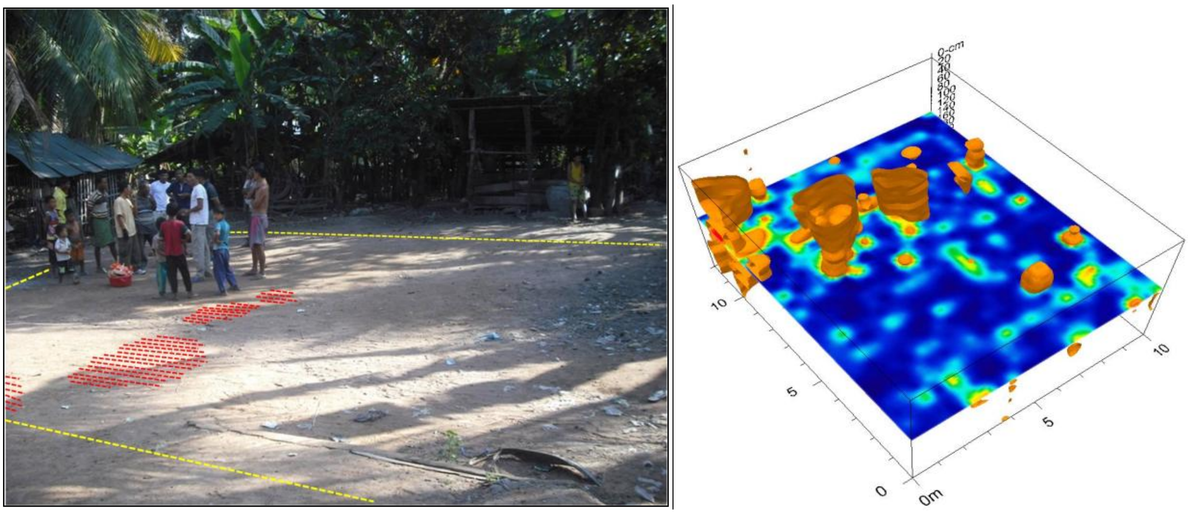


FIG. [28]: GPR RESULTS FROM PS_G3 DISPLAY POTENTIALLY LOOTED GRAVES (CYLINDER-LIKE FEATURES) WITHIN UNDISTURBED AREAS (BLUE).

The Cemetery of Sra Srang at Angkor

Part of the cemetery west of the reservoir of Sra Srang was excavated under supervision of B.P. Groslier in 1964.[638] The excavation at Sra Srang was one of the largest ever conducted in the Angkor area, considering the space excavated and the number of objects unearthed. Due to the absence of Angkorian skeletons, the excavation mainly revealed burial deposits, e.g. large ceramic jars, bronze jewellery and figurines.[639] The oldest remains in the cemetery were dated to the time of the first construction phase of Sra Srang in the 10th century, and the burial site lasted, with episodes of disuse, until the 15th century.[640] Groslier dated most of the graves to the late 11th and the beginning of the 12th century, the period of Jayavarman VII.[641] The excavation also revealed an area of temporary occupation associated with the construction period of the landing stage of Sra Srang. However, much of the resulting data was lost in the turmoil of the 1970s before it could be published.

The GPR survey at Sra Srang (SS_G2) was conducted in collaboration with APSARA Authority,[642] to assess if the cemetery had extended further to the south, where Groslier had not excavated.[643]

This included the search for burials of the Angkorian period in a potentially undisturbed area. The survey included two grids conducted south of the landing stage or jetty of Sra Srang, the first over the embankment of the reservoir, and a second one on a narrow strip south of the food stalls between the embankment and the main road. Similar to Phum Sophi, the shape of the anomaly to be expected was not the European rectangular grave style (formed by the size of a coffin) but rather the large jars or metal objects in small pits that were revealed in the earlier excavation; see Fig. [29]. The results were ambiguous, no clear evidence of pits or objects was found, possibly because of the similar ground composition of the refilled graves and their surrounding soil, and the dominating clayey sand layer in the Sra Srang area.[644] Large anomalies were associated with tree roots. Another reason for the small anomalies could be the survey location, as the grid was adjacent to the restaurants and food stalls, and many small metal objects were close to the surface, such as coins, cans or wire. Litter pollution has been a problem at all major tourist sites and needs to be taken into account for geophysical surveys done in these locations.

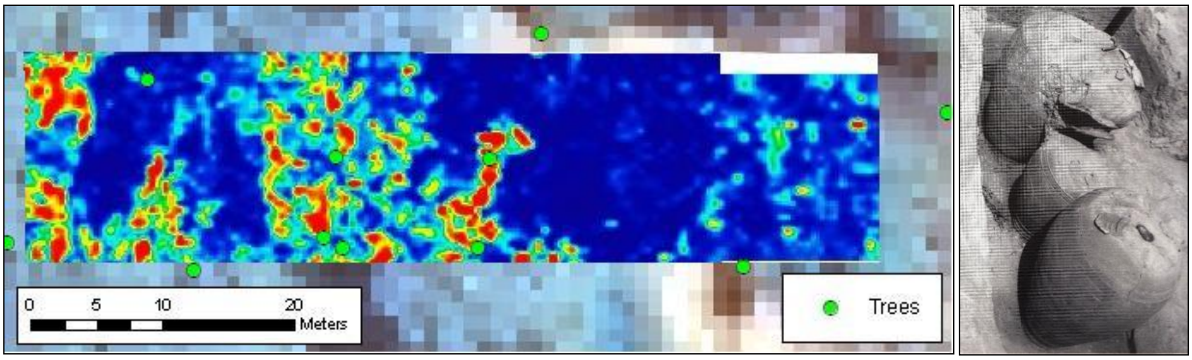


FIG. [29]: GPR GRID SS_G2 AND JARS REVEALED IN GROSLIER'S EXCAVATION (IMAGE: COURBIN, 1988, P. 32).

CONCLUSION

GPR and its potential at Angkor

GPR data acquisition, processing and analysis were adapted to regional environmental conditions at Angkor. The usefulness and limitations of the technique were elaborated by identifying challenging factors in the field work, such as ground composition, seasonal weather changes, and problems concerning safety. Preliminary results from the GPR surveys gave a preference to the 250MHz antenna as it provided significantly more depth than the 500MHz antenna besides having a comparable resolution – especially concerning the detection of water management features, which were detected even below 80ns. Several signal depth comparisons of excavated anomalies and the rather homogenous ground composition in the Angkor plain resulted in a set up of 0.1m/ns as an average velocity to measure the potential depth of anomalies, especially for gridding surveys. Concerning the water management, "depth", the distance of anomalies from the surface, was measured in ns.

There was limited potential to distinguish between used and unused space in formerly occupied areas due to a lack of density difference in the soil. This was the case concerning habitation mounds and undisturbed graves. While metal furnaces were detectable due to strong reflections, but not penetrable by the signal, the survey on kilns provided information on their extent and structural features such as depth and size of the fire chamber. If there was insufficient signal difference between an anticipated target and the surrounding soil, as it was the case in the search for undisturbed graves, GPR, as it was applied here, found its limits. A measurable variation in density or electromagnetic property is very important for small scale surveys, where the morphology of the subsurface is unclear. By narrowing the distance of parallel profiles in grids, the use of different antennae as well as larger survey grids might help to improve the outcome.

GPR has shown a great potential for the detection of looted graves and other areas where there is a clear distinction in density. Interpretable GPR results are dependent on the clear separation of different types of subsurface material, such as dry and compact compared to loose, clayey sand, the dominant top soil in Angkor, or masonry and sand, as the mapping of buried foundations close to masonry structures has shown.

CHAPTER (4) GPR AND REMOTE SENSING

For some minutes Alice stood without speaking, looking out in all directions over the country and a most curious country it was. There were a number of tiny little brooks running straight across it from side to side, and the ground between was divided up into squares by a number of little green hedges, that reached from brook to brook. (LG, II)

The combined use of remote sensing and ground based investigation methods is widely accepted in the investigation of large archaeological sites. From the 1930s-50s the EFEO under Victor Goloubew and Bernard-Philippe Groslier initiated the systematic evaluation of aerial images to complement ground-based landscape surveys.[645] The resulting maps were eventually interpreted to display chronological development of the landscape. Since the late 1980s additional aerial campaigns and a variety of satellite images have significantly improved the mapping of archaeological features of Angkor.[646] In combination with available GIS information, it was possible to display the extent of Greater Angkor. Archaeological landscape analysis by way of remote sensing has, however, so far largely left aside the subsurface as field of study at Angkor. For this chapter, the available geo-referenced maps and plans as well as new remote sensing data are introduced. They were used to find spatial configurations of monuments and potential connections between archaeological features. Some data had to be modified so that it could be used to plan the ground-based surveys, orientate the field surveys and help to interpret the collected GPR data.

(a) AVAILABLE REMOTE SENSING DATA AND MAPS

Alice had no idea what Latitude was, or Longitude either, but thought they were nice grand things to say. (AW, I)

i. AERIAL AND SATELLITE IMAGES

Since the early 1990s several sets of remote sensing data on the Angkor region were acquired. The variety of newly available techniques in recent years closed the twenty plus years lost to research due to the recent conflicts in Cambodia in the 1960-80s. The data sets acquired by EFEO and GAP, as shown in Tab. [2] were used to produce and recently complement the archaeological map of Angkor.

Mission / Data	Year of acquisition	Type of acquisition	Bandwidth	Use in Thesis
Finnmap	1992-93	aerial	Visual	Precise location in research sites & comparison with TerraSAR-X
JICA aerial survey	1997 (-2005)	aerial	visual	GIS, (photogrammetric Modelling of Temples [ETHZ])[647], topography study
SIR-C/X-SAR	1994	space shuttle	radar (c-band)	Comparison with TerraSAR-X
AirSAR/TopSAR	1996/2000 /2003	aerial	radar (p-band, l-band, c-band)	Comparison with TerraSAR-X, topography
Landsat7 (NASA/ Earthstar Geographics)	2002	satellite	visual	Interpretation of GPR results
IKONOS	2004	satellite	visual	Route planning & Interpretation of GPR results
CNES-Spot (Digital Globe/Google Earth)	2004	satellite	visual	Route planning & interpretation of GPR results
TerraSAR-X	2009	satellite	radar (x-band)	GPR analysis

TAB. [2]: DATA USED IN COMBINATION WITH THE GPR SURVEY.

ii. SAR (SYNTHETIC APERTURE RADAR)

The seventh square is all forest. (LG, II)

For further analysis, a new method was introduced. Besides aerial and satellite images covering the visual spectrum, Synthetic Aperture Radar (SAR) technology was used as well to interpret the results of the GPR surveys. The principles of SAR lie in radar pulses that are targeted from a moving sensor to the ground, from which the signal scatters. Parts of the signal are reflected and received by the antenna, stored, and post-processed to create an image of the region. The frequency spectrum used in SAR offer advantages to common sensors using the visual spectrum. Its potential for Southeast Asian archaeology was recognized in the early 1990s when data of the SIR-C/X-SAR Space Shuttle mission[648] was used to map circular pre-Angkorian archaeological sites in Cambodia.

The principal idea was to integrate the complete data set into GIS, to match up the ground-based and remote sensing data, and to investigate its potential of mapping the extension of features detected by GPR, such as canals or river beds which were not visible in the visual spectrum.

The Principles of SAR

Radar (short for "RAdio Detection And Ranging") instruments are physical sensors that transmit a radio signal in microwave frequency range to a remote object to determine its distance by measuring the two-way travel-time when the signal returns. The objective in *range imaging* is to measure the distance or range of targets in a scene. This is also the aim of *Synthetic aperture radar* (SAR), an echo-mode array imaging system[649] that is used in satellite or airborne remote sensing. The principles behind SAR are based on the *Doppler-Effect*. This is known from acoustic theory, where the frequency of an acoustic signal closing in is compressed and therefore higher than a departing one. The theory behind range imaging or echo location[650] was developed already early in the 20th century. The technique is now widely used for the acoustic or visual spectrum, e.g. in measuring the velocity of cars from a fixed position. For SAR the technique was reversed using a sensor moving towards and over a fixed reflector. Based on this technique, Carl Wiley in 1951 realized the first high resolution radar images.

The *aperture* is the actual antenna from where the radio pulse is sent, and defines the amount of energy transmitted and received. The length of a radar-antenna determines the resolution of the image: a larger antenna provides a higher gain and a narrower beam width, which results in a finer resolution. This was initially arranged by using several antennas which were spatially distributed in an array. The technical advantage in a *synthetic* aperture is the moving antenna. In SAR the real satellite antenna is moved along a series of positions along its flight track from where it sends its radar pulses towards the target, extending synthetically the length of the real antenna in the azimuth (along-track) path and with it improving the resolution of the image in this direction. Because of the high velocity of the satellite/ plane, the echoes of the reflections can be combined as it moves along. The anticipated images are built as the antenna moves. Additionally, the radar pulses are not pointed vertically downwards, but in an inclined angle to the Earth's surface to distinguish target points of different distances perpendicular to the flight direction by transit time measurement.[651] The transmitted signal needs, due to the greater distance, a longer time to the target point than for returning, the incoming signal is therefore Doppler shifted from the emitted one. When the Doppler shifted frequencies are compared to a reference frequency, the signals can be focused on a single point, presuming a very precise knowledge of the relative movement between antenna and target, and therefore effectively increase the length of the antenna synthetically. This is done for every single point in the image by computer programs and provides a much higher resolution than what could be achieved with a usual antenna.

While passing over the target, the imaging radar system sends out up to 1500 high-power pulses per second, with a frequency of 10-200 MHz, with each pulse having duration of 10-50 microseconds.[652] The pulse's bandwidth determines the radar's resolution in the range direction: the shorter the bandwidth, the higher the resolution. A phase correction is applied for successive radar pulses. The emitted signal is scattered on the ground, its reflection is called backscatter. Only part of the signal returns to the antenna, of which the SAR image is created. Every dot in the image refers therefore to a pulse that was sent out by the antenna, backscattered and again received. The amount of backscatter received from different targets creates the image, according to Oliver & Quegan it is a *"representation of the local scattering properties of the Earth, all the information is carried by our knowledge of electromagnetic theory."*[653]

Interpretation of SAR Images

Freeman states that *"backscatter for a target area at a particular wavelength will vary for a variety of conditions: size of the scatterers in the target area, moisture content of the target area, polarization of the pulses, and observation angles."*[654] From smooth surfaces such as the tarmac of roads or flat roofs as well as areas covered with water, the signal is either absorbed or, because of the smooth surface, reflected into a different direction than the antenna. For natural surfaces covered by vegetation, additional factors that affect the signal are the geometric and dielectric properties of the vegetation cover and the underlying soil.[655] For rough terrain, such as ploughed fields or the canopy of trees, a major part of the signal is backscattered towards the antenna.

The backscattering coefficient, which measures the amount of the signal returned, is measured in decibel (dB) and varies in a grey scaled image between considerable backscatter +5dB (very bright) and little backscatter -40dB (very dark).[656] Smooth surfaces are therefore represented by dark tones while a rough surface appears in bright tones. At the Angkor Archaeological Park possible differentiation in the signal return and the resulting varying tone of the image depends mainly on:

- **Land use**: a variety of turfs from open fields, such as rice field and grazing area, to bushland to dense forest cover and modern buildings.
- **Soil compactness**: sandy soil should appear less bright than a smooth clay surface from house mounds: compacted roads are detectable while paths depend on their width.
- **Soil moisture**: from dry areas raised over the floodplain to completely inundated rice fields and reservoirs. Using a high resolution sensor, even remnant stoneworks beneath the surface could be detected since it reduces the soil moisture content.

The satellites **observation angle** influences the resulting image. Vertical linear features such as fences or walls as well as some buildings backscatter differently when the signal hits the target as a larger area is hit in a low angle. Consequently the general rule of radar imaging says the lower the incidence angle the higher the backscatter. Additionally to that, also the **polarization** of the image can be of interest for the researcher, as some SAR antennas can send and receive signals in either horizontal (H) or vertical (V) polarization. Therefore the received image can be distinguished between HH (horizontal transmission and reception), VV, HV and VH.

To precisely determine what kind of image is needed for an object of interest with a number of characteristic properties, several important attributes concerning the setup of SAR are summarized by C. Oliver:[657]

- **System configuration**: polarization, wavelength, incidence angle, and revisit time
- **Choice of measurement**: phase difference, backscattering coefficient, texture parameter, and amplitude ratio

A combination of these attributes is used to produce multi-colour images. An advantage over common visible or infra red remote sensing methods is its independence from any illumination by the sun, as it is an active sensor, so that measurements can be made at any time of day or night. Additionally to this, the radar sensor is to some extent independent of weather conditions, such as, for example, cloud coverage.[658] This refers especially to long wavelengths, which are not influenced by atmospheric interference.

Over the last four decades SAR technology has developed from aerial low resolution imaging to the acquisition of multiple bandwidths and high resolution satellite data (see Tab. [3]), and its range of use has widened from oceanography to geographic purposes, such as creation of a global high resolution DTM.[659] The research interest determines what frequency is needed in archaeology. Low frequency c-band data provides ground- or at least foliage penetrating signals, but has still a too low resolution to detect structural archaeology, while the high frequency x-band provides higher resolution images with the signal being reflected from the surface and canopy.

SAR Types	Technique& Aims	Carrier	In use since	Wavelength
IfSAR/InSAR	Interferometric Synthetic Aperture Radar for topographic measuring	Airplane	1970s	
SEASAT	HH-polarized, fixed angle to monitor global surface wave field and polar sea ice conditions	Satellite	1978	L-Band
MRSE	Microsoft Remote Sensing Experiment (German DASA) using X-SAR	*Space Shuttle Spacelab*	1983	X-Band: 3.1cm
SIR-C/X-SAR	NASA -JPL Space Imaging Radar	*Space Shuttle*	1994	X-Band: 3.1cm C-Band: 5.8cm L-Band: 23.5cm
AirSAR /TopSAR	Airborne Synthetic Aperture Radar based on IfSAR technology	*Airplane*	1988-2004 (over Cambodia in 1994 & 2000)	C-Band: 5cm L-Band: 24cm P-Band: 68cm
GeoSAR	dual-band, single-pass IfSAR technology commercially used	*Airplane*	2000	X-Band: 3cm P-Band: 85cm
TerraSAR-X	Satellite SAR	*Satellite*	2008	X-Band: 3cm
TanDEM-X	Dual satellite SAR. Direct 3-dimensional	*Satellite*	2010	X-Band: 3cm

TAB. [3]: DEVELOPMENT OF SAR-TECHNOLOGY FOR TERRESTRIAL PURPOSES

Preceding SAR Surveys in Cambodia

The use of SAR technology for archaeological purposes has increased over the last two decades and its application dominated the discussion on landscape archaeology in Cambodia in the 1990s. The 1994 Space Shuttle missions (SIR-C/X-SAR, NASA JPL Space Imaging Radar) took radar remote sensing strip map images over Cambodia already in multiband form, that included data in radar spectrums from L-band (central wavelength at λ~23.5 cm), C-band (λ~5.8 cm) and X-band (λ~3.1 cm). In 1996 & 2000 the airborne AirSAR / TopSAR mission were launched using L- band (λ~24 cm), C-band (λ~6 cm) and P-band (λ~68 cm), and included images of parts of Cambodia.

The acquired dataset was intensely investigated by several research groups,[660] mainly to distinguish human made curvilinear elements as Pre-Angkorian settlements. Especially the canopy penetrating C-band data provided valuable information about earthworks and topography around Angkor. However, a resolution of 30m was too low for smaller sized architectural features. It was later used as one of the core data to extend the archaeological map mainly to the north.[661] The valuable outcome of those surveys had a strong impact on the decision to apply for new higher resolution radar data which was provided by TerraSAR-X in 2008.

TerraSAR-X Satellite Data

The satellite TerraSAR-X was developed by the DLR e.V. and launched in 2007 to acquire high resolution SAR data for scientific and industrial purposes. The satellite runs at 514km height and flies in a sun synchronous dusk-dawn orbit. As the name TerraSAR-X states, the mission provides X-band imagery with a frequency centred around 9.65GHz which corresponds to a wavelength of about 3cm. The high frequency implies that the signal is neither ground nor foliage penetrating. However the selected Spotlight Mode achieves a very high resolution. In this mode the radar antenna is steered in flight direction and the same target region is illuminated during the whole of the data recording by which an increased target illumination time is achieved.[662] This mode provides the highest resolution of SAR satellite imagery available to the public to date, with a maximum resolution of up to 1m.

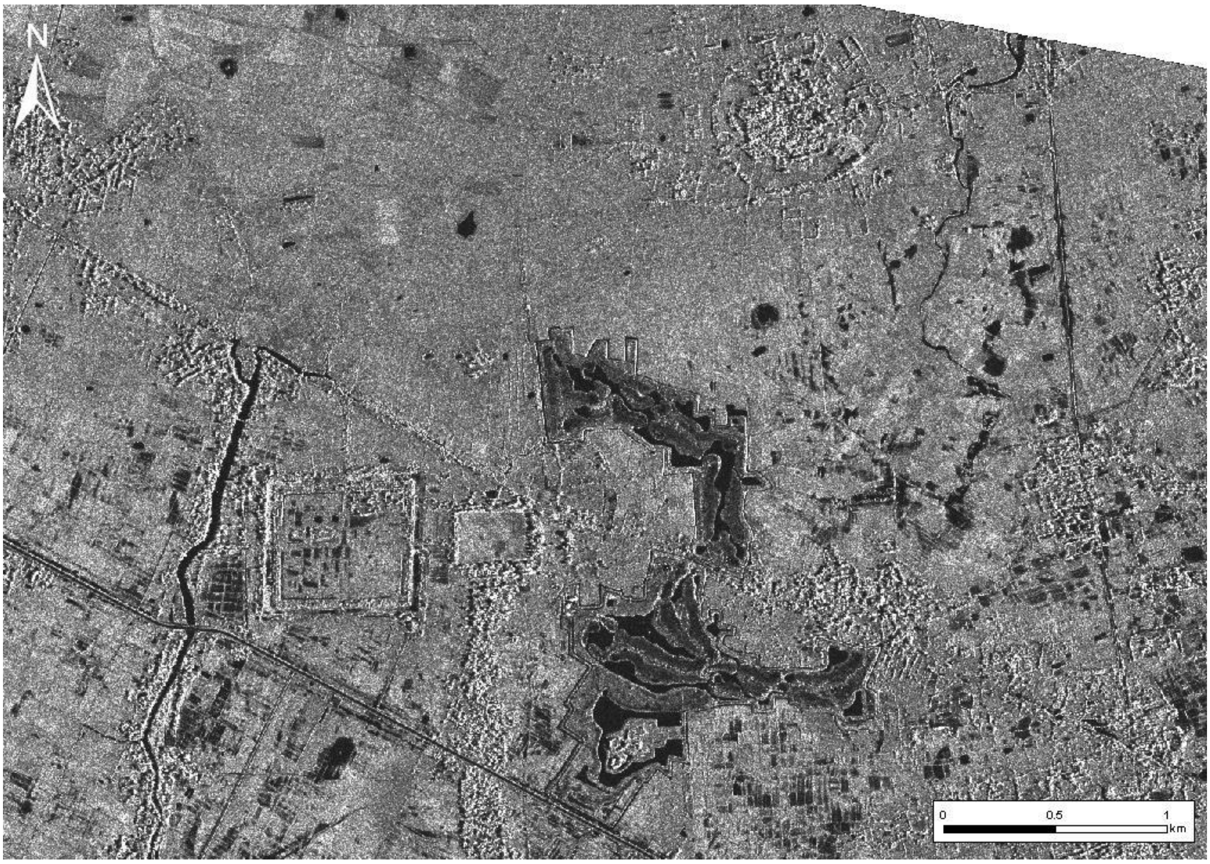


Fig. [30]: TerraSAR-X covering Banteay Sra, the Pre-Angkorian circular settlement of Lovea and a modern Golf Course.

Acquisition of Images

Under the project: LAN 0304 (category: land use) the author set up a research project to acquire the TerraSAR0-X images.[663] The images were provided free of charge by the *German Aerospace Centre*[664] based on the *Open Initiative* of UNESCO to support remote sensing data for World Heritage sites. Two areas were picked by the author to compare the ground based and -penetrating GPR data with satellite imagery;[665] firstly to assess the correlation between the two data sets and secondly to identify the extension of channel features detected with the GPR in the surrounding landscape. The sample sites Roluos and Banteay Sra (see Fig. [30]) were chosen based on their limited vegetation and high archaeological potential. Two additional images were taken a week later over Koh Ker with similar angles of incident. The area covered by each image is about 5 x 10 km. As explained above, the spatially enhanced *Spotlight* mode was chosen by the author to achieve the highest possible resolution of the area.

Post-Processing of Images

The images were processed by the DLR on request after acquisition of the images as GEC (*Geocoded Ellipsoid Correction*), which means that they are projected to a digital elevation model but no terrain corrections are performed. The data was resampled and projected to the WGS84 reference ellipsoid.

The highest achievable geospatial accuracy of the image depends on orbit precision, timing accuracy and specifically the elevation accuracy of the reference DEM.[666] The horizontal pixel accuracy therefore depends partly on the terrain of the DEM, and an error in an applied DEM affects the precise pixel localization. With perfect knowledge of the terrain and good localization accuracy, high resolution can be achieved for geo-coded data. Since both chosen areas are within the Angkorian floodplain and have very little elevation difference of only a few meters between the human made earthworks and the original plain, horizontal errors depending on the DEM could be neglected for the following mapping task.[667]

iii. GIS DATA SETS

'I'd rather see that done on paper,' he said. (LG, VI)

JICA

In 1996, JICA, the *Japan International Cooperation Agency,* arranged an agreement with the Cambodian Government, to provide accurate topographic and geographic maps of the central part of the Angkor Archaeological Park covering archaeological sites and surrounding areas within the Siem Reap region. In the aerial topographic mapping campaign of 1997 a region covering 577 km² was mapped, using black and white aerial images at a scale of 1:20,000. Additionally, the 100 km² world heritage park was mapped in detail in a scale of 1:5,000 using 357 coloured images. The images were triangulated with GPS ground control points (relative error 1.5 cm) and digitally plotted.[668] Furthermore geology and landform data was collected regionally in a very coarse scale of 1: 50,000. The detailed areas were extended in the following years nearly covering the complete southern floodplain of Angkor. From the large amount of the JICA data available, a number of GIS layers turned out to be very valuable for different purposes in the research. The key layers were:

Infrastructure (polylines)

The data set of roads 2003 & 2005 allowed the planning of GPR survey routes and the orientation in the field under heavy canopy where orientation was difficult because of a missing GPS signal, since JICA in a meticulous effort had mapped the smallest paths visible on aerial images even in heavily forested areas.

Structures (polygons)

The JICA map displays many outlines of buildings as polygons, including the temple sites. Major parts of the monuments including causeways and entrance gates are displayed, complementing the archaeological map of GAP, which only indicates temple sites. Historical monuments are categorized as such. The monuments were extracted from the complete data set for the thesis;

the data was then used to orientate and extend the centre axes of monuments in geometrical relation to other archaeological features.

Water features (polygons)

Areas that were flooded at the time of data collection were indicated on a separate data set. The data set proved useful to plan the GPR survey route and avoid potentially inundated areas.

Topography (polylines)

Topography data from JICA played an important role in the thesis. JICA 2003 & 2005 contour lines were combined, since the 2005 data did not include heights they were re-entered and adjusted primarily in relation to the 2003 map at their shared borders and on the basis of the 1:10,000 contour lines *(of interval 10 m, 5 m, 2.5 m and 1.25 m).* The combined data was used to create a Digital Elevation Model (DEM), covering nearly the complete central survey area. The new DEM, based on topographic linear features, is of higher accuracy than the available DEM from either satellite Landsat data (which includes the canopy height) or AirSAR, which had far lower resolution than the aerial images. The data was used for a variety of tasks: firstly to analyse the local topography; secondly to newly geo-reference the central part of the archaeological map, where possible (by Pottier, see below); thirdly to indicate the extension of linear earthworks such as canal embankments to see possible connections to monuments.

Mapped Archaeological Features

Since the first aerial surveys, the EFEO has produced increasingly detailed archaeological maps of the Angkor area.[669] Some of them, e. g. George Trouvé's plans[670] of 1933 and the EFEO map[671] of 1940 have been used within this study to interpret the data. The main dataset used for reference and analysis of GPR survey results has been a geo-referenced map of Angkor created by Pottier within his PhD that concentrated on archaeological landscape features.[672] Until then precise archaeological mapping had been concentrated mainly on monuments. The mapped features are based on archaeological evidence detected in remote sensing data, showing, as Pottier put it, *"every available feature relating to ancient land use and the environment"*.[673] The displayed features were based on a series of remote sensing datasets, notably the aerial images of Finnmap.[674] The majority of the mapped archaeological sites had been confirmed by field walking. Pottier classified the archaeological features into five different categories:

Watercourse - rivers and streams with naturally carved bed as well as redirected rivers

Reservoir - large water storage devices that have either been excavated (such as household ponds or temple *trapeang*) or surrounded by earthen embankments such as the *baray*

Moat - excavated rectangular water features surrounding a temple site

Channel - artificial linear water course with either embankment on one side or on both

Mound - any type of artificially raised earthen feature or earthwork, including raised temple platforms, (habitation) mounds, kilns, as well as road and canal embankments

Additionally to the five categories Pottier initiated the mapping and interpretation of Angkorian rice field outlines.

The mapped area was digitized by GAP,[675] and extended to the north and on its borders by Damian Evans[676] using a combination of aerial and satellite remote sensing data, as well as data from the original SAR missions.[677] The geo-referenced dataset represented the first detailed archaeological map covering the Angkor plain, and provided information on the archaeological landscape features. They were mainly based on topographic changes detected in stereo view, and were related to earthworks, either excavated and filled with water or raised. Because the original categories had been broadly chosen and included several different features, Evans et al. modified and subdivided some of those classes, see Fig. [31], and added the category of *Temple Site* in the area he had investigated.[678]

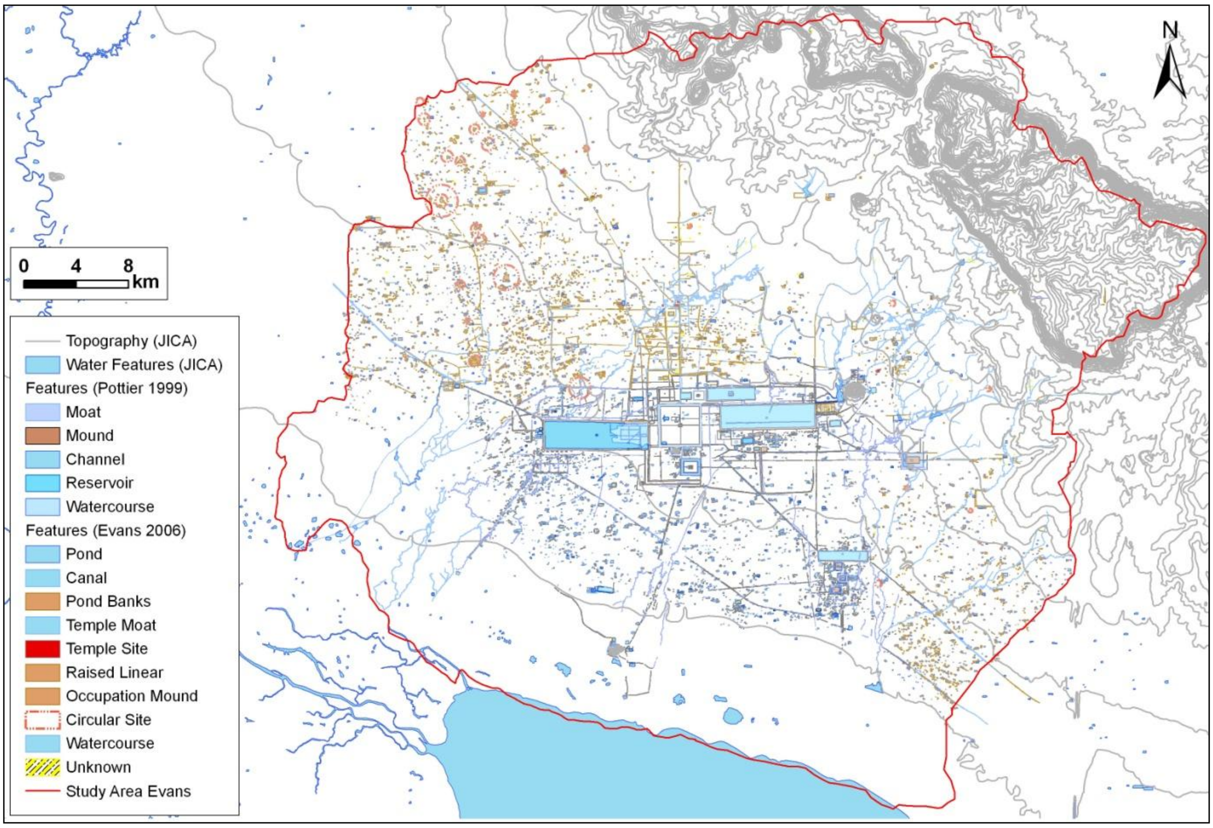


FIG. [31]: ARCHAEOLOGICAL MAP OF GREATER ANGKOR (COURTESY: GAP/POTTIER/EVANS/JICA).

(b) DATA MODIFICATION AND ANALYSIS

'You may look in front of you, and on both sides, if you like,' said the Sheep: 'but you can't look all round you - unless you've got eyes at the back of your head.' (LG, V)

i. ADJUSTING THE ARCHAEOLOGICAL MAP

The available data sets, along with recent Google Earth images, and TerraSAR-X acquired by the author, were used in the thesis. New data sets were integrated into a Geographical Information System (GIS) environment,[679] geo-referenced in the worldwide commonly used WGS84 (World

Geodetic System of the year 1984) datum (EPSG: 4326), in a Universal Transverse Mercator (UTM) Projection in Zone 48N.[680]

Neither version of the archaeological GIS map included detailed depictions of the historical structures, while some had been displayed in the original hardcopy created by Pottier. For the purpose of geometrical association between temples, the available monumental features were included from the JICA map into the current data base. In some cases they were additionally mapped. The outcome of the GPR survey depended greatly on the accuracy of the data especially by the topographic and geographic map by JICA and the archaeological map by Pottier/Evans, since it was mainly used to test some hypotheses concerning the water management theory. The central part of the digitized archaeological map displays geo-referencing errors and lacks spatial accuracy.[681] Some features are irregularly shifted up to 30 meters compared to the JICA map that was checked in the field with the DGPS, which is possibly the most accurately geo-referenced body layer for this region.[682] Since there is no continuous shift of the distance and direction, the error probably happened in the original mapping process before the digitization[683] due to inaccuracies when the aerial photos were referenced individually. As it is immensely important for the interpretation of the GPR results, that the discovered subsurface anomalies are correctly associated with the existing map, features of the map were, wherever possible, shifted to a more accurate position related to the *JICA topography* layer, or redrawn in agreement with the JICA data. Single features, however, such as small ponds not related to any large structure/earthwork that JICA had included in either topography or building layers, have only been shifted when overlain by an aerial/ satellite image.[684] To relate the mapped features with the GPR survey, especially the marked difference between raised earthworks and channel depressions have been of importance for the thesis. In the GPR profile a channel is of similar appearance as an embankment. When related to remote sensing, the two categories were not always detectable on the available remote sensing data without stereo view. All data sets were used for positioning in the fieldwork. Reduced versions of the available GIS files were uploaded to a GPS device[685] to plan the travel route on site and to improve orientation in the field. Since UTM displays relative distances in meters, it provided accuracy and information for orientation as well as measuring grid corner points in the field.

ii. SPATIAL CONFIGURATIONS

'I can't go no lower,' said the hatter: 'I'm on the floor, as it is.' (AW, XI)

Scaling the Landscape

As described earlier, the vast archaeological landscape needed to be scaled to use the full potential of GPR at Angkor. The study targeted research objects of different dimensions and the principal (GPR) and secondary (remote sensing) survey techniques were used accordingly:

(1) The remains of masonry **shrines** and their buried counterparts; generally situated within some kind of enclosure.
Task: to analyse spatial configurations within the ceremonial and political centres and to find missing features, mainly using the 3D grid method with additional architectural plans and JICA historic *building* data.

(2) The **reservoirs** and their infrastructure which served those centres as part of the water management system.
Task: to find and analyse inlets and outlets associated to the large reservoirs, using GPR profiles and grids in combination with GIS data (JICA *building* and *topography)*.

(3) Possible connections of **earthworks** with other structures, the **network** of canals and embankments and the original riverine system.
Task: A landscape analysis to measure mapped and find undetected parts of the former natural streams and the canals of the water management network, earthworks which had either decayed or were destroyed by new constructions, using long GPR profiles and remote sensing data to appraise archaeological maps.

Temple Axes

The orientation and central axis of temple axes was outlined to investigate potential connections to other monumental structures or related earthworks. The extended graphs connected supposedly unrelated features (e.g. monuments or earthworks) and allowed to compare them with anomalies in the GPR survey.[686] JICA data served as reference data, using entrance gates of the temple or the enclosure, the so called *gopura* or as reference points. Depending on the potential influence radius of the temple, the axis was elongated several kilometres, until it e.g. reached or surpassed a neighbouring centre, see Fig.[32]. The detected potential connections were tested by GPR on site in the case of:

- **Phnom Bakheng**,[687] where a channel/road feature was marked on the Angkor Thom map in direction Baphuon, that was not in line with and oriented in a slight angle to the network of roads and canals.[688] Considering the work of Victor Goloubew, the other directions of the Phnom Bakheng axes were surveyed.
- **Ta Keo** (late 10th to early 11th century, Jayavarman V) and the **South Khleang** (late 10th to early 11th century, Suryavarman I) share one east-west axis.
- **East Mebon**, which was oriented in a slight angle to the embankment of the Yasodharatataka. Because of this the continuation of the east-to-west axis reached the outlet structure at Krol Romeas.

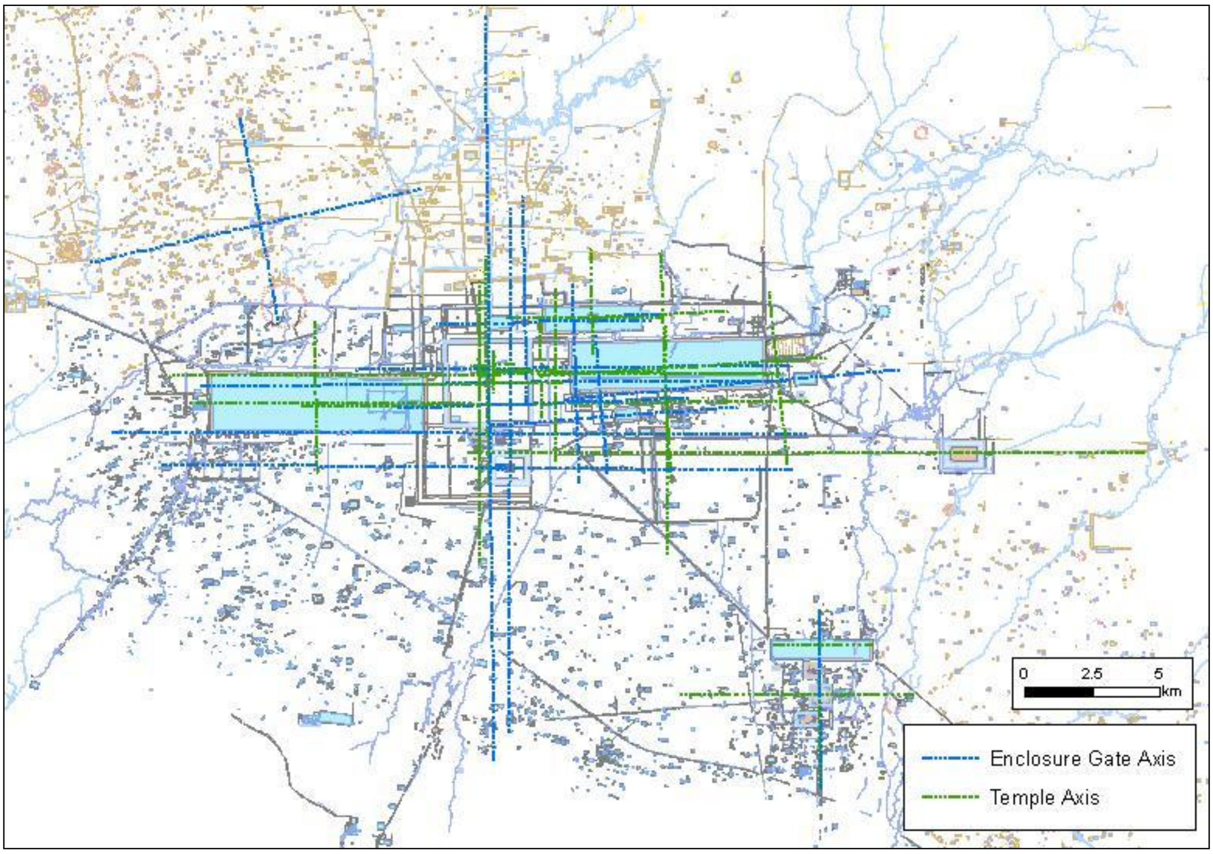


FIG. [32]: AXES OF MAJOR MONUMENTS AND ENCLOSURES AT ANGKOR (BASE PLAN: POTTIER/EVANS).

Linear Earthworks

To analyse the connection of earthworks to each other and in relation to masonry structures, linear and straight earthworks on the map were overlain with straight lines and those lines were extended graphically into the landscapes, to find out if parts of an earthwork had been destroyed or were removed for new constructions; see Fig. [33]. The extensions were extracted and integrated as well into Google Earth to identify features mapped on the satellite image:

- Connecting the **central axis of the *baray*** with the embankments, the line cuts through areas of the western and eastern embankments. At the eastern side of the **Indratataka**, the JICA topography data showed a gap in the embankment corresponding to the central axis; see Chapter (8).
- As Claude Jacques has pointed out, if the connecting causeway from the **Indratataka** to Yasodharapura had continued in a straight line, it would have reached the site of the Royal palace; see Chapter (8).[689]

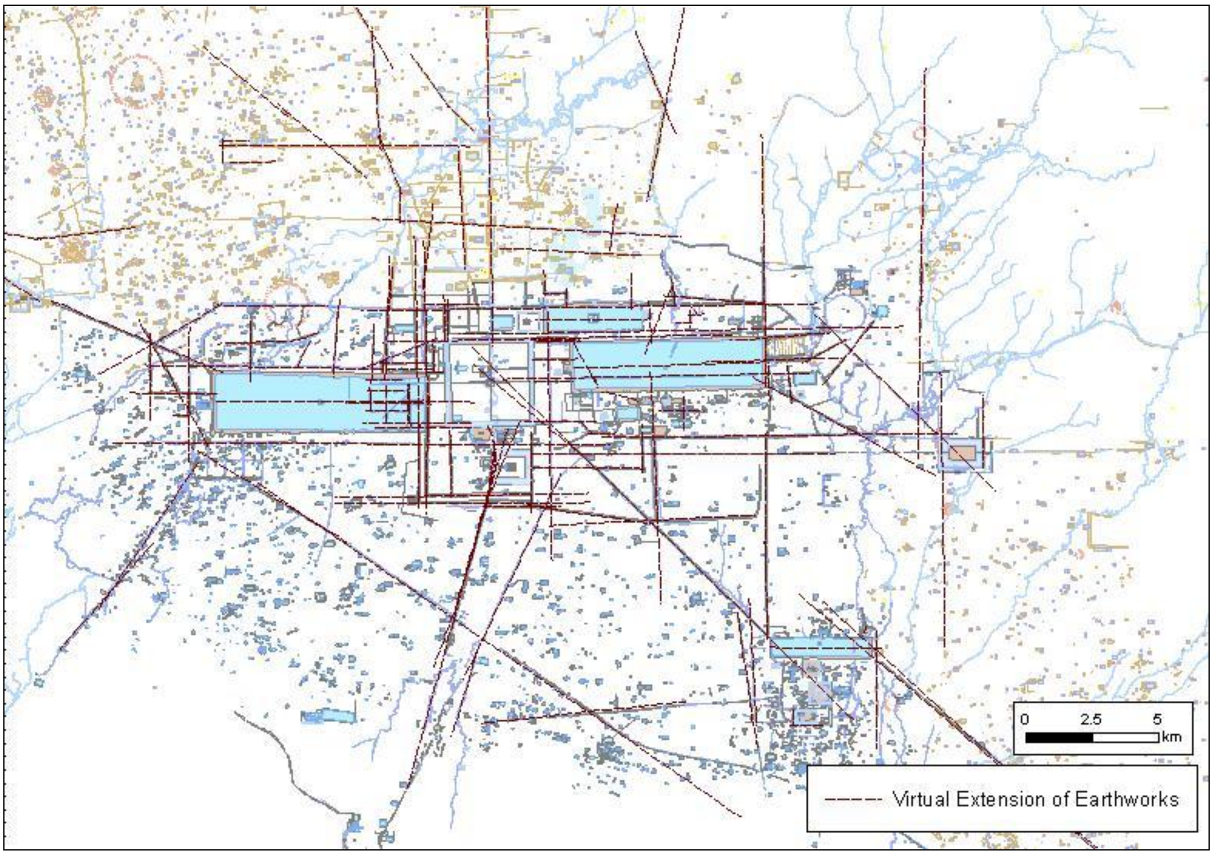


FIG. [33]: VIRTUAL EXTENT OF LINEAR EARTHWORKS AT ANGKOR (BASE PLAN: POTTIER/EVANS).

iii. CLASSIFICATION OF ANOMALIES

'If only I knew,' she thought to herself, 'which was neck and which was waist!' (LG, VI)

Connecting GPR and GPS

GPS[690] recordings from the field surveys made it possible to integrate information from the GPR data into the virtual GIS environment. The interpretability of GPR results was dependent on the precision and durability of the GPS. Since GPS precision depends on the number of satellites it can detect, it was challenged especially in densely forested area, and when satellite coverage was low.[691]

Initially the route of the GPR survey was recorded by directly connecting GPR and GPS devices, but constant material connection failure made individual recording of both data sets necessary, before they could be integrated into GIS.[692] GPR survey profiles were tracked as linear features. If this was not possible, starting and end points of the profiles were recorded. If satellite coverage was insufficient over a period of time, the profile was terminated at road intersections or landmarks, such as buildings on the JICA map, and later integrated into GIS according to the mapped JICA paths. Concerning the location of grids, each corner point was recorded with the GPS, increasing the precision by averaging over several hundred recorded points. Integrated in the GIS environment, the GPS data was later evaluated using available GIS maps of high precision.[693] If offset errors were detected in the recorded track/point, they were adjusted according to the GIS maps.

Localisation of GPR Anomalies in Long Profiles

The long GPR profiles conducted resulted in radargrams ranging from several tens of meters to over two kilometres length and were integrated in a GIS data base according to the geo-referenced maps[694] and remote sensing data. Interpretation and categorization of anomalies in the post-processing was based on the local geography and topography, to associate the anomalies with visible landscape features if possible.

FID	Shape *	Id	Geometry	Anomaly	File	Start	End	Depth ns	Interprete	t Start	t End
852	Polyline ZM	0	curved	channel	AS_DAT_0053	176	216	20	large shallow channel	178	218
764	Polyline ZM	0	curved	channel	AT_DAT_0002_2	14	20	25	small canal	14	20
824	Polyline ZM	0	curved	pond	AT_DAT_0003	402	416	35	pond	399	413
827	Polyline ZM	0	curved	channel	AT_DAT_0003	726	748	40	medium size pond or channel	720	742
828	Polyline ZM	0	curved	pond	AT_DAT_0003	820	836	30	small pond	814	828
829	Polyline ZM	0	curved	pond	AT_DAT_0003	848	856	25	small pond	842	850
830	Polyline ZM	0	curved	pond	AT_DAT_0003	860	868	25	small pond	853	861
765	Polyline ZM	0	curved	channel	AT_DAT_0003_2	32	48	30	medium size channel	34	51
766	Polyline ZM	0	curved	channel	AT_DAT_0003_2	122	152	40	medium size channel or moat	131	161
767	Polyline ZM	0	curved	channel	AT_DAT_0003_2	342	352	30	small canal	367	378
19	Polyline ZM	0	curved	moat	AT_DAT_0106	124	150	30	moat of Kleang	129	155
643	Polyline ZM	0	curved	moat	AT_DAT_0107	16	28	25	moat of Kleang	16	28
644	Polyline ZM	0	curved	embankment	AT_DAT_0107	126	138	15	embankment	129	141
831	Polyline ZM	0	curved	moat	AT_DAT_0107	4	12	50	moat	4	12
641	Polyline ZM	0	curved	moat	AT_DAT_0108	120	132	25	moat of Kleang	123	135
642	Polyline ZM	0	curved	moat	AT_DAT_0108	16	28	25	end of moat	16	28
645	Polyline ZM	0	curved	moat	AT_DAT_0109	0	30	25	moat of Kleang	0	30
836	Polyline ZM	0	curved	breach	AW_DAT_0001	16	24	25	filled embankment	16	24
837	Polyline ZM	0	linear	masonry	AW_DAT_0001	154	166	15	possible masonry platform	154	166
838	Polyline ZM	0	curved	channel	AW_DAT_0003	114	120	15	small channel or pond	114	120
839	Polyline ZM	0	curved	channel	AW_DAT_0004	112	118	25	small channel	112	118
883	Polyline ZM	0	curved	channel	AW_DAT_0005	124	134	30	canal	127	137
840	Polyline ZM	0	curved	channel	AW_DAT_0007	12	20	35	medium size channel	12	20

FIG. [34]: SCREENSHOT OF THE GIS ANOMALY DATABASE.

Error corrections

The resulting radargrams were searched for anomalies. The exact location of the anomaly depended on the precision of the GPR distance measurement wheel attached to the equipment. Due to obstacles, rough ground and reading errors of the measurement wheel, the length of the radargram recorded over great distances was less than the actual distance walked, as intruding sand and water stalled the wheel at some point. The length of the GPR transect was therefore adjusted by hand when digitally mapped by hand into the GIS map, the distance covered was calculated automatically, according to the additional information from maps and aerials. The discrepancy of true distance covered and length of the radargram affected the exact location of the anomalies. A general rule was: the longer the GPR profile, the more likely and the larger the error. To display the anomalies at their actual location in GIS, a formula was developed and applied to accurately display start- and endpoint of each anomaly:

$$\frac{\text{Length of survey calculated from GIS [m]} * \text{Location of anomaly on radargram [m]}}{\text{Length of survey measured by wheel [m]}} = \text{Actual location of anomaly [m]}$$

The calculated correct positions on the profile were added to the table and the improved location of the anomaly marked on the map.

Database of anomalies

For each anomaly a screenshot of the detected anomaly was saved from the filtered data displayed in *Mala Groundvision,* the image saved as a JPEG under an individual classified name in a database, see Fig. [34], to be able to compare classified anomalies.

Abbr. of Location/Region _ Name of Profile (DAT_XXXX) _ Start- and Endpoint in m

e.g.: BK_DAT_0001_25-40m

If several profiles with the same name were recorded in the same region, they were named

Abbr. of Location/Region _ Name of Profile (DAT_XXXX) _ No. of Survey_Start- and Endpoint in m

e.g.: BK_DAT_0001_2_25-40m

Potential of a Statistical Evaluation of the Data

> *'What's one and one and one and one and one and one and one and one and one and one?' 'I don't know,' said Alice. 'I lost count.' (LG, IX)*

About 900 anomalies were recorded and mapped and had to be classified. Concerning the amount of data collected, there are several reasons why the long radar survey does not qualify for a statistical approach, why there is no quantitative statistical approach based on the data to improve the understanding of the water management system and why the analysis had to be done qualitatively. As regards stacking the anomalies, and analysing them by width, depth and form seems reasonable:

- The surveys were conducted at different times of the year, mainly in the dry season from November till March. The slowly retreating flood water and sinking ground water provides a varying saturation of the subsurface, which influences the GPR signal in penetration depth.
- Some areas were not accessible - less due to not yet demined areas, but mainly due to continuing flooding or dense forest. Most water saturated rice fields are only accessible on raised tracks, while forested areas could only be observed from paths. This prevents a statistical analysis of the quantity of channels crossing an area.
- Some areas of high density clay, larger roads and GPR did not retrieve any information due to an unsuitable ground composition.
- The signal depth varies depending on the overlain ground and ground composition. As the GPR transects were done on elevated roads or paths, the actual depth of the features depends on the height of the path or road over the landscape.
- The horizontal angle of the survey to a linear feature. Since the GPR transect analysis is a 2-dimensional approach, detected anomalies display the extent of a canal only in one direction. If the feature was in a wider angle to the survey line, the anomaly mapped would be larger than the actual width of the feature.
- The analysis of the data, the extent of the features, and the interpretation of the results to classify an anomaly must therefore be subjective to a certain degree.

A statistical approach would only work either for multiple transect on single channels or when the GPR profiles could be run in a large grid over the landscape.

iv. GPR Pattern Analysis

'It's called a "wabe" you know, because it goes a long way before and a long way behind it -' 'And a long way beyond it on each side,' Alice added. (LG, VI)

A preparatory task regarding the water management system was the classification of archaeological features. From the features introduced by Pottier[695] and described earlier in this chapter, the author mainly kept those classified as *rivers*, *canals* (artificial channels), *moats* and *ponds*. Features were interpreted as either **natural**, **historic** (Angkorian/Pre-Angkorian) or **modern** according to their appearance in the radargram and their location in relation to the archaeological map, see Tab. [4]. The features marked and measured in the profiles are highlighted bold in different colours. Further differentiation of water management features was done in the following chapters concerning some archaeological sites.

Anomaly	Colour	No. Classified
Disturbance	yellow	156
Channel	green	559
Moat	blue	24
Pond	purple	25
Breach	orange	24
Masonry	red	78
Embankment	brown	22

TAB. [4]: LIST OF GPR-ANOMALIES CLASSIFIED IN GIS.

Natural Features

For long profiles the concerning features are related to the development of the water management system of Angkor. This includes features that were part of the original landscape or will have formed independently from human interaction. Of the historic features detected, most were no longer functioning as intended in their time of construction; water holding features have silted up, masonry structures have been covered by sand and raised earthworks have suffered erosion and have been breached.

Disturbance (yellow)

Analysis and interpretation of GPR profiles over lacustrine floodplains have been described in Stevens and Robinson (2007) as *"complicated depositional environments that exhibit a high degree spatial variability."*[696] River beds and lacustrine deltas with sandy ground have been analysed by GPR before, by e. g. Jol & Smith,[697] Stevens & Robinson,[698] and Mumpy *et al.*[699] Stevens & Robinson (2007) used low frequency 50 and 100MHz GPR antennae to measure a distributer channel[700] for a Pleistocene delta. They observed a penetration depth of about 8 m and distinguished radar facies as variations in sedimentary patterns to display the sedimentary profile of the river delta. Mumpy *et al.* implemented *"selected seismic reflection patterns and* *relationships"*[701] for their GPR survey analysis, to create a 3-dimensional stratigraphy over an active braid bar of a river. Wright et al. describe sediment load and seasonal variations[702] as dominant factors to form the pattern of facies in lacustrine deltas, *"zones that can be distinguished from one another by variations in sedimentation rates, patterns and grain size."*[703] Based on those previous surveys, the sedimentological attributes of parts of the riverine system at Angkor were analysed by GPR. Similar patterns were expected of anomalies referring to former natural rivers in the floodplain. A profile showing a broad anomaly and great depth of a chaotically layered reflection signal indicates loose, sandy sediments which were deposited when the area was part of a stream basin of presumably natural origin. The sides of the river bed are not easily distinguishable, due to the sedimentation process and uneven non-horizontal layering from silted up former river beds. Since river beds are naturally formed features, no age or period of flow can be associated using historic sources. Results of the survey at Angkor are described in Chapter (8).

Tree Roots and Vegetation

Tree roots are visible as a sharp upward pointing hyperbola in the radargram. For long profiles they can be neglected due to their small size compared to the mapped features. Roots however are important for the interpretation of grid data, as the profile of a straight root can be misinterpreted as a masonry wall. Roots are also used as soil velocity indicator.

Natural topography

Natural topography had no importance for long profiles. Small height differences and other topographic changes in the floodplain have not left a distinct signal in the radargrams since the ground composition of the topsoil in undisturbed areas does not change significantly. The majority of the small scale topography (earthworks) is artificial. GPR profiles conducted close to hills (Phnom Bakheng/ Chau Srei Vibol) detected the rock formation below the top soil, which was more important for the interpretation of grids to distinguish between natural rock and masonry.

Historic Features

Channel/canal (green)

The signal characteristic of a channel is generally narrower and shallower than that of the disturbance referring to a naturally created river bed. A type of signal-form, also measured in trenches of excavated canals, is roughly v-shaped, sometimes displaying a sharp drop in the centre and displays sides of a much lower gradient, see Fig. [35] There is an abrupt change in the signal between the sides of the canal to the natural soil below. Most of the canals had been excavated in Angkorian times at least once; therefore the ground was disturbed, while the excavated material was used to raise the embankment. The channels filled with sand probably due to flooding in the wet seasons, which happened, according to Fletcher, more slowly in the north and rapidly in channels to the south of Angkor,[704] assuming a fluvial deposition process that strongly affected the water management network. The material deposited in a channel is predominantly layered horizontally; sometimes several layers can be determined. Bishop *et al.* display a broad and shallow pre-Angkorian canal at Óc Eo,[705] a similar signal measured by GPR was identified in an excavation at the West Baray.[706] The annual flooding of the landscape has often extended and deformed artificial canals. Even one single canal can vary over its distance in form, size, depth, gradient of its sides, probably due to irregular accumulation of material inside. While many recorded channels were in combination with the remote sensing data positively identified as human made canals, it is problematic to classify a channel anomaly unmistakably as artificial. The term channel therefore describes the distinct shape and not the potential purpose of the marked anomaly.

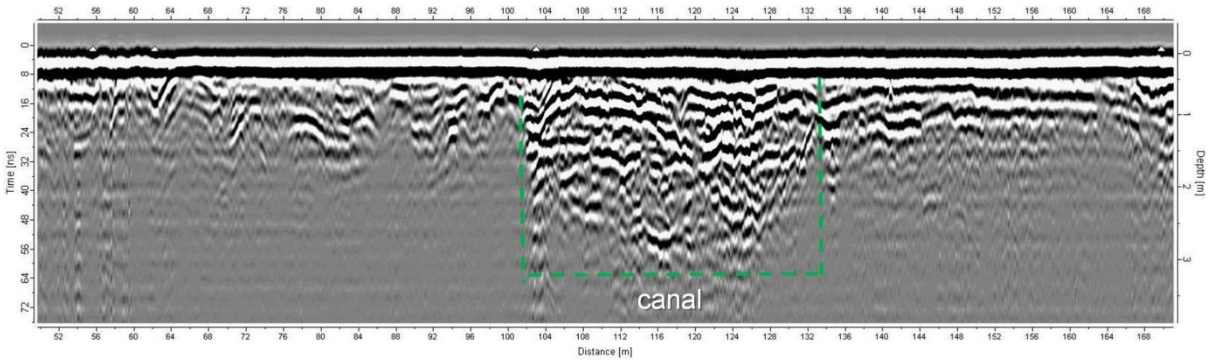


FIG. [35]: TRANSECT THROUGH THE NORTH-SOUTH CANAL OF HARIHARALAYA (RL_DAT_0011).

Moat (blue)

The signal reflection of a *temple moat* appears as a broad v- or u- shaped signal response with strong side reflections, similar to the one in canals, as the construction must have followed the same process, see Fig. [36]. A moat however is generally in association with a temple. Its disconnection from the water network has produced a horizontally layered, even sedimentation, either Aeolian or from accumulated vegetation, and is independent from seasonal flooding.

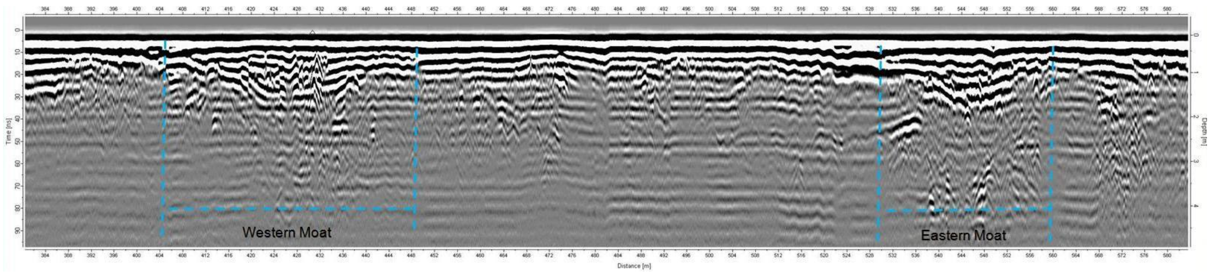


FIG. [36]: ANOMALY PRODUCED BY A SAND-FILLED TEMPLE MOAT; HERE OF PRASAT O KAEK (SITE NO. CP369, BK_DAT_0017_4).

Pond/trapeang (purple)

A *trapeang* is an artificially excavated pond close to a temple or settlement. The GPR returns a u- or v-shaped anomaly. Due to the 2-dimensional display, the return signal of a pond is not easily distinguishable from canals; especially if the *trapeang* is not marked on any GIS map or visible in aerial images. Crossing it from several sides reveals the extent, as it was done at Preah Ko; see Fig. [37]. *Trapeang* can only be mapped by remote sensing if they are either filled with water or marked by raised embankments. However, if excavated at some point in time, numerous *trapeang* must have silted up naturally, were filled to level the area for other use, or were overbuilt by a road. The GPR signal displays that some *trapeang* may have been excavated again after silting up, as it can be seen from the side of the pond that displays several superimposed sedimentation layers. As they are independent from the water management system, sedimentation could only be due to wind or natural annual flooding. As mentioned in Chapter (1) there is also a number of potentially natural ponds distributed over the floodplain.

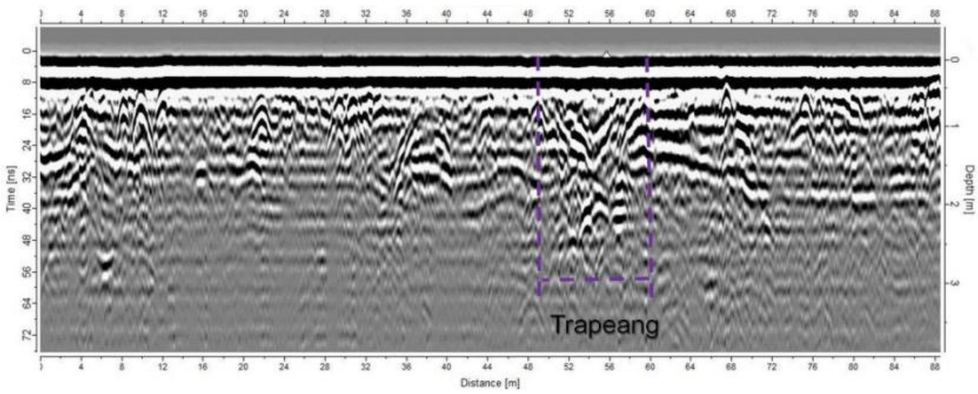


FIG. [37]: ANOMALY PRODUCED BY A SMALL SAND-FILLED TRAPEANG INSIDE THE ENCLOSURE OF PREAH KO (PK_DAT_0002_2).

Embankment /Angkorian road (brown)

Embankments consist of clayey sand that has been piled up above the floodplain and compacted. Shallow embankments are distinguishable in the field from the associated canals by small changes in topography and are sometimes covered by vegetation.

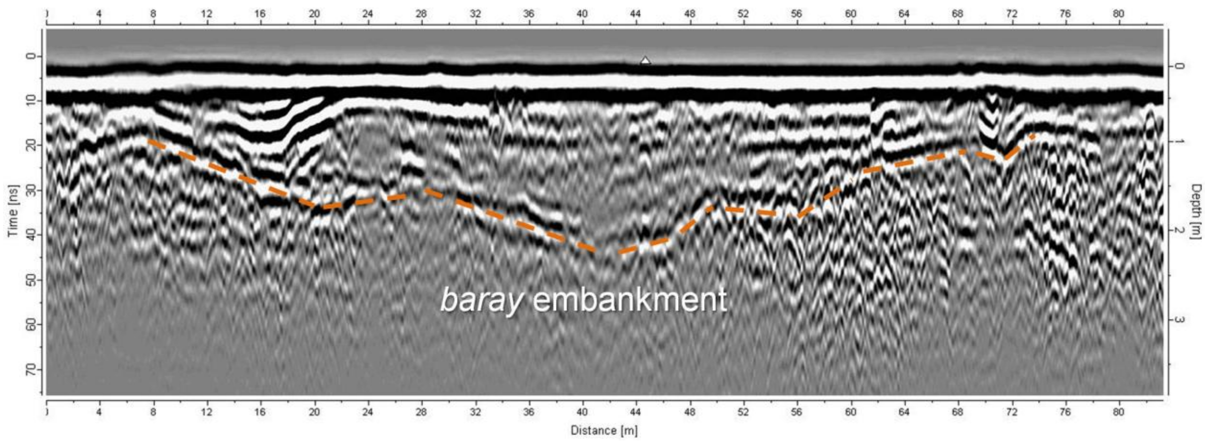


FIG. [38]: VERTICAL TRANSECT THROUGH THE INDRATATAKA EMBANKMENT (IB_DAT_0147, S-N).

Generally the earthworks have eroded substantially and their sides consist of accumulated softer sand from erosion, covering the natural soil. When the GPR is run perpendicular to the embankment, small channels on both sides of the earthworks and filled possibly with the embankment deposits indicate that the excavated material was once used to construct the earthwork. The extent of the earthwork is measurable in the profile as a horizon that follows a downward gradient in accordance with the rising embankment, see Fig. [38]. The compacted sandy clay of the earthwork is nearly impenetrable for the signal. Regarding GPR profiles that were run on top of embankments, anomalies like breaches were marked in the map but not the earthwork itself.

Rice Field Borders

Anomalies appear as a small u- or v-shaped feature if detectable at all. The features are too small to be marked in the map, but were used to associate distances of the profile with Google Earth data in the open field, e. g. Banteay Chhmar, and between the *asrama* and the Yasodharatataka; see Fig. [39].

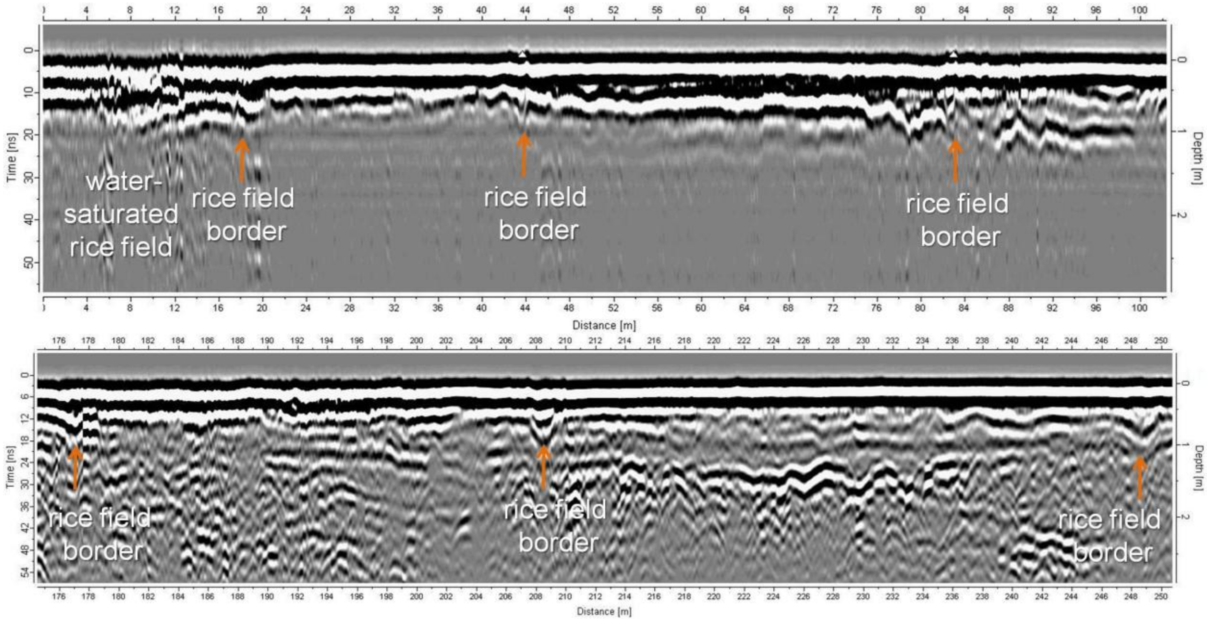


FIG. [39]: RICE FIELDS AND SOIL DIFFERENCES AT BANTEAY CHHMAR (BC_DAT_0023, ABOVE) AND SOUTH OF YASODHARATATAKA (AS_DAT_0146, BELOW).

Breach (orange)

The top of reservoir and canal embankments were searched for *breaches*, artificial or naturally eroded gaps in the embankment that have later been refilled with new material. Large breaches in reservoir embankments appear in GPR profiles steeply inclined at the side, and have a similar appearance as a filled canal but can easily be distinguished due to their location, see Fig. [40]. Depending on the height of the embankment and low penetration depth on embankments, the bottom of the feature might not be visible and its depth can only be guessed.

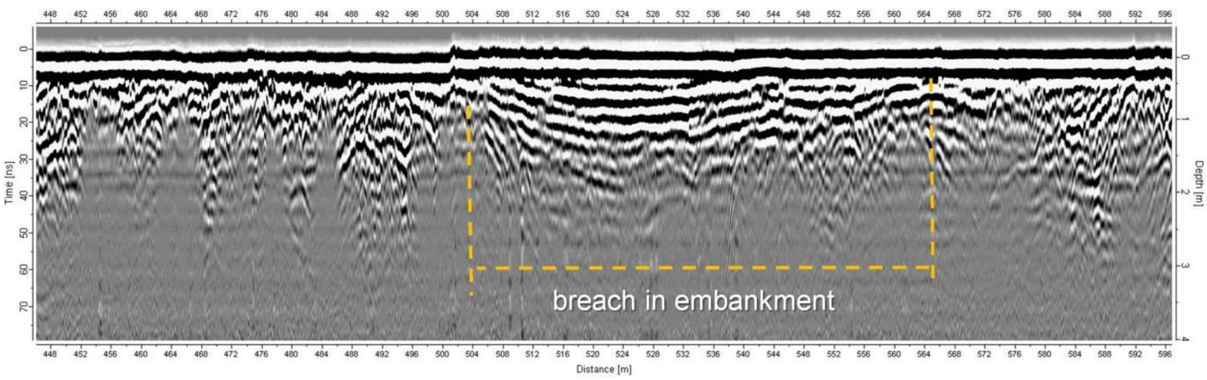


FIG. [40]: LARGE BREACH IN WEST BARAY EMBANKMENT AT WB_DAT_0001_504-564M.

Small breaches in canal embankments may indicate the use of canals to distribute water to the rice fields. Such breaches were detected, but due to their small size (<1m) only barely recognizable in the radargram. Some Angkorian canal embankments are heavily eroded and barely exceed the surrounding in height. However, breaches for distribution purposes must have been cut deeply into the embankment corresponding to the water level in the canal.

Masonry (red)

Anomalies classified as *masonry* in the profile show a strong linear reflection, a substantial horizontal line of even thickness. Sometimes the feature is slightly curved, see Fig. [41] Those anomalies, nearly exclusively found on embankments differ strongly from the surrounding soil and can refer to a masonry surface, such as covered masonry inlets or outlets of reservoirs, buried bridges, or laterite platforms. Sometimes, so at the Indratataka, they are interpretable due to their neighbourhood to known features. Further analysis and different types of masonry features are described under grid anomalies.

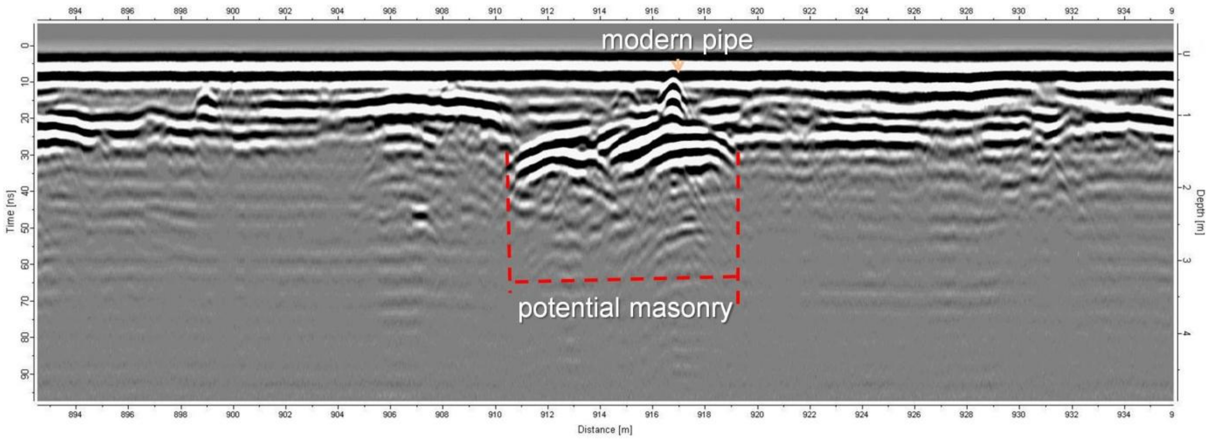


FIG. [41]:] POTENTIALLY MASONRY REMAINS (BRIDGE OR FLOOR AT BK_DAT_002_1_910-918M).

Settlement Patterns

More difficult to distinguish from the surrounding soil are hardened floors, indicating *settlement*. The packed, for the GPR signal nearly impenetrable clayey sand floor of a habitation mound differs from its surrounding, as it blocks and disperses the signal. It provides only shallow penetration depth, and below the surface it has a very low signal to noise ratio. The investigated locations apparently contain no other material than clayey sand, and generally the raised mound over the years of its use has been compacted to appear as cement-like material. A varying penetration depth was measured on some raised embankments, which could refer to a former occupied area, e. g. at the northern embankment of the Indratataka, as described in Chapter (3).

Modern Features

Modern features include visible objects measured with the GPR that were constructed or installed after the demise of the Khmer Empire, usually of 20th century or later origin. Some features have noticeably been restored or reused, e.g. concrete pipes in the road using an old canal. The often strong anomalies from modern material (e.g. steel/concrete) were classified as modern features and have not been marked. Modern features have usually been still in function at the time of the survey.

Bridges & Modern Canals

A modern canal is usually small and filled with water; therefore on a GPR image it is only recognizable due to the bridge covering it. In the reinforced concrete used for the construction of a bridge running over a modern canal the steel is easily recognizable due to the multiple reflections that produce a strong continuous alternating (strong and weak) reflection signal, see Fig. [42].

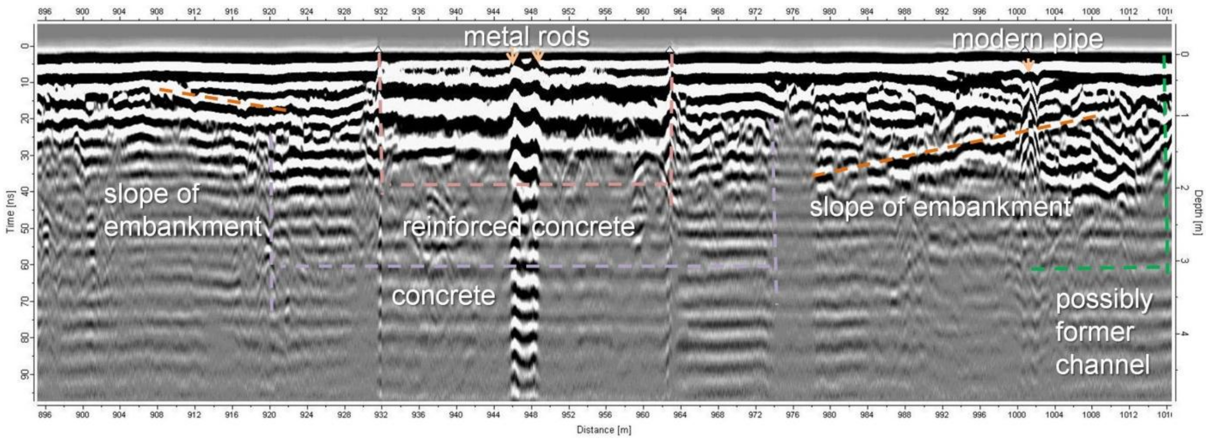


FIG. [42]: MODERN BRIDGE WEST OF BAKONG (BK_DAT_0006_4_932-964M).

Concrete Pipes & Modern Roads

The signal of a concrete pipe is easily recognizable in the field as a large and strong hyperbolic reflection (in contrast to small ones referring to tree roots).

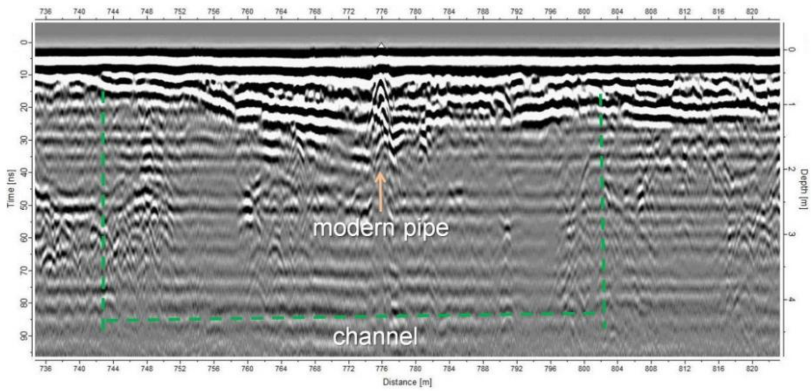


FIG. [43]: CONCRETE PIPE WITHIN OLDER CHANNEL AT HARIHARALAYA (BK_DAT_0006_4_752-796M).

Part of the actual pipe is often visible at the side of the road it underpasses. As these pipes were constructed to direct the water flow from one side of a road to the other, they can be found in areas where GPR will show an older canal or a naturally formed river bed that has been cut by the road. If the geometry of the feature is known, it can be used for hyperbola-fitting velocity and corresponding depth analysis.[707]

Already described in 'obstacles,' smaller roads are usually unpaved, consisting of compacted clayey sand. Penetration depth of the GPR can be expected to be reasonable. If recently covered with modern pavement they have become impenetrable - due to the accumulated rubble layer which is covered by several layers of tarmac.

CONCLUSION

The Combined use of Data in GIS

The archaeological maps have shown that not only were many monuments modified after their construction but the Angkorian archaeological landscape must be seen as a palimpsest created over hundreds of years of settlement in the region. While there is no evidence of an intended master plan for the construction of the monuments, an analysis of remote sensing data has revealed earthworks and canals associated with the centres, and has produced chronologically ordered maps of the region, that display the growth of Angkor.

GIS has served as an integrative tool to combine very different types of remote and close range sensing data into one digital environment, to directly associate horizontal 2-dimensional remote sensing data and vertical 2-dimensional GPR results. The anomalies discovered in long-distance GPR transects were measured and classified as disturbances, channels, breaches, moats, ponds and embankments, and integrated into the digital maps, where they were compared with archaeological maps.

The GIS data and maps provide the base to analyse spatial relations of archaeological features. The vast number of archaeological features, initially mapped by aerial and satellite remote sensing methods, were spatially adjusted if necessary, and virtually extended to interpret and classify the anomalies identified in the radargrams. Several previously unmapped buried structures were discovered this way and could be associated with known archaeological features. The interpretation of those discovered anomalies in relation to the remote sensing data will be part of the following chapters.

CHAPTER (5) SHRINES AND TEMPLES

The shop seemed to be full of all manner of curious things - but the oddest part of it all was, that whenever she looked hard at any shelf, to make out exactly what it had on it, that particular shelf was always quite empty: though the others round it were crowded as full as they could hold. (LG, V)

Almost all visible structures of the medieval Khmer are former shrines and temples. Built of durable construction material - bricks, laterite and sandstone - many are found within the precincts of enclosures. Geometry and the symmetry of Angkorian architecture helps in the identification of collapsed and demolished parts of monuments. Sometimes, however, only the foundations still remain. Most GPR surveys targeted at foundations were conducted close to still existing monuments or within enclosures - which provided a delimited area for the application of the GPR gridding method. The smaller surveys were conducted to search for the remains of potentially missing architectural features, including foundations of masonry or wooden beams, as well as sand-filled foundation trenches, representing the original outline of the monument. The main target area to search for structural remains has been the western side of Angkor Wat. By covering 2.5 hectares with GPR grids, from the moat to the main temple, the foundation of six towers were identified in vicinity to Gopura 4 West, the western entrance. The survey was followed by targeted excavations to further understand the construction history of this site.

(a) BUILDING AND DESTRUCTION

All the King's horses and all the King's men couldn't put Humpty Dumpty in his place again. (LG, VI)

i. ANGKORIAN CONSTRUCTION TECHNIQUES

Geometry of Buildings

The first European visitors to Angkor used the geometric appearance of Angkorian monuments to describe them.[708] The image of perfectly symmetrical configurations fascinated them, as seen in an early architectural ground plan of the Bayon by Louis Delaporte.[709]

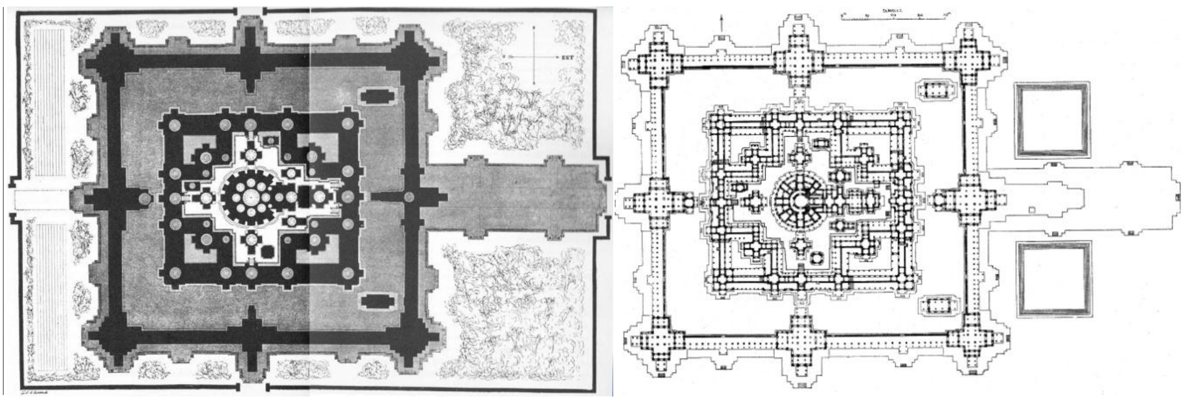


FIG. [44]: DEPICTION OF THE BAYON BY LOUIS DELAPORTE (1880) AND MAURICE GLAIZE (1944).

Much later measurements revealed that only one quarter of the temple had been mapped initially, and the remaining three quarters had been mirrored,[710] creating an appearance that was idealized as being more symmetrical than it actually was; see Fig. [44].The geometric attributes of the monuments have led to interpret the initial site plan based on mathematical, religious, or astronomical belief. Stencel *et al.* analysed the potential astronomical and cosmological intentions the planners of Angkor Wat had - in relation to the other monuments.[711] Eleanor Mannikka, co-author of the publication by Stencel *et al*.,[712] followed up on this idea, basing the temple architecture of Angkor Wat on the *mandala*. She set the number of features of the monuments, their width and length in relation to each other to reconstruct the monuments as intentionally integrated in a greater construction plan.[713] This can be misleading, setting up an over-interpretation of the original intent of the building complex.[714] The obvious geometrical attributes of the Angkorian monuments as images of divine powers are, however, undisputed by modern historians, as J. Dumarçay shows:

> *"Geometry plays an important role in this first moment of constructing a building, not only because it is a proof of the existence of divine powers, but also because it integrated the future structure into its environment, which itself contains geometric shapes used by the creator."*[715]

The intended symmetry has been an important factor for the search of missing architectural features using GPR. The remaining structures, in accordance with symmetrical and geometrical attributes of Angkorian monuments, provide impressions of the layout of the original plan, which can help to define the survey areas.

Construction Material

The use of material for temple constructions changed with the development of the Khmer culture, as discussed in several publications by P. Royère, J. Dumarçay and O. Cunin.[716] The properties of building material were described by Uchida *et al*.[717] Regarding pre-Angkorian construction, the use of brick was the dominant building material for large ceremonial monuments, as seen in examples of the Kulen or at Ak Yum. This material remained important for some time also in the Angkorian period for the construction of village shrines and smaller structures:

> *"Brick buildings vary greatly in form, but technically they remained the same throughout the Angkor period. Even when stone began to be used for large monuments, the corbels were still made of brick, as is the case of Ta Kev, for example. Nevertheless, from the 12th century onwards, bricks were used less and less, without disappearing completely. Buddhist structures constructed during the 13th century only rarely used ground bricks and the joints became much thicker, sometimes over a centimetre thick."*[718]

In the Angkorian period brick was increasingly replaced by quarried stone. The sandstone cladding of Bakong temple in Hariharalaya marked the transition from the pre-Angkorian to the Angkorian period with the use of both sandstone and laterite. In conjunction these materials were used for the majority of ritual constructions. Wood was used as a supporting material and in the construction of secular architecture. Dumarçay gives an account of quarrying and building construction techniques of the stone materials used at Angkor:

> *"There is no difference in the cutting technique between laterite and sandstone. However, taking into account the formation of a crust due to the evaporation of water of the quarry of the sandstone, there is a major difference in their use. While, for laterite it is easy to make a stock of stones ready for use, the*

same cannot be said of sandstone. Sandstone must be used as rapidly as possible and its reuse is almost impossible for sidings."[719]

Foundations

Foundations are often the only remaining evidence of a demolished monument. The primary target for the detection of structural remains is the archaeological footprint created by human interference. With regard to the detection of below ground architectural remains, two subsequent modifications must have occurred to receive an interpretable signal from the subsurface: (1) initially the foundation of a building, for which the original ground was removed and filled with new material, followed by (2) active demolition or natural decay which either buried the feature, or left the foundation in the subsurface as the only remaining evidence of the structure, leaving a measurable variation in the soil composition.

For the interpretation of GPR results it was therefore important to have an understanding of Khmer construction techniques and the composition of foundations, which has been revealed by excavations. Dumarçay has given a description of the foundation of the Bayon,[720] based on excavations performed by Marchal in the 1920s, see Fig. [45]. More recent sources on the configurations of Angkorian foundations are provided by Pascal Royère at the Baphuon,[721] and the Japanese excavations at the Bayon[722] as well as at Prasat Suor Prat.[723] In all excavation trenches a similar stratigraphic pattern was observed. Before the construction of a monument, an area of comparable size was excavated and filled with separate horizontal layers of clearly distinguishable foundation material: layers of sand alternating with very thin layers of small rocks, mainly sandstone splinters. In addition, larger pieces of andesite[724] were put into the matrix. Due to the small percentage compared to sand and sandstone fragments, it is however uncertain whether the material had a structural role or had only spiritual purpose. In the case of the Bayon, a layer of laterite blocks separated the first of such a series of sand/chips/andesite layers from a second one above.

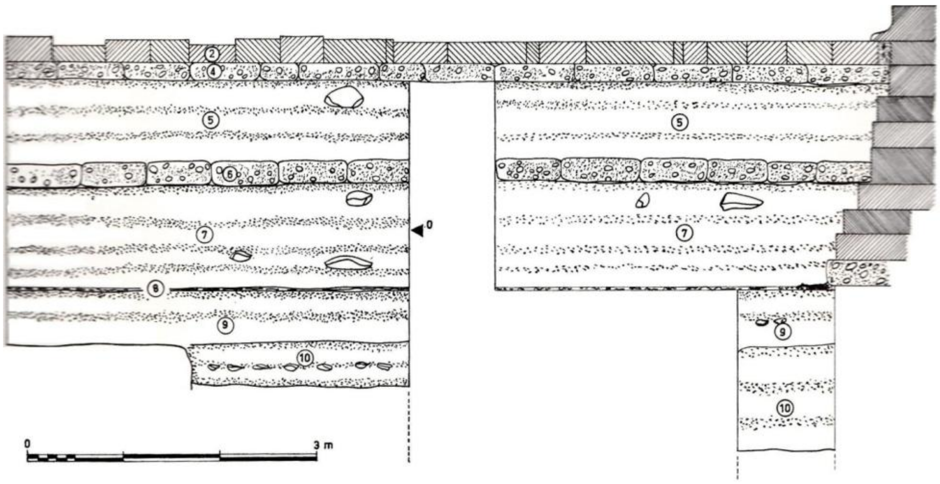


FIG. [45]: INTERPRETATION OF ANGKORIAN FOUNDATION (DUMARÇAY & GROSLIER, 1973, PL. XI).

Secular Masonry Structures

Besides being used for the construction of ceremonial monuments, laterite was also particularly used for other structures. Some laterite masonry structures had a clearly protective character, such as the walls of Angkor Thom, while the purpose of others are under discussion. A massive circular structure is located to the north of Angkor Thom, which the locals named Krol Romeas or "*rhinoceros enclosure.*"[725] According to Marchal it was possibly an elephant training ground, which is why it is sometimes also called Krol Damrei, the "*pen of the elephant*."[726]

Most other masonry structures served purely engineering purposes. In those cases laterite was used to resist continuous and large flows of water, and so was used for such purposes. Examples are the masonry bridges of the major Angkorian roads.[727] Most masonry bridges have been interpreted as late additions to the imperial roads, installed in the reign of Jayavarman VII[728] or later, to replace preceding wooden versions.[729] Angkorian bridges are predominantly constructed of several layers of laterite blocks, with narrow corbelled arches connecting pillars of varying length depending on the surface topography.

There are other water management devices such as another site named Krol Romeas, in the eastern embankment of the Yasodharatataka and the northeast inlet of the Jayatataka; see Chapter (7). The technique used for their construction is the same as for the temples - at Krol Romeas the laterite blocks of the first stage are neatly carved and well connected. Some masonry inlets within the embankments of the *baray,* such as one in the northern embankment of the Jayatataka would have served a double purpose, to channel water as well as functioning as bridges. Some reservoirs and smaller ponds have been clad with masonry. A massive laterite structure at Bam Penh Reach, identified as a potential overflow device, where the river Siam Reap is redirected from its original bed towards the centre of Angkor,[730] and the massive wall or dam to the north of the regional centre of Koh Ker, both display clear evidence of heavy usage.[731] The latter especially serves as an example that even massive stone walls that were supported by embankments were not able to resist the pressure of the water, being destroyed over a length of 50m possibly by floods, as the blocks were widely dispersed.

ii. Modifications and Reuse of Material and Space

In the search for structural remains, GPR was used to target empty spaces close to monuments, in order to seek evidence of previous occupation or use. There are many known examples that show modification of the monuments, as well as reuse of material from demolished structures that possibly had been in their vicinity.

While the exact period of use of the state temples at Angkor is difficult to determine, their importance was likely reduced after the construction of a later state temple. Very few temples were continuously in use during and after the Angkor period, such as Angkor Wat, which was in use as a monastery even in the 19th century. Freeman & Jacques mentioned that Phnom Bakheng was abandoned just 21 years after its construction in AD928, but then *"briefly rehabilitated"*[732] in AD968. Numerous modifications and additional elements that display more than one architectural or art historic style and have been dated to a later construction phase are evidence for longer periods of use. Dumarçay mentions *"[...] two attitudes for architectural reworking: either, after damage or poor workmanship it is necessary to repair a structure and restore its former appearance, or on the contrary the master builder is looking to create a new appearance of the building."*[733] One of the best studied is the Bayon, with different building phases described by Philippe Stern[734] and recently by Olivier Cunin.[735] Vickery named three major points of controversy if the temple had been finished by Jayavarman VII. *"(1) the dating of the phases of construction, (2) the meaning of the tower faces and (3) the dating and significance of the two galleries of the bas-reliefs."*[736] Cunin proposes, however, that the Bayon was entirely the work of Jayavarman VII.[737] Occasionally preceding monuments were integrated into the new configuration (e. g. Phimeanakas and the Baphuon into Angkor Thom) and therefore must have retained or received new importance.[738] The area surrounding a former state temple also passed through significant change if it lay within the occupation zone of a succeeding monument. The vicinity of the Bayon serves as an example, as for the area inside Angkor Thom no restraint had to be kept to transform the landscape. On the other hand older structures were neglected and nearly completely buried, as in the case of Ak Yum at the West Baray, or were used as a quarry for material for new constructions for which they were completely dismantled, e. g. the shrine that was dismantled for the construction of Spean Thmar, the bridge which once crossed the Siem Reap between Ta Keo and the east gate of Angkor Thom. The bridge includes stone blocks with artistic elements.[739]

The case where the material of demolished monuments was integrated into new structures produced structures of minor quality. According to Dumarçay, the knowledge to work sandstone quickly after its quarrying, *"was forgotten by the Khmers at the end of the 13th century. We can see numerous restorations with reused stones, which had disastrous results for buildings on which the protruding surfaces quickly eroded away."*[740] Two examples are the breaches in the northern, southern and eastern side of the enclosure wall of Angkor Wat, which were filled with masonry material,[741] and the outlet of the Yasodharatataka at Krol Romeas, which was modified at least once and possibly several times in later periods.[742] To summarize, the detection of remains from Angkorian structures by GPR was supported by the way monuments were designed and demolished:

- The construction of an architectural/engineered feature at Angkor principally started with an excavation for a footing/foundation trench, followed by the in-filling of this trench with substructural material, and then the construction of a building.
- If a feature was abandoned, it stood a good chance to remain standing until its collapse.
- A structural feature was only demolished to fulfil a new need; e.g. to make space for another construction, or the material was reused for new structures.
- When the structure itself was destroyed, the remains of the foundation or at least its excavation trench left an archaeological footprint in the subsurface.

(b) DETECTION OF MASONRY USING GPR

'I think I'll go down the other way,' she said after a pause: 'and perhaps I may visit the elephants later on. Besides, I do so want to get into the third square.' (LG, III)

i. SMALL TEMPLE SITES

The archaeological footprint of small temples has been identified by B.P. Groslier[743] and later defined by Pottier[744] using aerial photos. Several types of small temples existed in the Angkor region, serving different purposes in relation to the community. The most common temple in the Angkor plain was the local temple as the cult centre in a rural community. Another type of temple was the *dharmasala* which had been constructed along the Angkorian highways as so called “rest houses.” GPR surveys here were able to detect and map additional structures, measure the extent and depth of the moat and ponds close to the temple sites, and to provide a more complete plan of the site.

Local Temples

Local temple sites served as the centre or focus point of a village. The archaeological remains of a typical village temple consist of a small fairly rectangular mound, on three sides surrounded by a depression, and are generally roughly oriented east to west. The surrounding depression was originally filled with water serving as a moat,[745] which could be used for the year round water supply. Similar to the majority of the large temples, the entrance usually faced to the east and an earthen causeway connected it to the outside. Some sites had in addition a small pond (*trapeang*) in their vicinity, used as a supplementary water and food source.[746] From the central position of the temple within a village, rice field patterns were radiating outwards in the prehistoric period, while from the pre-Angkorian period onwards rice fields were aligned with the temple’s orientation.[747] Often no superstructure has remained and nothing is visible above the surface besides a raised earthen base and a denser ceramic scatter, since the shrines were probably constructed of perishable material such as wood or bricks that were used elsewhere. Nevertheless, what remains of a temple site can usually be differentiated from a simple so called “house mound” or other earthen platforms, as these are neither surrounded by a moat nor oriented to the east.

The objective of a GPR survey was to identify potential structural remains such as a masonry platform or the foundation trench, and to ascertain their orientation and depth, as well as identify any archaeological features around the temple site. Surveys were carried out at Doun Kaev to find structural remains of two neighbouring local temple sites. The temple sites are located northwest of the West Baray.[748]

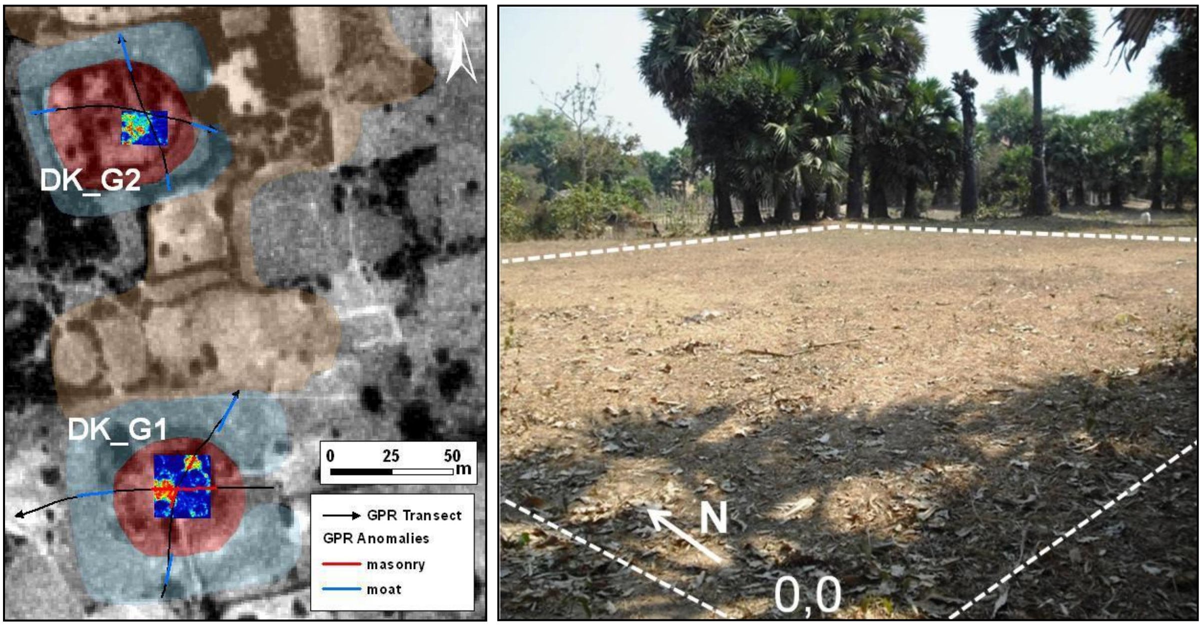


Fig. [46]: Plan of and Kok Song (above) and Doun Kaev I (CP96) & area of grid DK_G1.

The layout of Doun Kaev comprises two small temple sites close to each other.[749] The southern temple mound, CP96, only named *Srah* in the site register, lies 150m south of the northern temple mound of Kok Song (LL600). It represents a typical local temple, with three sides enclosed by a moat, now empty, and an earthen causeway crossing the moat from the central platform to the east, see Fig. [46]. Both temple sites are roughly oriented east-west. The layout of the earthworks and limited scatter of pieces of ceramic sherds are the only remains indicating a temple site. There is no visible evidence of masonry structures.

CP 96

CP96 had no remaining visible structures left on the surface. The central earthen mound was at its side flanked with palm trees and bushes, but the middle of the area was empty and provided a smooth and flat earthen surface for the GPR survey.

A 30x30 meters grid was laid out on top of the earthen platform. Additionally several single profiles were carried out, starting in the moat and running over the platform to the other side. The survey results display two rectangular and without doubt masonry features which are positioned to each other in a 90 degree angle. The main and roughly squared feature, of a dimension of 9m x 9m, is in alignment with the entrance causeway on the western side, the second one of a dimension of 6.5m x 6m lies to the north. A third, less obvious feature of 7m x 3.5m matches the smaller one on the southern side. A thin linear feature that connects the corners of the three features might be the connection to an additional platform to the east.

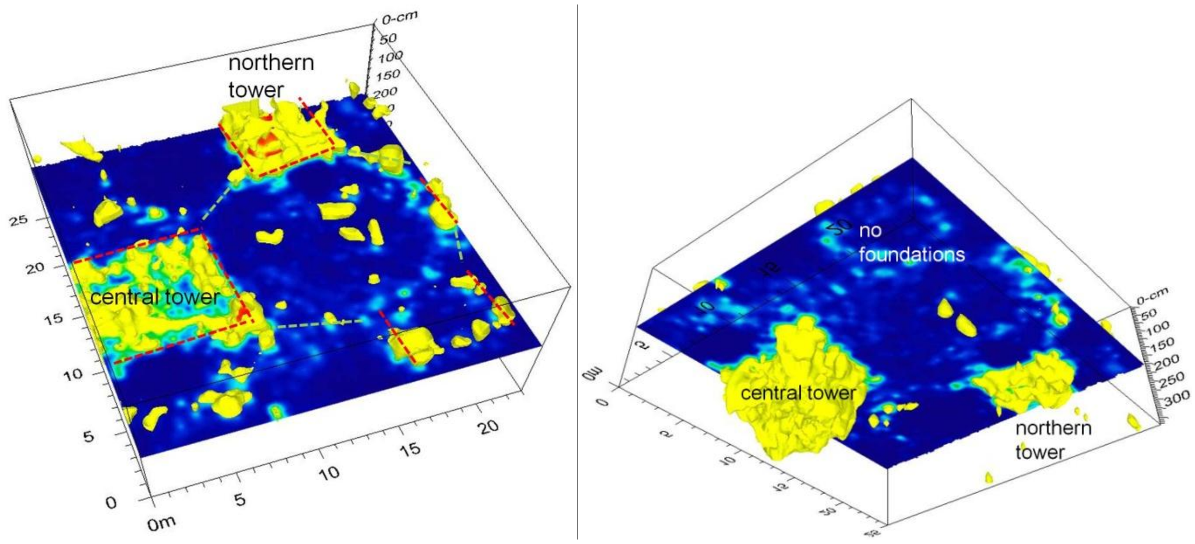


FIG. [47]: ISO-SURFACE OF TOWER REMAINS IN GRID DK_G1 SEEN FROM ABOVE (LEFT) AND BELOW.

Concluding from the results, there is evidence of the foundation remains of two masonry towers, and a less clear signal of a third one. The larger one could represent the central temple tower which faced the entrance to the east; its importance is also visible in the vertical extent of the foundations; see Fig [47]. The smaller northern shrine could have matched another small shrine to the south, of which the foundations were removed. The whole ensemble displays a symmetrical outline between the three features which might have been connected by a small wall.

Kok Song

Regarding the second temple site at Doun Kaev, the middle of the earthen mound of Kok Song is dominated by a ring of clayey sand. It appears as if the central part was excavated at some time, possibly due to looting. The earthen ring wall complicated the survey and limited the survey grid.

The analysis of the data shows that the original size of the structure is not clearly visible. As the GPR results mainly were consistent with what is visible on the surface, it could indicate that the masonry foundations have been partly removed.

The GPR survey results concerning both sites confirmed the expectations regarding small temple sites: although visible masonry remains have disappeared, the foundations that were revealed by GPR provided an image of the original outline of the structures.

Rest Houses

An inscription[750] states that the majority of the 121 *dharmasala*, also referred to as fire temples, were installed as part of "rest houses" for travellers under the direction of Jayavarman VII.[751] For that reason they were placed roughly at equal distances of 14-15km[752] from each other next to the major Angkorian roads. From the inscriptions and field surveys, initially by Lunet de Lajonquière,[753] it is known that they were mainly constructed on the road from Angkor to secondary centres of the empire such as Phimai and Preah Khan of Kompong Svay.[754] Generally they were close to a pond and occasionally surrounded by a moat. Regarding the structural components of the buildings, some *dharmasala* were made of wood, others were dominantly made of laterite or bricks. Sandstone was limited to representative doorframes or lintels. The stonework used for the construction of the *dharmasala* indicates that they were used for worship rather than being actual rest-houses.[755] In recent years several additional archaeological sites have been identified beside the roads of the Khmer empire as remains of *dharmasala*.[756] Clearing, surveys and excavations were carried out to improve the knowledge on their religious or secular purpose.[757] The task for the GPR survey was to support the interpretation of results from small excavations performed at two *dharmasala*; surveys were conducted around the complexes.[758]

Prasat Phtu (Site Reg.: MH407)

The small temple site is a *dharmasala* located about 500m north of the northwest corner of the temple complex of Preah Khan at Angkor and 1km east of the north canal. Built mainly of laterite walls with some carved sandstone for artistic additions, the main temple structure stood on a raised clay mound of about one meter height compared to its surrounding; while the side walls were still standing, the stone roof had collapsed. Two small grids were laid out and several profiles concentrated on the surrounding area, see Fig. [48]. The intention was to find the extent of the platform on which the structure was built, as this is known from other *dharmasala*.[759] Additionally transects were laid out to analyse the surrounding landscape features by identifying the existence of two potential areas of *trapeang* alongside the monument, and measuring their original extent and depth.

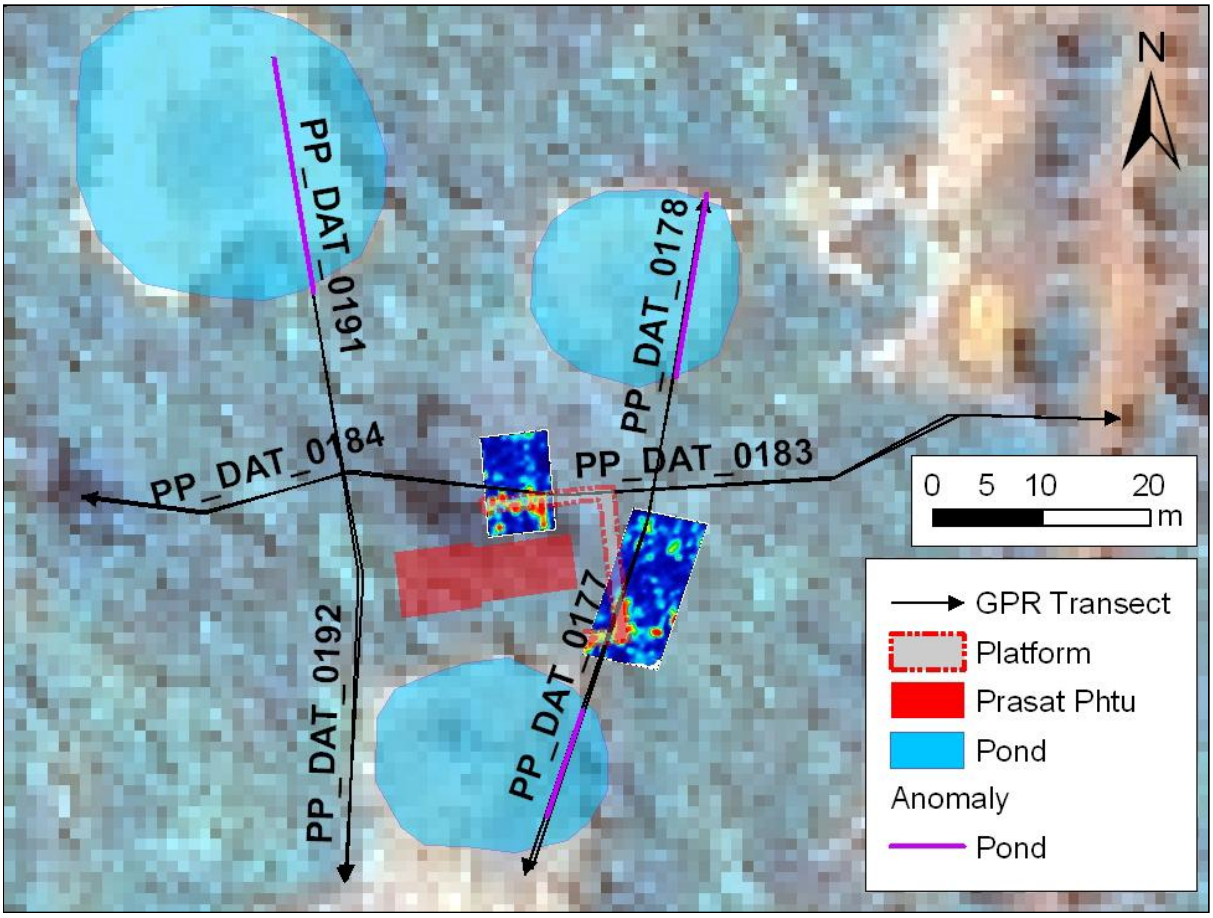


FIG. [48]: GPR RESULTS OF PRASAT PHTU (BACKGROUND: IKONOS).

The treeless area north and south of the temple mound was at the time of the survey dry and used as farm land. The features were clearly picked up by the GPR signal as former ponds that had silted up since their use as *trapeang*. The depth and extent of the ponds was measured; see Fig. [49]. The two grids were laid out directly next to the temple. The lower part of the structure was buried under soil which rose to about one meter next to the outer wall of the temple.

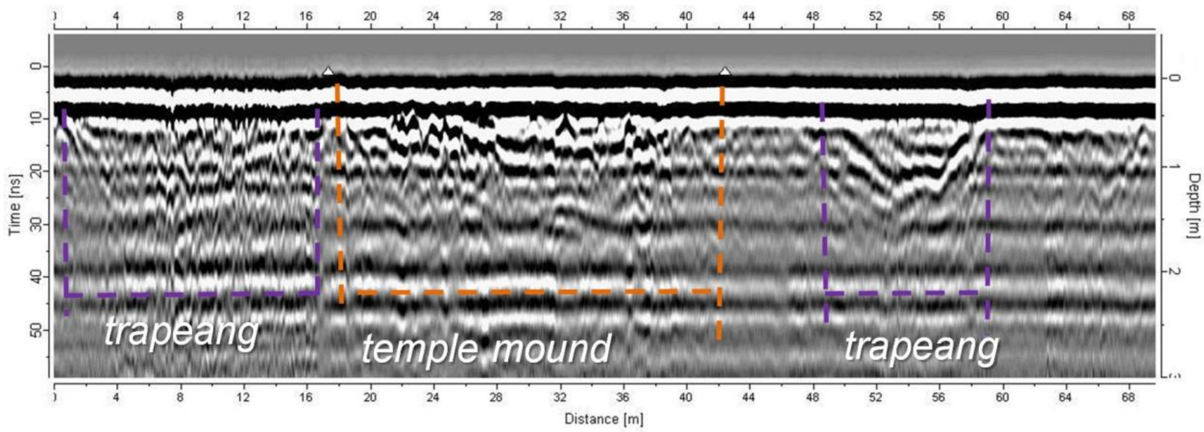


FIG. [49]: GPR-PROFILE PP_DAT_0177 TRANSECTING THE AREA OF PRASAT PHTU.

Due to the topographic problem, and the limited space for the survey due to the vegetation, the GPR results from PPGrid1, which was positioned adjacent to the north wall of the temple, were difficult to interpret. Possibly though the step of the platform was detected, as in PPGrid2 on the temple's eastern side, where part of the masonry rim of the platform was discovered 4m from the temple to the north east side, supporting the evidence known from other *dharmasala*.[760]

Prasat Sampou

Prasat Sampou (site register: MH495) is a *dharmasala* located roughly 5.8km to the north of the northwest corner of Angkor Thom. The monument was built mainly of laterite with sandstone additions and is of similar size to Prasat Phtu. It stood fully intact about 130m west of the Angkorian road to Phimai oriented in east-west direction with a small portal opening to the west. Evans had mapped double embanked earthworks in combination with moats around the monument using aerial images.

The intention of the GPR survey was to measure the extent of the laterite platform at the monument, which was measured 6m out from the central structure to the north and south, as well as the existence of the large earthen enclosure. A long survey was conducted towards and over the earthen Angkorian road, to analyse any possible relation between the temple and the road (see Chapter 8). The laterite platform detected by one grid and single profiles extended from the temple about six meters out, supporting the results from Prasat Phtu. A large grid to the west of the temple revealed linear features running south to north. However, they did not correspond exactly to the earthen enclosure mapped by Evans.

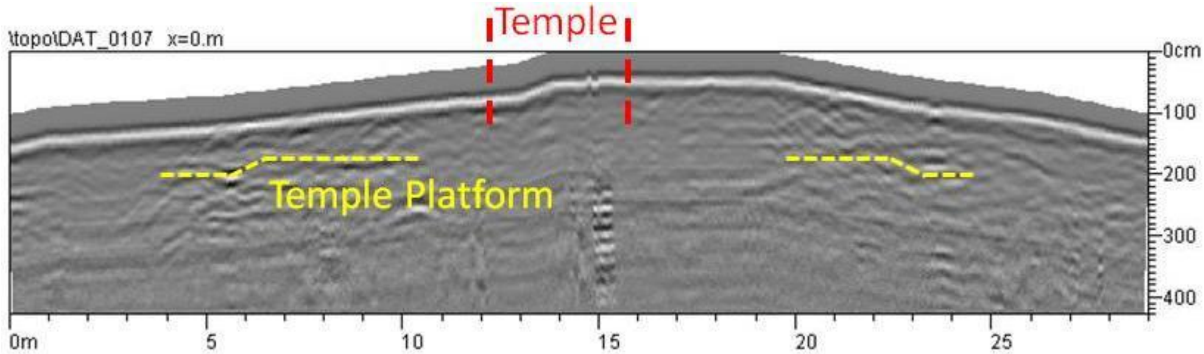


FIG. [50]: GPR-PROFILE PS_DAT_0107 TRANSECTING THE FRONT OF PRASAT SAMPOU.

Local Shrines

An excavation at Nokor Krau II[761] unearthed the foundations of a rectangular masonry platform, interpreted as a small shrine. The location is on the western side of the North Canal, a tributary to the moat of Angkor Thom, which reaches the northern gate of Angkor Thom 300m further to the south. No structural evidence was known prior to the excavation, and the landscape lacked the features of a traditional village temple in shape or outline, neither was the earthen mound surrounded by a moat. The GPR survey conducted after refilling the excavation, revealed the total extent of the structure, which was considerably bigger than the excavation had shown, and demonstrated that there was no other structural feature close by.

Regarding the GPR results conducted over small temple sites, they showed that it is possible to detect underground masonry structural features and additional architecture of known archaeological sites. Particularly buried laterite and sandstone structures provided clear results and differed strongly from the clay and sand matrix it was usually embedded in. GPR proved valuable for detection of additional features and to extend the information obtained by excavations.

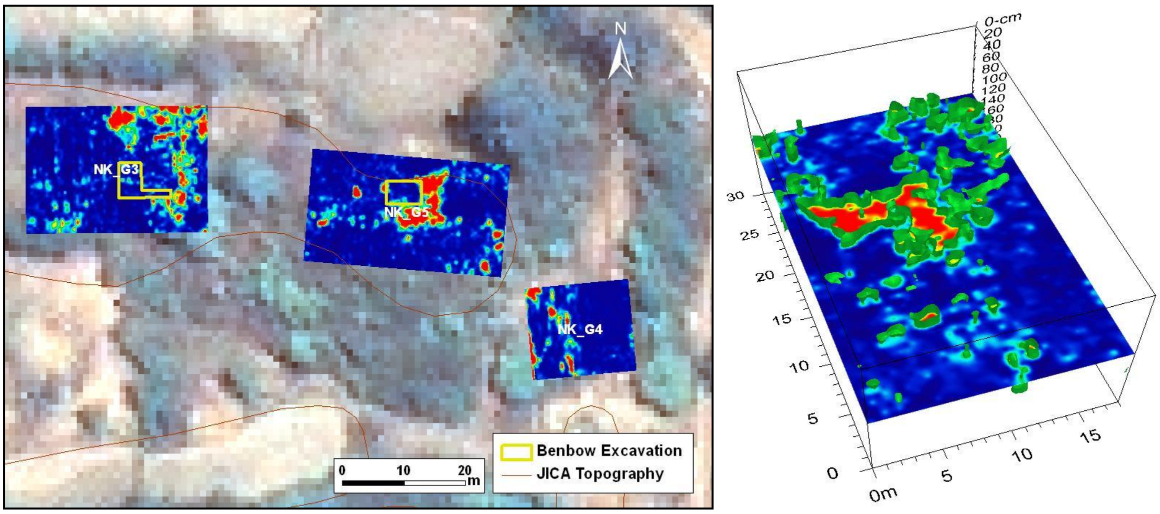


FIG. [51]: GPR GRIDS AT NOKOR KRAU II. THE ISO-SURFACE HIGHLIGHTS THE EXTENT OF THE PLATFORM OF NK_G5 (BACKGROUND: IKONOS).

ii. INSIDE HARIHARALAYA AND ANGKOR THOM

Several GPR surveys searched for potentially missing elements of a structure. The survey areas were chosen based on the assumption of symmetries - that if an element was in place on one side of a ceremonial structures, at some point in time existed a matching counterpart may well have existed on the other side - this turned out to be the case for several structures and *trapeang*.

The Walls of Prei Monti

The archaeological site of Prei Monti to the south of the Bakong consists of a small shrine in the eastern part of a large enclosure which is surrounded by a moat. Prei Monti is today considered to have housed the former royal palace of Indravarman I.[762] While the remains of the masonry double enclosure wall exist on the northern and western side, there was no evidence of it visible on the surface in the south-eastern corner. Therefore Prei Monti represented a classic example of missing geometry. Several GPR profiles and grids (PM_G2 and PM_G3) conducted in the vegetation free area southeast of the temple towers displayed the south-eastern corner of the inner enclosure wall, and twelve meters further to the east the remains of the outer enclosure wall about 50cm under the surface.[763] An additional grid (PM_G1) displayed masonry remains at the site where the *gopura* was proposed, see Fig. [52]. Archaeological excavations following the survey revealed the remains of a masonry structure, which was however not associated with a *gopura*.[764]

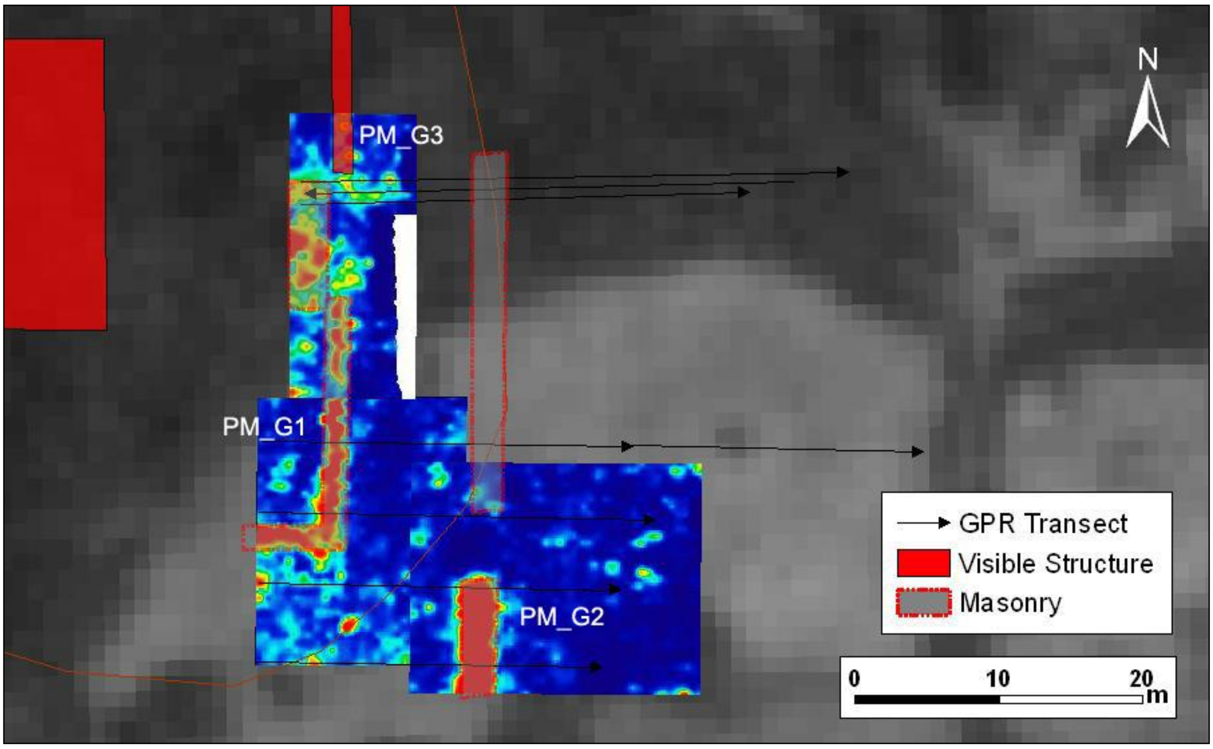


FIG. [52]: INTERPRETATION OF GPR RESULTS FROM PREI MONTI.

The ponds of Bakong and Preah Ko

While not a masonry feature, the survey at the south-eastern end of the enclosure of Preah Ko, a temple of Hariharalaya, was conducted for a similar reason as the preceding ones: to assess the existence of an expected piece of the original geometry of a temple configuration. The proposed initial configuration of the Bakong to the south, as proposed by Pottier[765] consisted of several approximately 50m wide square water tanks aligned on both sides of the road, leaving the Bakong from the central axis to the north and east in a regular spacing. Starting from the outer moat each side would have had five ponds. While the remains of the second north-western water tank was visible as an opening in the southern bank of the moat, Pottier assumed that with the excavation of the moat of Preah Ko and the raise of the earthen platform of the enclosure, the third, fourth and fifth pond had been filled, showing that at least the outer parts of Preah Ko are of a later construction stage than the first stage of the Bakong. A set of 17 GPR transects in north-south and east-west direction was conducted to cover the forest free south-eastern corner of the enclosure like a mesh of 80 m x 80 m. The signal penetration depth of the 250MHz antenna reached beyond 500cm. The results display very strong disturbances on the eastern side towards the moat. The disturbances continue even beyond 500cm (see Fig. [53]), which evidently indicates that the area next to the moat had once been excavated and then filled with material at a later stage. The anomaly, however, was situated to the east of where the pond was expected, and therefore not in the right location to support the hypothesis of a filled third pond. A 1m-spaced grid (PK_G1, 22m x 14 m) was conducted in its centre to further investigate this feature, but did not reveal any additional information. Additional profiles to the north and south of the east-west axis to the east of the temple did show a strong disturbance on the southern side of the moat of Preah Ko, but not corresponding to the plan where the pond would have been.

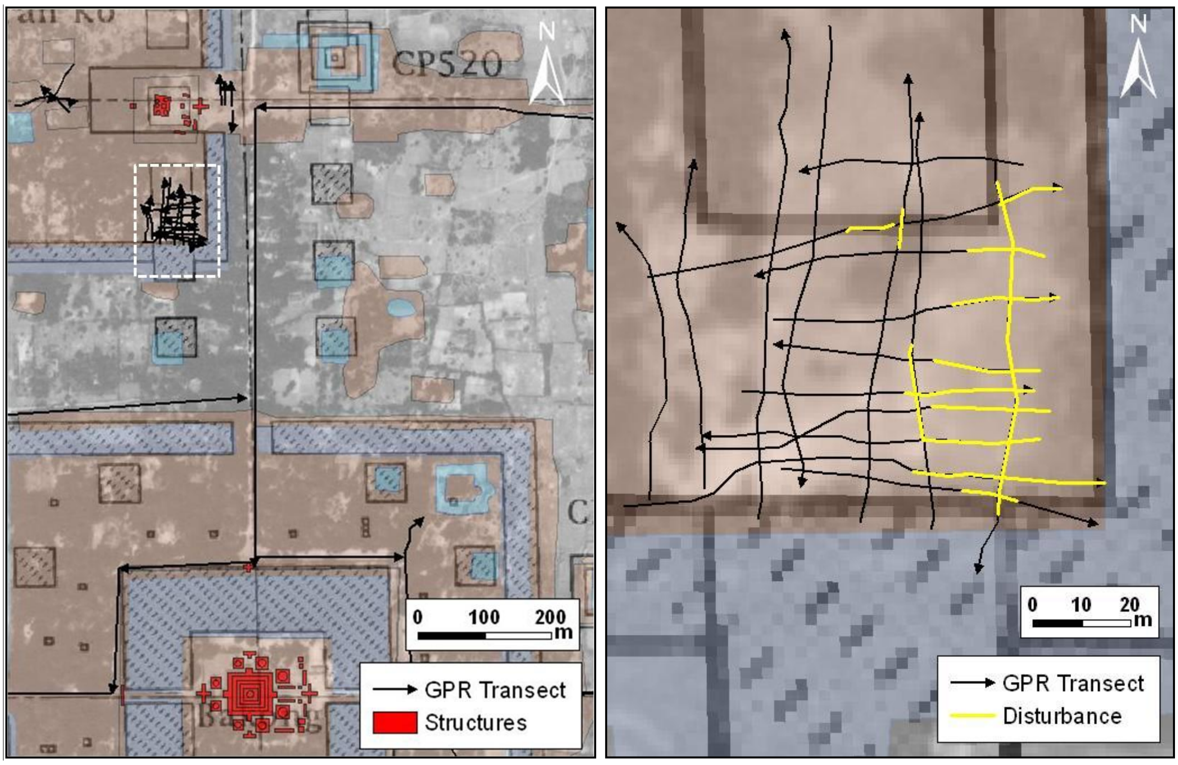


Fig. [53]: Outline of the Bakong tanks and GPR survey at Preah Ko. (Background: Pottier, 1995/1999, JICA, Finnmap)

The Enclosure of the Baphuon

The enclosure wall of the Baphuon, a temple that functioned as state temple for the greater part of the late 11th and early 12th century, closely surrounds the main structure. On the northern side there is only a 3m space between the masonry wall that also serves as the southern wall of the palace site and the Phimeanakas, and the temple. The wall continues towards the east in front of the temple, and approximately 40m from the temple it cuts into a corner, narrowing the space of the enclosure by 2m on the east by several meters. The unfinished stones indicate that it had been a later addition and Groslier[766] raised the question whether the enclosure wall of the Baphuon had been originally much closer to the temple, and had been modified to extend the enclosure. He then investigated it with a small excavation conducted on one of the corners. The outcome was recently investigated again by Royère.[767] Historic evidence shows several kings were involved in the construction of the Baphuon. It is said to have been initiated by Suryavarman I (AD1002-1049) and was reportedly continued under Udayadityavarman II (AD1050-1066). According to Pascal Royère the superstructure remained unfinished,[768] and later the Baphuon was integrated into the ensemble of Angkor Thom.

A GPR survey was conducted using the 500MHz antenna, to identify the possible former outline of the enclosure to test the excavation results, and find potential additional features, see Fig. [54]. Several East-West and North-South transects were conducted through the eastern courtyard, which at the time was covered by blocks from the restoration, and parallel to the temple. A small grid (BP_G1, 5m x 8m) was laid out in the area where the enclosure was supposed to have been removed, running the GPR against the enclosure wall. Weak disturbances were detected in 2m distance to the wall; however, there is no evidence that it is produced by buried masonry remains. The disturbance might result from Groslier's excavation. A second narrow grid (BP_G2, 42m x 4 m) covered the area between the staircases of the causeway and the wall. The results clearly reveal throughout all profiles within the grid a strong linear disturbance between 10m and 20m from the central causeway at 50 cm depth, indicating a masonry platform and showing that despite the hardened surface GPR was able to detect anomalies at the Baphuon. The results however did not provide enough evidence to support or reject the hypothesis of a changed location of the enclosure wall.

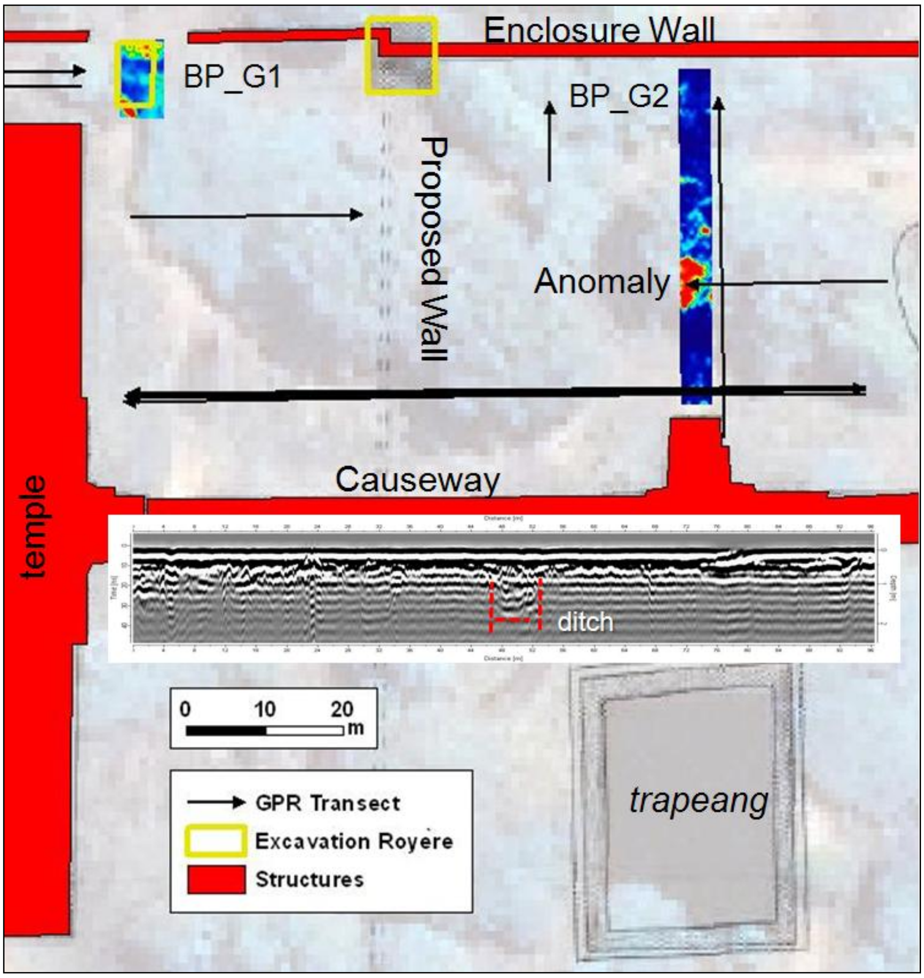
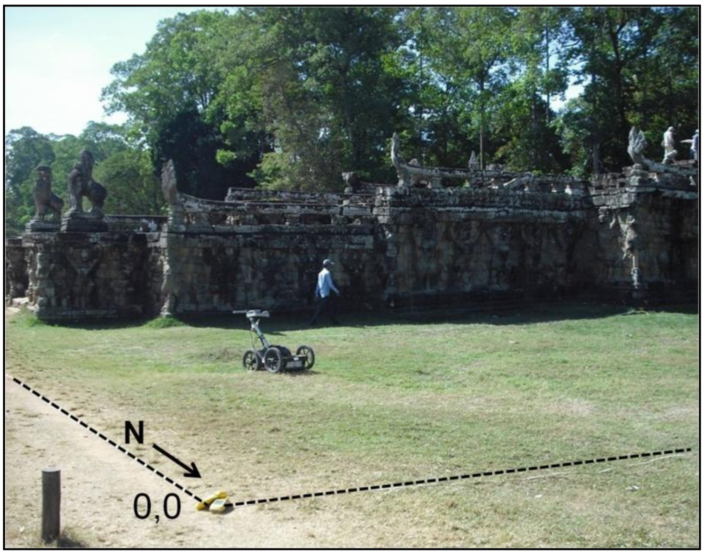


FIG. [54]: GPR SURVEY EAST OF THE BAPHUON AND THE PROPOSED ORIGINAL OUTLINE OF THE WALL (BACKGROUND ROYÈRE/ IKONOS).

The Elephant Terrace at Angkor Thom

The Elephant Terrace is a large linear masonry structure running north to south and is part of the ensemble now called the Royal Plaza in the central part of Angkor Thom. Its construction was initiated by Jayavarman VII who ruled from AD1181 to approximately AD1218,[769] and is named for its carving of elephant figures into the eastern side. The repair of the Elephant Terrace in the 1990s[770] unveiled a series of succeeding constructions and remodelling of the monument, which Dumarçay & Royère attribute to Jayavarman VIII, who was also related to the construction of the Terrace of the Leper King. At this terrace, additional walls had been built which covered the preceding outer walls and had been destroyed.

The GPR investigation was intended to reveal whether there had been additional outer walls that had later been removed around the central staircase of the Elephant terrace. Two GPR grids (ET_G1 on the southern side and ET_G2 to the north of the staircase, see Fig. [55]) measured a strong disturbance adjacent to the northern part of the staircase. Concluding from other surveys, it most likely represented the extent of the foundation trench that had been excavated preceding the construction of the staircase and filled with sand, rather than an additional wall or masonry foundation material. Distinct strong linear anomalies on the south side of the staircase however represent the remains of masonry. The stepped outline of the anomaly, disconnected from the staircase, could correspond to blocks of laterite or sandstone. The results indicate that there had been an additional wall on the southern side of the central staircase, now removed.



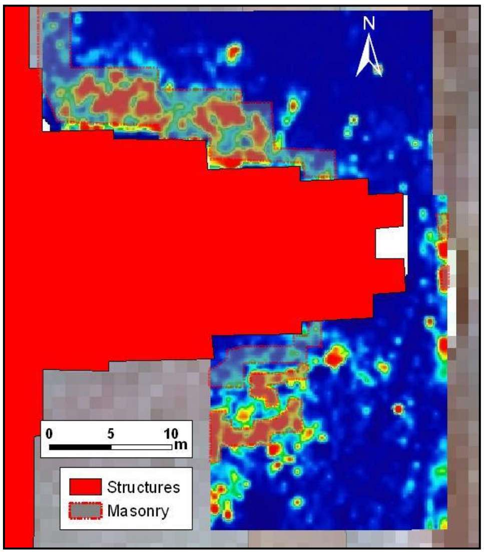


FIG. [55]: INTERPRETATION OF THE GPR SURVEY AT THE ELEPHANT TERRACE AND AT_G1 ON NORTHERN SIDE.

(c) GOPURA 4 WEST OF ANGKOR WAT

'We only found it to-day. It's as large as life, and twice as natural.' (LG, VII)

An extensive GPR survey conducted primarily between the western moat and the temple of Angkor Wat (see Fig. [56]), revealed a whole range of subsurface features including six tower bases, remains of a *quincunx* structure, enclosure walls and roads. After the first detection of structures, the method was used predominantly as a mapping tool, to provide the extent, outline and spatial relation of the structures. The measured depth of the underground structure provided information where to set up and what to expect from an excavation, which followed after the survey. The information extracted from the literature research provides the supplementary information to solve the construction history of Gopura 4 West (from now on named G4W).

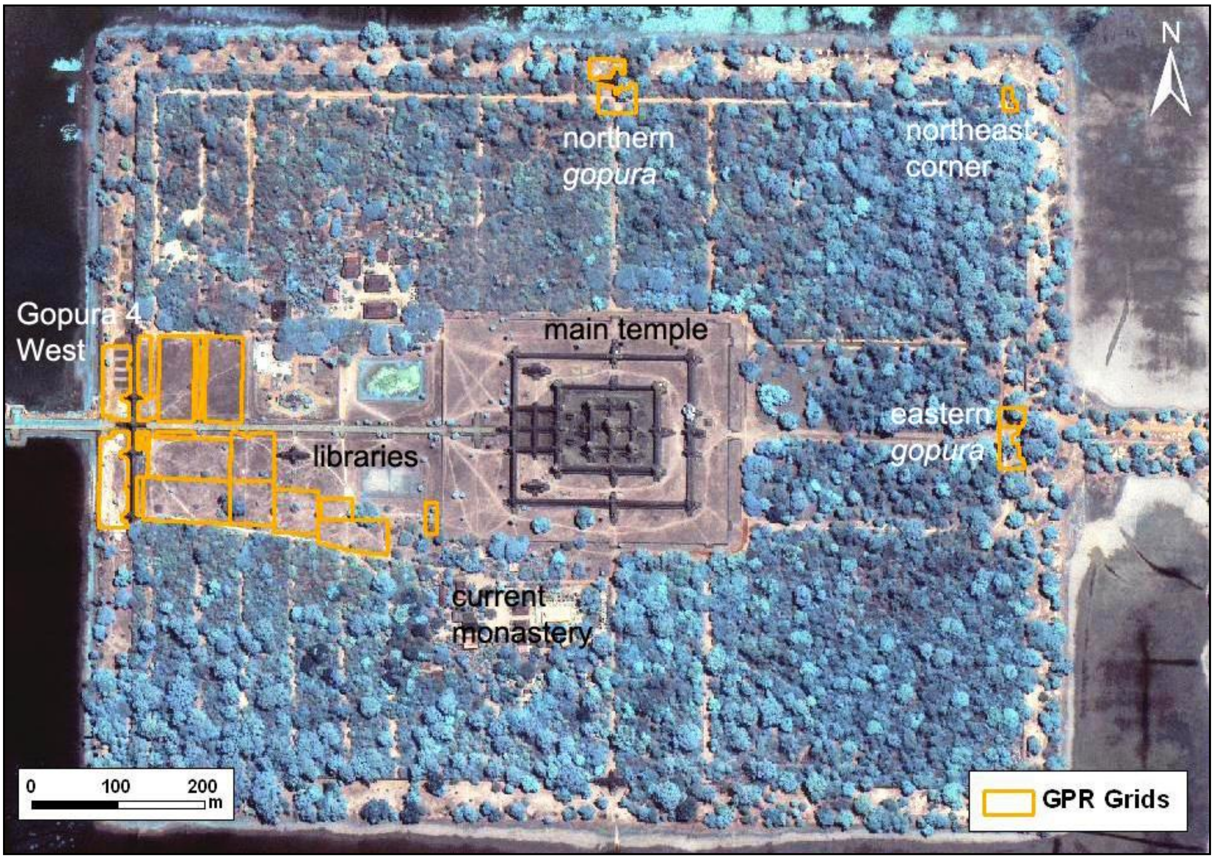


FIG. [56]: ANGKOR WAT - OVERVIEW AND GPR SURVEY GRIDS.

i. CHRONOLOGY OF ARCHAEOLOGICAL WORK

The use of Historical Plans and Photos

For the analysis of change in a region, historic maps, architectural plans and photos were consulted. Fairly accurate plans and maps, which had been produced following architectural surveys and archaeological excavations in the 19th century, were integrated into GIS and geo-referenced to interpret results from the GPR survey, particularly for Angkor Wat, see Fig. [57]. GIS in this part of the survey served mainly as a data base and method to accurately associate, locate and present the GPR data. The analysis of historic photos of monuments of Angkor from EFEO[771] displayed changes to structures and landscape that had occurred within the last hundred years. The images helped to identify a considerate number of walls, columns, and other architectural features, which had been seen as rather late additions by the first archaeologists and architects and had therefore been removed or reburied in the last century.[772] Since Angkor Wat had been in the spotlight from the beginning of research, the area is documented since the 19th century.

FIG. [57]: PHOTOS OF ANGKOR WAT AND GOPURA 4 WEST FROM THE EARLY 20TH CENTURY (IMAGES COURTESY: EFEO, ~1909).

Early Work at Angkor Wat

Archaeological research on the temple of Angkor Wat in the 20th century was mainly dedicated to reconstruction work and architectural surveys. Nevertheless several clearings and excavations took place in the vicinity of G4W in the early and mid 20th century. The *Société d'Angkor*[773] started their work at Angkor Wat in the year 1909, two years after the Kingdom of Siam ceded Cambodia's northern provinces, including Siem Reap and the temples of Angkor.

Early work was supervised by Jean Comaille. The main intention was to free the area of undergrowth and to clear the sides of the main causeway – running from the entrance gate to the temple - of debris, that had accumulated in some areas to not less than 2 meters or up to the height of the causeway. In the clearing process more than 5000m^3 of earth were moved out which was used just to reconstruct the embankment of the southern road of Angkor Wat.

This work was followed by the restoration of the causeway in the following years, after Comaille's death in 1916 under the direction of his successor Henri Marchal. The most important art historic find when clearing the southern part was a small *dvarapala* statue which had features similar to another one found at the North Khleang.[774] A lot of the fragments of sculptures discovered by then were stored away; they were sorted and identified as late as 1966 under Groslier.[775]

The Stupas – Evidence of Post-Angkorian Occupation

In 1909 two small cone-shaped mounds (see Fig. [58]) situated just east of G4W, between the central and the two outer towers flanking the causeway had been revealed. In the process of the removal of those mounds, Marchal excavated the southern one in June 1919, a mainly earthen build up mixed with sandstone chips and bricks that rose 3.9m above ground level and limited to all sides by a 1.4m high balustrade. He identified the earthen build up - due to the characteristics of the mounts, their size, structure and the discovered items - as a *chetdei*, the Thai/Khmer term for *stupa*, and referred to them as recent Buddhist addition to the Hindu temple. From the findings of the excavation that included several hundred Thai coins which were still in use, the French researchers assumed the mounds to be not older than 60 years old.[776]

Three Japanese swords, with engravings that Marchal & Parmentier referred to as of "*very modern*"[777] origin, were as well excavated, see Fig. [58]. To identify and date the described swords precisely, specialists would have to be consulted. Unfortunately though, the artefacts are not any more in the Royal Museum in Phnom Penh, where they were presumably taken, and have been lost since. The remaining black and white image does not allow more precise conclusions.

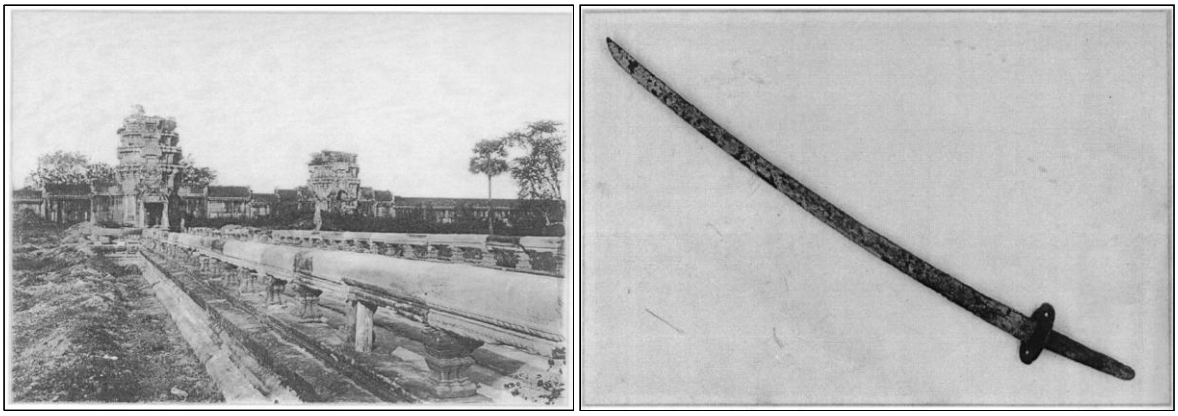


FIG. [58]: G3W WITH *STUPA* AND ONE OF THE EXCAVATED SAMURAI SWORDS (SOURCE: EFEO ARCHIVES).

Although nothing similar has been discovered in Cambodia, the finding of the Japanese swords in a stupa are not surprising because Japanese presence at Angkor Wat was already recorded in the beginning of the 17th century, as shown in the earliest plan of Angkor Wat.[778] Other evidence are Japanese inscriptions at the Angkor Wat temple walls, one of them dated to 1632[779] which could indicate that there had been a Japanese Zen-Buddhist "colony" in the area at that time.

The evidence of Japanese occupation was associated possibly with the Japanese community from the capital of Udong where several hundred Japanese occupied a whole district of the city. The Dutch researcher Van der Kraan has identified them mainly as catholic refugees[780] who had fled from religious repression of the newly established Edo-Empire in Japan. Additionally a small number of unemployed Samurai provided their service to the Cambodian kings. The other possibility is a connection to the Ayutthaya Kingdom (1351-1767), which dominated the Angkor region until the provinces were returned to Cambodia under the French protectorate in 1907. Ayutthaya as well housed a large Japanese expat community in its capital.[781] A lifelong relation of the Japanese warriors with their sword was based in the philosophy of Zen Buddhism.[782] The swords therefore could have been offerings by Japanese pilgrims living in Cambodia or Thailand could have been responsible for the construction of the *stupa*. Another, simpler option was the trade between Thailand and Japan. Japanese steel was extremely valuable in Thailand and so were swords, and became common trading products; the *stupa* therefore could as well be of Thai origin.

Excavation of Column Bases and Platforms

Following the earlier clearing work at Angkor Wat, Henri Parmentier, "Chef du Service Archéologique", directed his focus to the area north of the causeway starting in August 1919.

Parmentier continued with the complete removal of the *stupa* remains and revealed under them laterite structures in the immediate vicinity of the centre pavilion of G4W. Adjacent to the northern and southern tower of the entrance, the remains of two rectangular platforms (N1, S2) with porticos facing in the four directions N, S, E, and W, were discovered. Parmentier identified those platforms as bases for probably wooden structural additions to the northern and southern tower.[783] Marchal excavated in the southern part of the *gopura* at the same time and unearthed substantial laterite foundations (S3) 40m further east. At that time they were not seen in any connection to the existing buildings.[784] The extensive clearing and levelling of this area was finished in April 1920. It left behind the excavated remains of several small column bases that had been bedded in nearly one meter of foundation sand, see Fig. [59].

FIG. [59]: COLUMN BASES EXCAVATED BY PARMENTIER & MARCHAL, 1919/1920 (SOURCE: EFEO ARCHIVES NO. 05393).

In 1931 drainage was installed west of G4W, associated with the repair of the stairs in the north. Work inside the enclosure resumed much later in July 1949, when laterite walls, that had been built up out of lose stones for defensive purposes when the civil war reached Angkor in 1947, were removed. The effort continued with excavations north of the causeway in 1951 under Jean Boisselier, see Fig. [60].

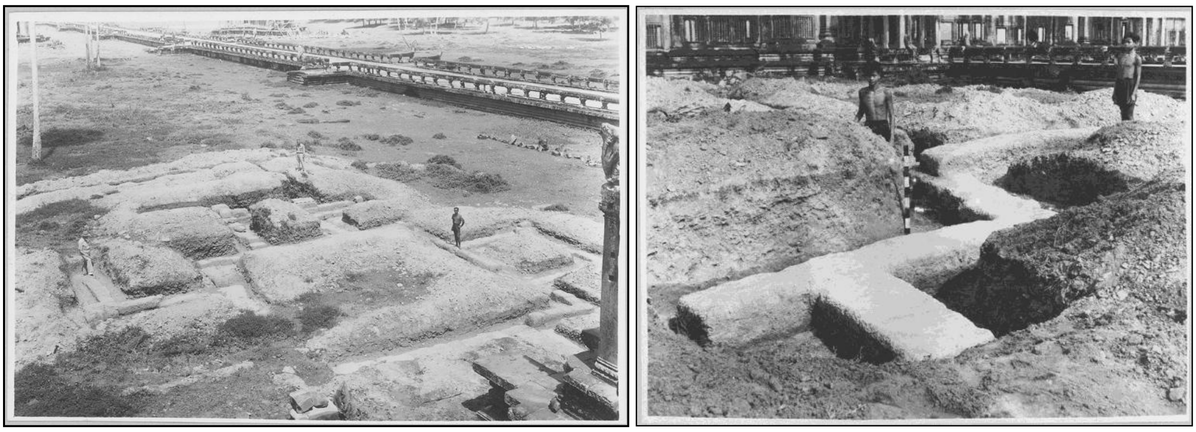


FIG. [60]: EXCAVATION BY BOISSELIER - NORTHERN PLATFORM N1 AUGUST 1951 (EFEO ARCHIVES NO. 6798) AND JULY 1951 (EFEO ARCHIVES NO. 6817).

Two laterite platforms directly east of the staircases of the northern and southern *gopura* towers were unearthed, and Boisselier noticed that the platforms were in symmetrical alignment on both sides of the causeway.[785] They were though the ones Parmentier and Marchal had detected (N1, S2), because Boisselier mentioned that even the more substantial foundations of laterite blocks were degrading or had deteriorated since their earlier unearthing in the 1920s.

Unfinished carved sandstone blocks line up as small walls in front of the *gopura* towers; obviously constructed after the original building in the 12th century. While their unsophisticated appearance and lose connection to the tower made Boisselier refer to them as “parasitic fungus”, he nevertheless left them standing for historic interpretation. Two archaeological plans of the time display the work done in the 1920s and 1950s which included the later removed set of masonry columns; see Fig. [61].

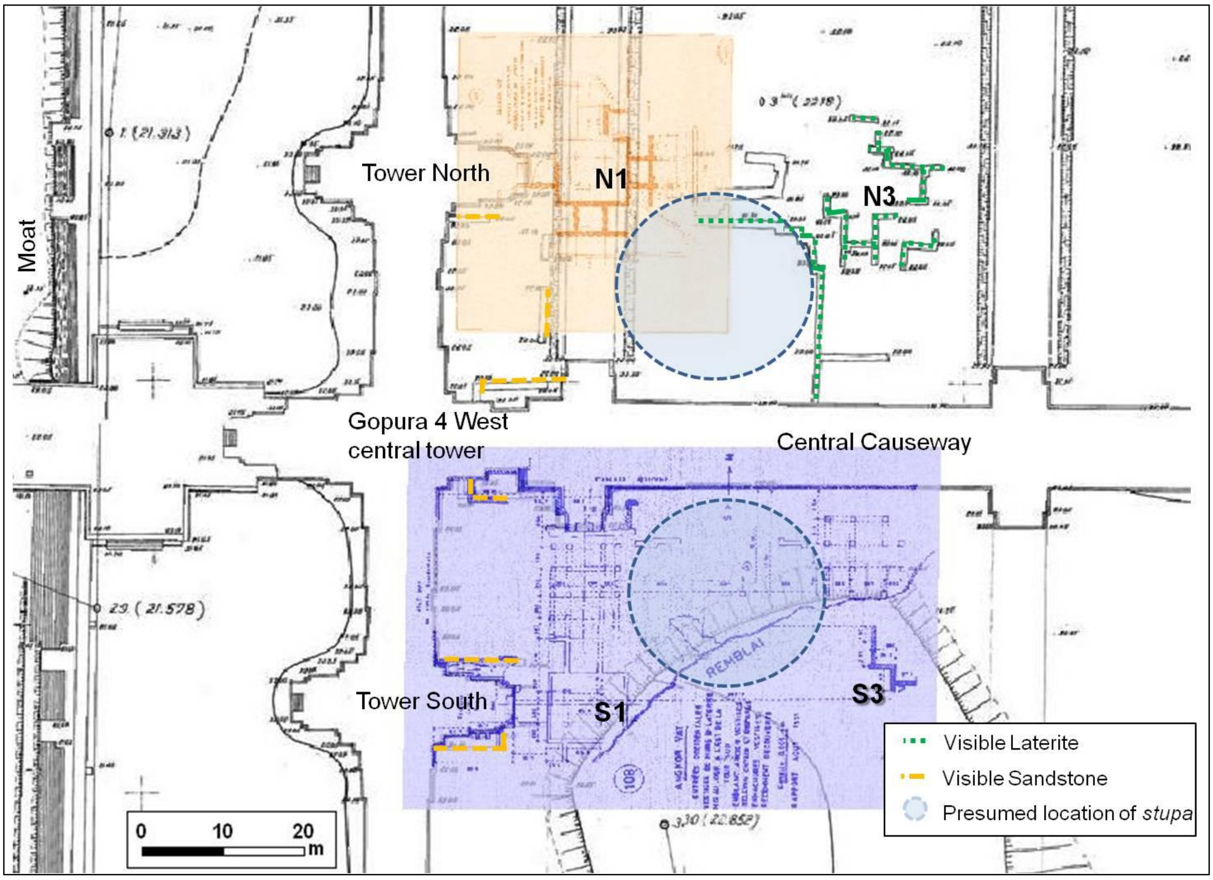


FIG. [61]: EXCAVATION PLANS OF 1919 (MARCHAL), 1920 (PARMENTIER) AND RE-EXCAVATION IN 1951 (BOISSELIER) OVERLAID ON REMAINING STRUCTURES (BASE PLAN: POTTIER, 1993).

Further work took place from 1966 onwards under Bernard Philippe Groslier. The area north of the causeway was levelled and the still partly existing earthen causeways were restored with new material, each starting from the stairs of the causeway to the north. Additionally dug drainage channels sent the floodwater, which accumulated in the area in the rainy season, to the north of the enclosure into the moat. Because it is not mentioned in earlier reports, this levelling might have uncovered the laterite tower foundation 40m east of the northern pavilion of Gopura 4 West, which is still visible today (N2).

The documentation remaining of the substantial work carried out in the area was very valuable to interpret the results of the GPR survey and the following excavations. Nevertheless it shows that, although there was interest in the underground structures, especially shown by Jean

Boisselier who integrated earlier work in his plans, the revealed foundations were considered as later additions and several of them were therefore removed in the process. At that time, none of the archaeologists associated any of the larger foundations with an earlier or contemporary construction period compared to Angkor Wat.

Recent Work on the Western Side

Since the 1950s some parts of the area west of G4W, between the moat and the pavilions, have undergone reconstruction. EFEO reconstructed the moat steps in front of the *gopura*, and initiated the restoration of the main causeway, completing the southern half. The restoration of the northern half was initiated in 1995 by APSARA and Sophia University, using the northern area between the *gopura* and the moat to store stone material from the central causeway. To protect the stones, layers of rubble were piled in lines in front of the gallery next to the base, now overgrown but still in place. Those layers are visible in the IKONOS satellite image of *2004*.

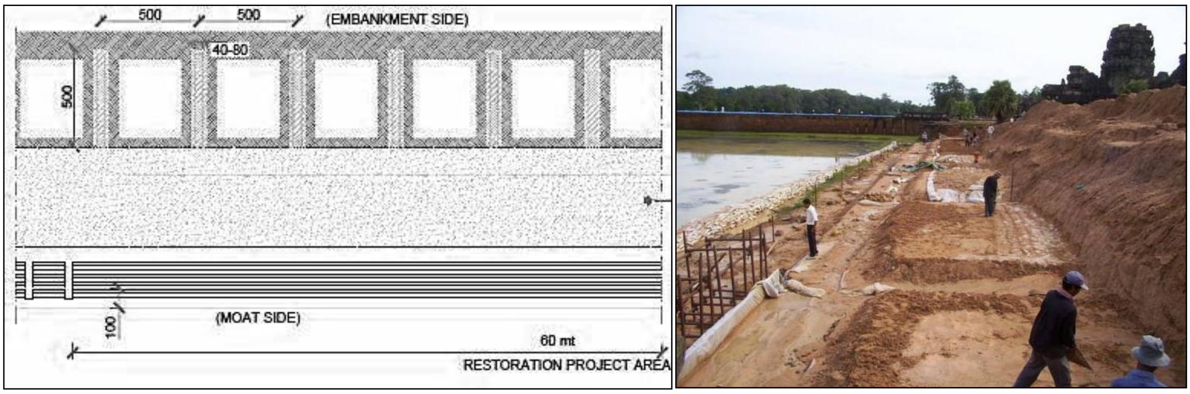


FIG [62]: WORK CONDUCTED ON THE SOUTH STEPS OF THE MOAT BY THE ANGKOR WAT – WESTERN EMBANKMENT RESTORATION PROJECT OF 2002 (PLAN & IMAGE: COURTESY V. SANTORO).

In the late nineties, the sandstone steps of the moat located south of the causeway collapsed between the two southern staircases. They were reconstructed in 2001/2 by an Italian-Cambodian team lead by Valter Santoro and field architect Kong Kanthy, see Fig. [62]. The excavation work for the reconstruction and an emplacement of drainages seemed not to have extended further than 5 m from the top steps, and therefore only partly affects the results of the GPR survey.

ii. THE GPR SURVEY

A ground-penetrating radar (GPR) survey at Angkor Wat was conducted over eight days from December 2009 into January 2010; see Fig. [63] and for interpretation Fig. [64]. The purpose of the survey was to investigate potential additional buried archaeological features inside the enclosure of Angkor Wat, around Gopura 4 West to the temple platform. The area was extended to conduct additional surveys in June 2010 to reveal potential symmetrical features at the other *gopura*. A total of 22 grids, covering overall an area of 42903m² or 4.3hectares was surveyed. The survey detected several groups of structural features – some to the west of the entrance gate but mainly east of G4W. The symmetrical assembly of the cluster of structures east of the *gopura* was further emphasised by a linear masonry structure surrounding them.

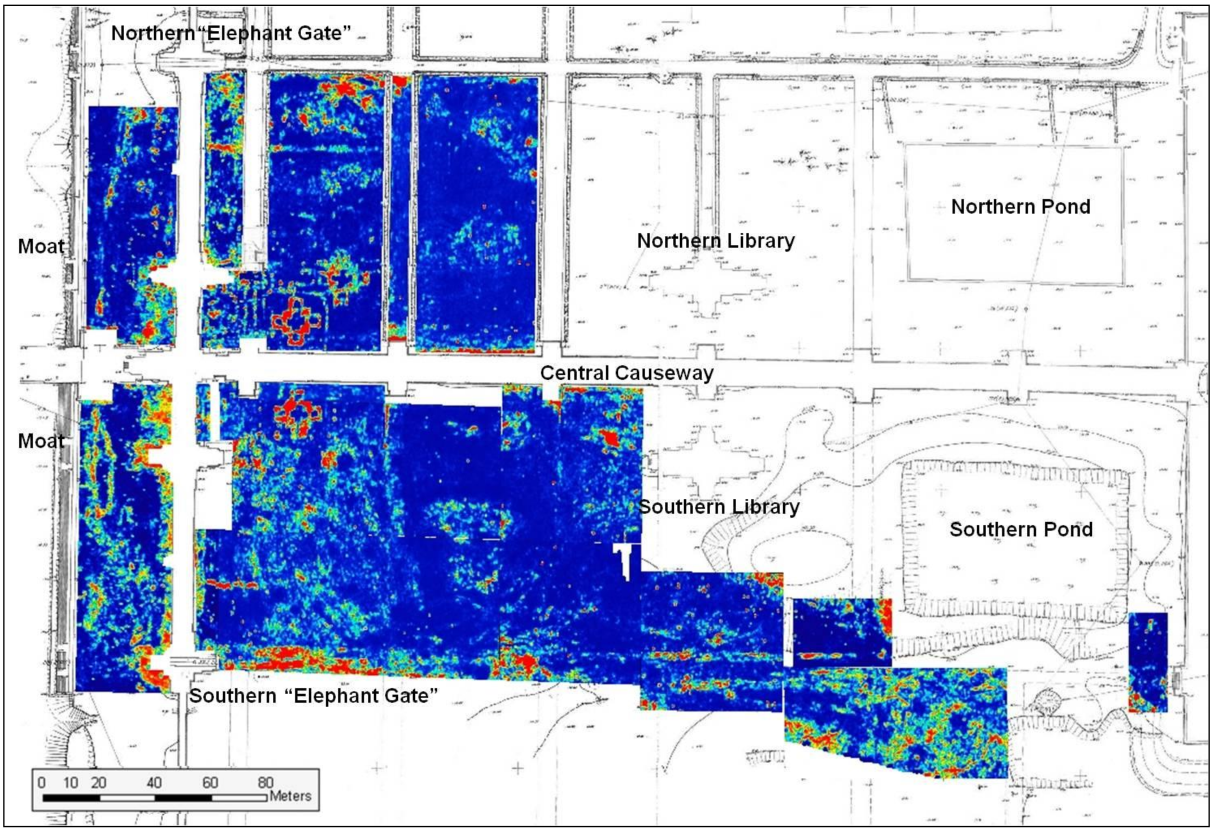


FIG. [63]: GPR-SURVEY OVERVIEW, CENTRAL AREA (BASE PLAN: POTTIER, 1993).

Survey Area between the Moat and the Gopura 4 West

West of the G4W, thus outside the large enclosure of Angkor Wat, the GPR results display strong evidence of two linear features, almost symmetrical, running north (N6) and south (S6) from the main axial causeway. Each feature follows about 50 meters straight north and south and then inclines towards the elephant gates at the extremities of the G4W. The strong reflection, its depth as well as the symmetry of the features, indicates laterite or sandstone masonry and they are unlikely to be just compacted earth. Another smaller feature (S12), that showed very strong reflection by the GPR signal in about 2 m depth is in the far south just east of the southern "elephant gate" in front of the staircase of the moat. As described above, the lanes of rubble in the north, from the restoration of the causeway and visible in aerial images, are confirmed in top soil images, but do not affect the results overall. The area that was excavated in the south is showing up in the results as well, though the linear feature is still detectable. Finally, the GPR identified another couple of symmetrical anomalies (N5, S5) located between the central and the two side pavilions of G4W. The western portico of the central pavilion is framed on each side by what has been interpreted as a masonry wall or a foundation substructure corresponding probably to the remains of a platform. Nothing is presently visible on the surface.

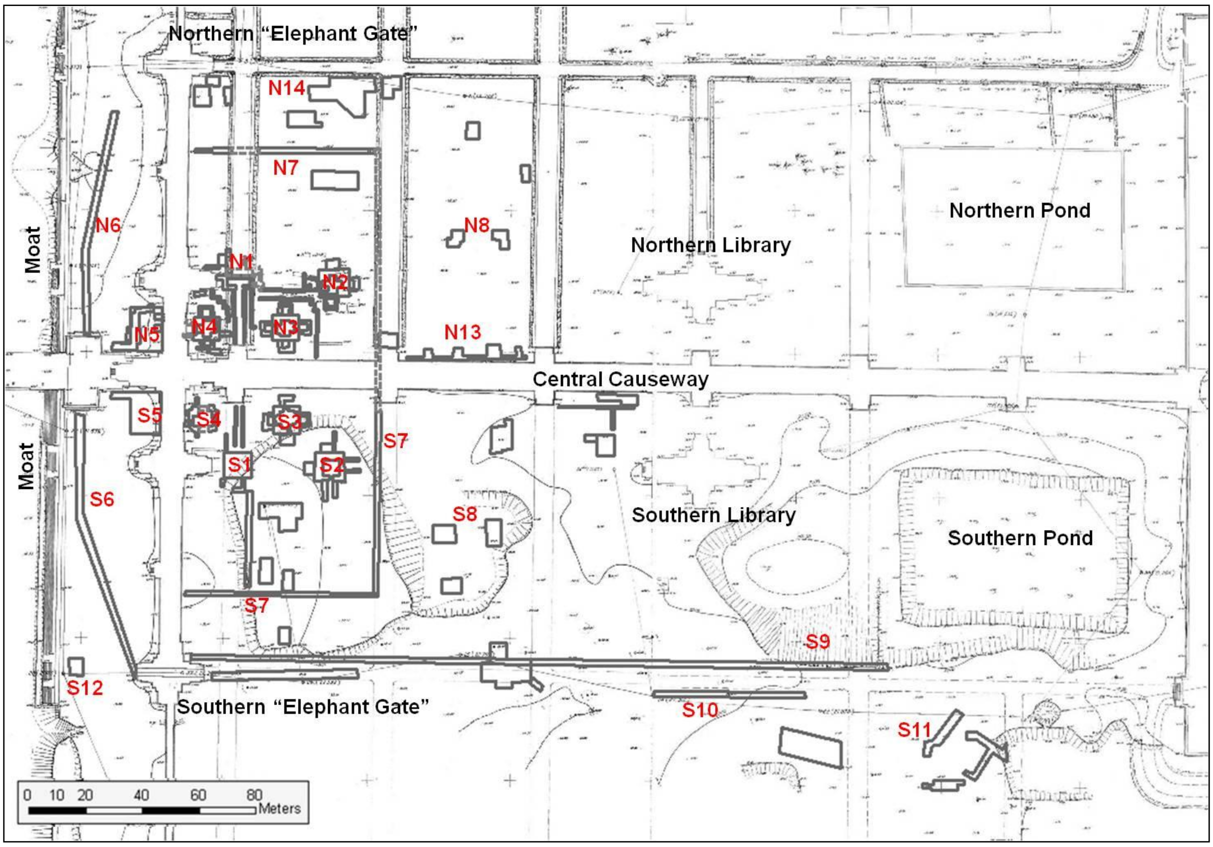


FIG. [64]: GPR-SURVEY INTERPRETATION, NUMBERING OF ANOMALIES (BASE PLAN: POTTIER, 1993).

East of G4 W: The Central Part

East of the G4W, and inside the large enclosure of Angkor Wat, the major features identified by the excavations of 1919, 1920 and 1951 were confirmed in the survey, see Fig. [65] However, the survey shows that some of the features partially noted previously formed a distinctive configuration which can be interpreted as an inner and an outer set of cruciform features centred on (and partially covered by) the axis of the central causeway and aligned with three pavilions of the G4W. The many rough, low, square columns noted in the southern part of the old EFEO excavation plans might not have been visible in the GPR surveys because of a survey line spacing of 50 cm.

The survey identified six square stone foundations, each of about 10m x10m, and showing remains of porticos on the sides in each axial direction. Among the five structures, the two eastern ones (N2, S2) are aligned with the northern and southern side pavilions of the G4W, forming nearly a square. Within this rectangle, four structures (N3, S3, N4, and S4) are also visible in symmetrical alignment, forming another smaller square in its centre. Two additional and similar laterite bases have been unearthed in 1919 and 1920 directly east of the southern and northern side pavilions of G4W. The northern one is not clearly distinguishable in the survey and might have been destroyed since the excavations, perhaps when the path to the north was constructed. A long linear feature has been identified in the area. It defines a kind of "enclosure" on the eastern side of G4W, which contains all the foundations mentioned above. Its eastern side is about 50 meters east of the central pavilion of G4W, turning at right angle to the west at a distance of about 60 meters away from the axial causeway, and joining the eastern side of the galleries of G4W. The north half of its east side was not detected north of the causeway as it corresponds presumably to an area unsuitable for the GPR survey (where the open drainage channel is located that is associated with the 1960s reconstruction of the path perpendicular to the second staircase of the causeway). Nevertheless the northern side of the feature was detected, showing the existence of a symmetrical layout north of the causeway.

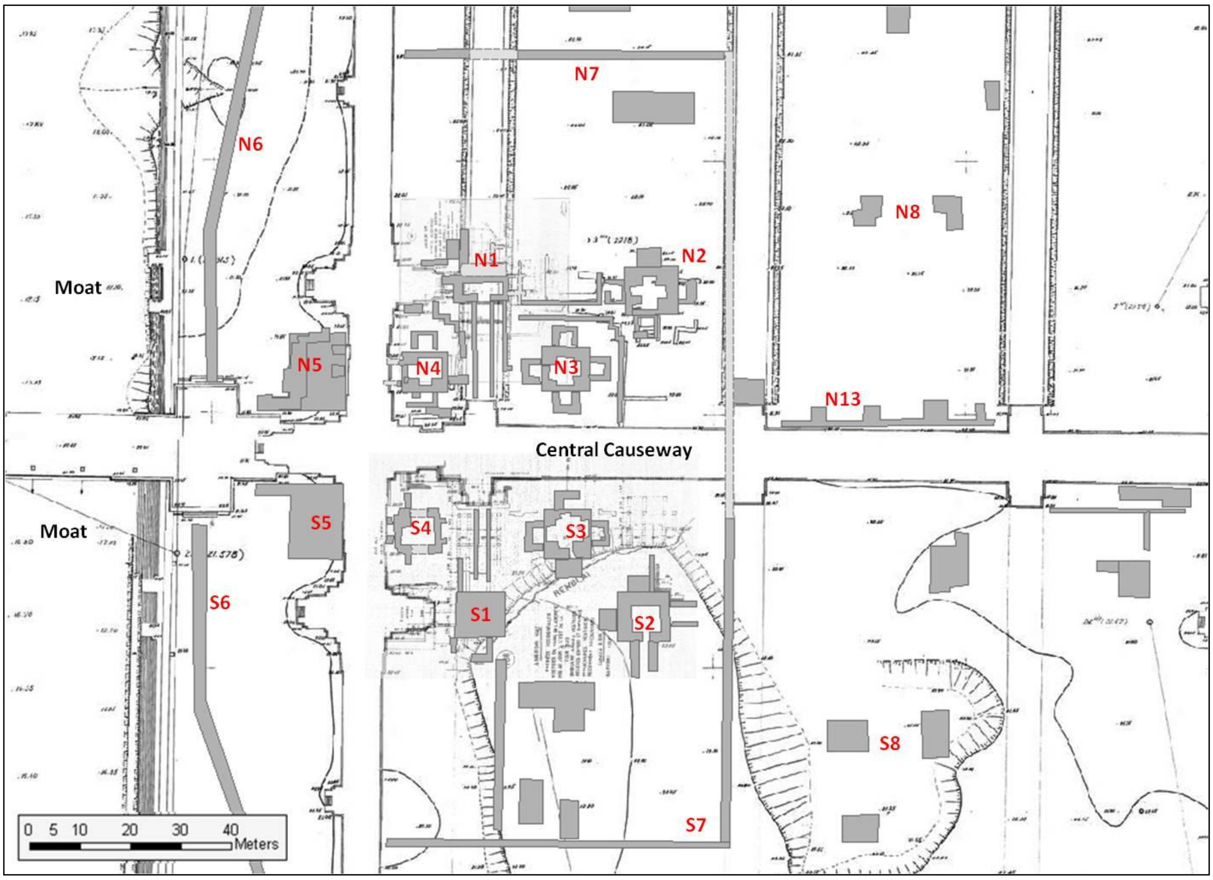


FIG. [65]: INTERPRETATION OF GPR RESULTS, CLOSE UP TO CENTRAL AREA (BASE PLANS: POTTIER, 1993 AND BOISSELIER, 1951).

Outside the "enclosure" in the east several potential structures are worth mentioning. There are four irregular features (N13) visible directly adjacent to the causeway west of the "enclosure wall", that could indicate remains of an earlier, but now overbuilt configuration of the causeway. Finally just east of the enclosure wall, there are two features north and south of the causeway - the northern one (N8) showing very weak radar reflection, while the southern (S8) one clearly indicates a lateritic structure. Although the features are not in direct symmetrical alignment with each other, they could be related to the enclosure.

Northern and Eastern Gopura & Northeast Corner

Additional surveys followed - on the implication that the discovered enclosure could have been mirrored by similar structures on either one of the *gopura*. The results, displayed in Fig. [57], possibly revealed the remains of small platforms inside the enclosure in front of both entrances, but nothing similar to what was discovered at G4W.

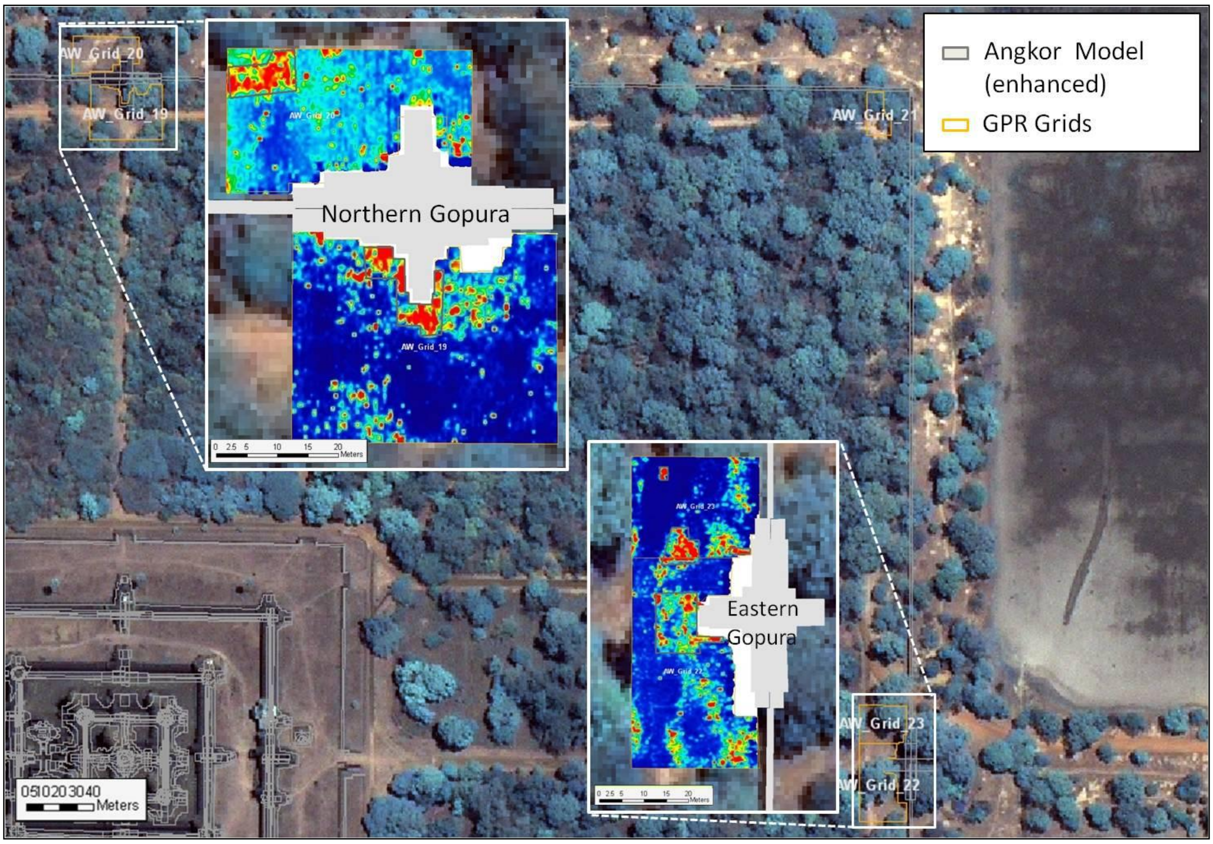


FIG. [66]: GPR RESULTS AND INTERPRETATION FROM THE NORTHERN AND EASTERN *GOPURA* (MODEL BY THE AUTHOR, BACKGROUND: IKONOS).

South of the Study Area: A Road Alignment and Features in the East

While the modern road from the northern “elephant gate” (the northern pavilion of Gopura 4 West) leads parallel with the central causeway towards the main temple, the southern counterpart drives a curve towards the south to surround the temple.

The GPR survey covering this area revealed a strong linear anomaly (S9) of over 200m length and aligned in east-west direction starting at the southern so called “elephant gate” running parallel to the main causeway, in the direction of the south-west corner of the temple platform, see Fig. [56] The strong reflection implies that it corresponds to masonry remains. In part of the grids it is aligned by another linear anomaly 10m further south (S10), suggesting that these two anomalies could correspond to the alignment of a former road. In the precincts of the south-west corner of the temple platform, another grid was conducted in order to check if the road at some point continued all the way to the temple, as the direction indicates, to reach the southern staircase of the temple platform. The results however display no evidence that it continued all the way to the staircase. Additional evidence of a masonry alignment is provided by a set of laterite blocks, overgrown but still visible under the roots of the large “pagoda tree”, which is located on the extended road feature near the south side of the south pond. While only bordered by stones, this 10m wide “southern road” was as wide as the central causeway; an excavation would provide information of the original outline and structure.

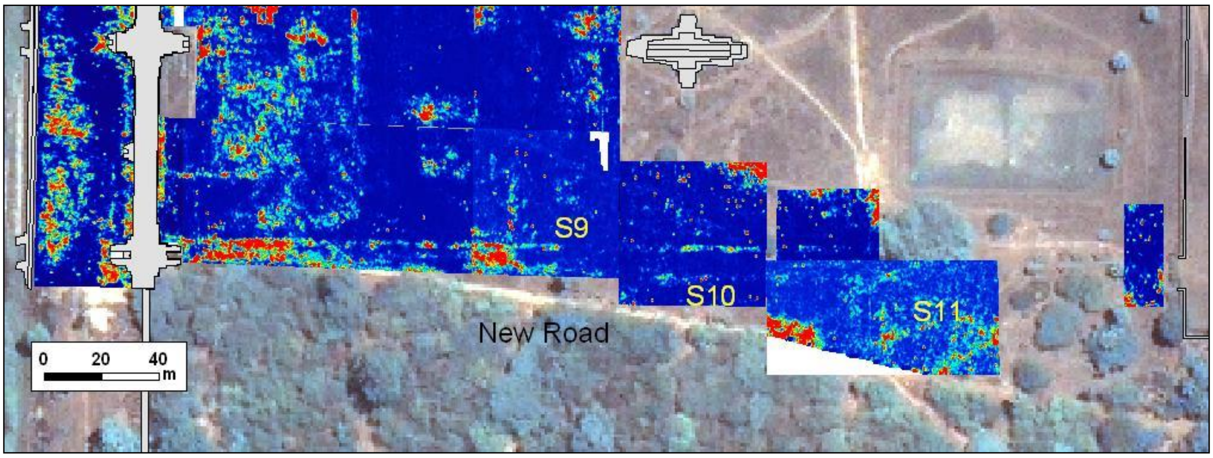


FIG. [67]: ALIGNMENT OF THE ORIGINAL SOUTHERN ROAD STARTING FROM THE ELEPHANT GATE, AT ~150CM DEPTH (MODEL BY THE AUTHOR, BACKGROUND: IKONOS).

South of the large "pagoda tree", as this named by a local tour guide, and thus south of the "southern road" several nonlinear anomalies (S11) indicate occupation in this area. Further east, other features in a NE-SW direction were identified. Their orientation suggests that they are of a different time period than the construction of the main temple.

iii. FOLLOWING THE MAPPING

Excavations at the Towers

Excavations were carried out by GAP in June and July 2010 to potentially date the features and understand their relation to Gopura 4 West. Two locations for trenches were chosen, the first one (Trench 1) to verify the existence of one of the southern tower bases and the second (Trench 2) to verify the existence of the presumed enclosure wall.

Trench 1

For Trench 1 an area south of the main causeway was chosen which covered the outlying tower base S3 under the small mount. While the northern part of the tower base had been excavated in July 1951 and revealed arranged laterite blocks (as displayed in Fig. [60]), it was presumed that the south-eastern part was left undisturbed in modern times. In discussion with Prof. Roland Fletcher and Dr. Christophe Pottier a 5 m x 2 m trench in north-south direction was chosen that was intended to reveal the south-eastern flank of the tower base and would extend further to the south-west in search for potential occupation layers. On site the exact location was again identified by GPR, the profiles clearly displaying strong changes in the signal at the chosen spot.

For the excavation[786] of Trench 1 the EFEO's code of work was used for this excavation, which means that at the start of the excavation the trench was horizontally divided into ten equally sized parts of one square meter, the grids named from 1 to 10 starting in the northeast corner. The soil was removed in spits of 10cm depth; each layer was numbered starting at the surface layer with No. 1001. Different types of artefacts from each grid per depth were collected in separate bags. Archaeological features received a new consecutive number and the artefacts were as well put in a separate bag. Since the excavation took place on a slope, the lowest lying south-western corner was specified as the vertical zero.

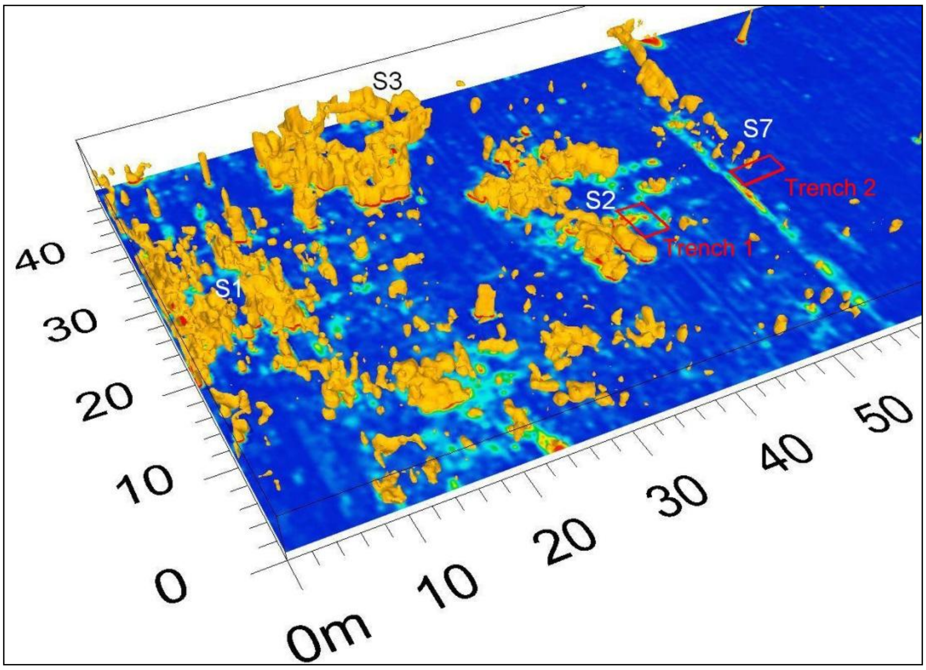


FIG. [68]: LOCATION OF EXCAVATION WITHIN AW_G2, TRENCH 1 TO ANALYSE S2, TRENCH 2 TO ANALYSE S7.

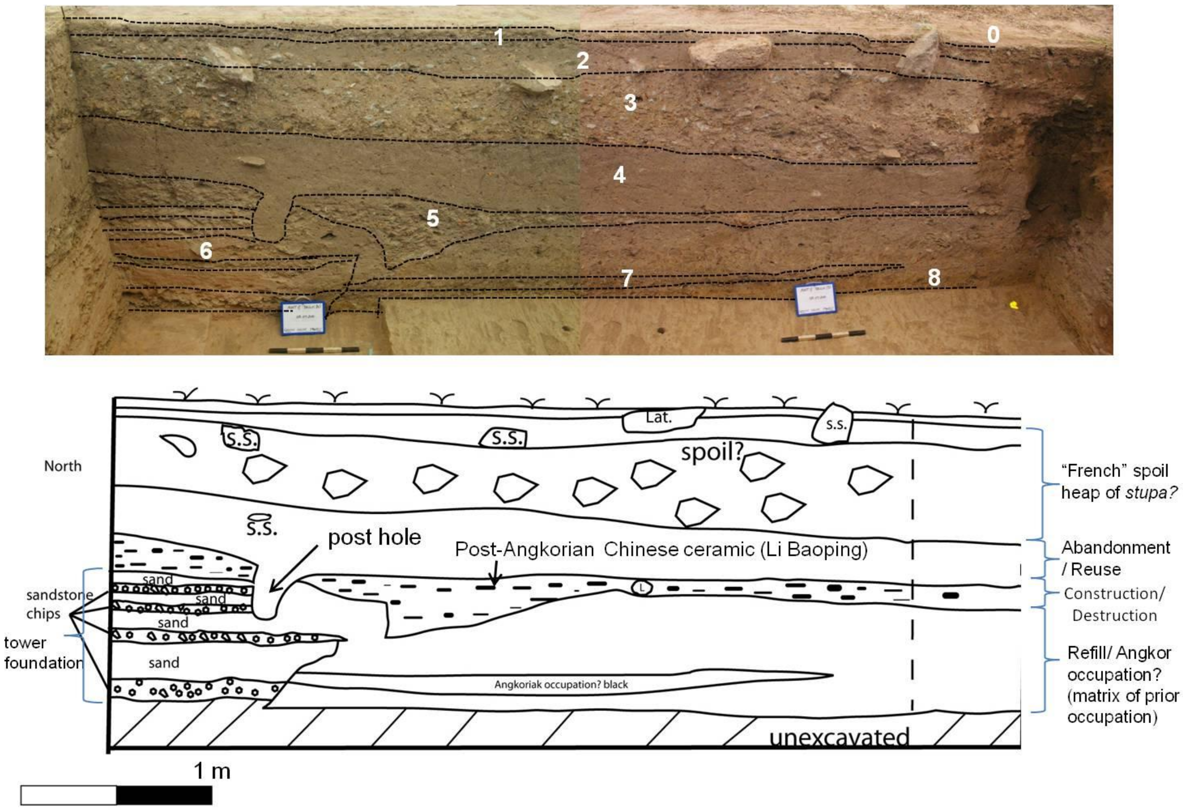


Fig. [69]: Excavation of Trench 1 and interpretation (O'Reilly/ Sonnemann /GAP).

Despite the fact that no intact laterite structure was found, the excavation revealed clear indications for the structure's prior existence. About eight very distinctive layers of deposit were identified, see Fig. [69]. Having decided to excavate part of the tower base as well as the area next to it, the south-eastern grids of the excavation were significantly different from the others. The layers identified with the characterizing matrix and the artefacts discovered are described in Tab. [5] starting with the surface as No. 0.

Layer	Thickness	Location	Matrix	Artefacts
0	5 cm	Complete	surface	Piece of exploded ordinance
1	0-10 cm	Complete	top soil: very dark brown silty	Chinese blue decorated porcelain Small sandstone chips
2	15-20 cm	Complete	Very hard sandy /silty soil matrix with sandstone chips	Large number of Sandstone chips Large sandstone and laterite fragments Mixed earthenware and less Chinese ceramics
3	40 cm	Complete	Very hard sandy/silty soil matrix with sandstone chips	decreasing number of roof tiles some bricks large number of sandstone chips
4	30-40 cm	Complete	Soft dark earthen soil	contains very few sandstone chips and ceramics charcoal 6 mould features filled with sandstone chips could represent postholes
5	10-20 cm	Complete	Very hard compact soil, sand with sandstone chips.	Large number of sandstone chips Large and small pieces of Chinese ceramics Quartz crystal Large animal tooth & bone fragments Ceramic concentration in NW corners
6	110 cm	N & W (G: 1, 2, 6,7,8,9,10)	Alternating Layers of Sand and compressed sandstone chips	On top: Carved stone artefact of 15 cm in N-S direction Below: suspected very thin laterite floor Several volcanic boulders in sand foundation
7	5-10 cm	E (G: 2,4,5)	Thin dark clay rich material,	Angkorian period ceramics Very few Chine ceramics (Li Baoping: older than from Layer 5)
8	40-60cm	E (G: 2,4,5)	Very clayish sand, only in eastern grid	No artefacts

TAB. [5]: INTERPRETATION OF STRATIGRAPHY IN TRENCH 1 (COURTESY: O'REILLY)

Trench 2

The 4m x 2m Trench 2 was intended to cut through the expected enclosure wall, therefore was aligned 15m to the east of Trench 1 in east-west direction.[787] A similar hard layer full of artefacts as in Trench 1 was not unearthed, though the soil revealed a large quantity of roof tiles. No clearly identifiable remains of a wall were detected in situ, but the results revealed two alternating layers sand and sandstone chips at the marked position of the linear feature, which could indicate the remains of a foundation. Large fragments of laterite (30-50cm long and wide, 10-20cm thick) were found chaotically piled mainly to the west of the alternating layers; some smaller fragments also on the eastern side. This could indicate that the wall collapsed or was destroyed or that it was partially a terrace which was largely removed. 40 cm further west of the alternating layers, large worked sandstone blocks of different size were revealed in place but only partly excavated. If the linear feature that was detected by GPR was a wall or the side of a platform, was not determinable, however, the limited horizontal size of the foundation layers, and the fragments of laterite that may have fallen towards the *quincunx* structure would possibly rather speak for a small wall.

Analysis of the Excavation

Following the two excavations, the intention was to relate the variety of features to different construction periods.[788] The artefact rich Layer 2 and Layer 3 in Trench 1, a combination of sandstone chips, bricks and laterite blocks, appeared as a mixed deposit from different time periods, and may have been the spoil heap created when the EFEO removed the "Japanese" *stupa* and cleared the sides of the main causeway. Another possibility is that it was disposed in this area from another part of the enclosure. Despite the find of debris there is no indication that bricks were used in the construction of the towers.

The nearly void layer 4 indicates natural sedimentation - potentially Aeolian deposition over a period when Angkor Wat was barely occupied. The lower part reveals several filled holes that could indicate postholes of a later occupation. Li Baoping identified the Chinese ceramics in Layer 5 as import ware contemporary with the Ming Dynasty (1368 to 1644 AD),[789] and therefore possibly post-Angkorian. This led to the conclusion that accumulation of Layer 5, which was full of sandstone chips, potentially resulted from construction processes, such as the carving of reliefs, or destruction when a superstructure was removed in Post-Angkorian time. However, it was not necessarily associated with the tower bases. The complete destruction of the tower superstructure created an even ground around the entrance gate, either to remove the traces of the old construction or to build something new.

The alternating foundation layers below are of sandstone chips and sand, an construction technique which has been revealed at several excavations of Angkorian structures, e.g. at the Baphuon, the Bayon and Prasat Suor Prat.[790] Those layers were dug and built up in a matrix of nearly void material (Layer 8), only interrupted a layer which displays Angkorian and Chinese ceramics contemporary with Angkorian time.[791] This Layer 7 shows that the quincunx structure was not built into virgin soil but in an area which had been used already in the Angkorian period. It can be expected that the region of Angkor Wat, in direct vicinity to Phnom Bakheng was already occupied before the construction of the temple, indicating, that construction of the main temple of Angkor Wat had already begun before the quincunx structure was built.

Concluding from the GPR-Surveys and Excavations

The results from the GPR survey and the excavations lead to several conclusions which partly follow and build up on each other. The evidence allows a preliminary interpretation of the features, to tell whether the towers existed already before the construction of Angkor Wat, were constructed within the same period, or followed the completion of the main temple. As there is some support for all of those contradicting options it could indicate that the structures were built in several stages. Understanding the purpose of the buried structures is directly linked to their time of construction. The geometrical alignment of the outer towers (N2 and S2) with the towers of G4W, and the enclosure wall with the two *trapeang* of Angkor Wat, indicate a coherent relationship to the main temple. The double squared outline of four towers surrounding a central tower is an Angkorian architectural feature which has been a basic form since the construction of the Phnom Bakheng. Philippe Stern saw this quincunx structure as first introduced with the East Mebon.[792] From then on it appeared several times in different varieties. This design was used always in relation to pyramidal temple mounts. No other example of four additional outlying towers surrounding a quincunx group at the same level has been found at Angkor. Boisselier associated the style, of a tower with porticos facing in all four directions, as feature that appeared in the Takeo in the late 11th century[793]; see Fig. [70].

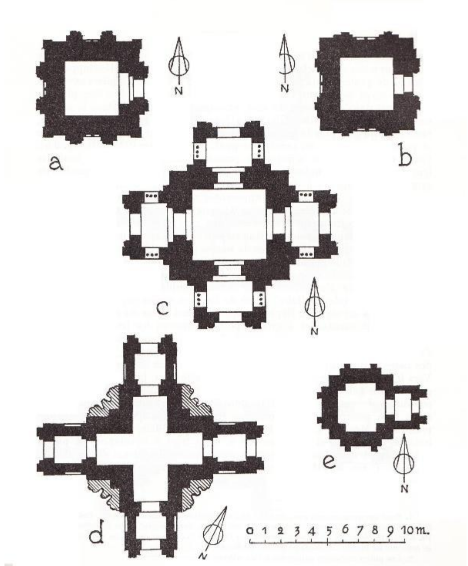


FIG. [70]: STYLES OF PORTICOS AT ANGKOR: A. BAKONG, B. BAKSEI CHAMKRONG, C. TA KEO, CENTRAL SANCTUARY, D. PREAH THKOL, E. MANGALARTHA 487 (SOURCE: BOISSELIER, 1966, P. 63)

The GPR results show that there is no evidence that similar constructions occurred near Gopura North or Gopura East, the remains detected were therefore a singular construction in relation to the main temple. The GPR results display that the tower bases S3 and N3 extend against the walls of G4W and either continue under it or were displaced by its construction, indicating that the towers were built earlier than G4W. A question is however, why the remaining blocks of the towers were not removed when the foundation trench for the construction of G4W was excavated. The laterite blocks close to the wall have to be further investigated to identify their association to G4W.

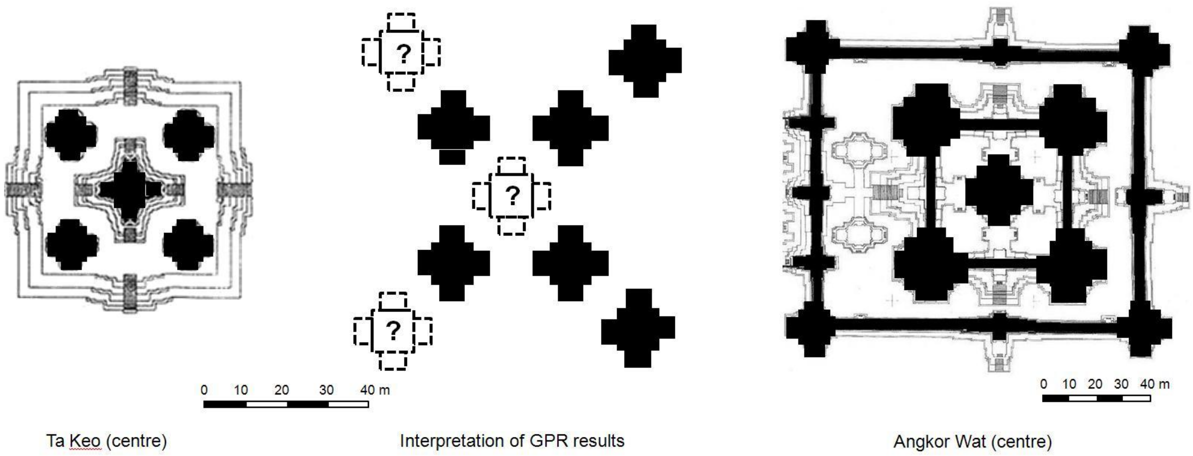


FIG. [71]: QUINCUNX STRUCTURES AT ANGKOR IN COMPARISON (BASE PLANS: GLAIZE 1944 &POTTIER, 1993).

It is unlikely that the long linear features lining up with staircases of the causeway are Angkorian or modern drainage channels. According to sources, the only Angkorian drainage channels pass below the original enclosure wall further north and south of the outer "elephant gates". Additional ones were constructed by Bernard Philippe Groslier in the 1960s next to the paths, directing the water to the north. The excavation results from Trench 2 revealed that the remaining foundations were constructed using an Angkorian technique of alternating sand and sandstone splinters, and could be the base of a wall or perhaps a terrace edge.

No trace of a continuing northern or southern wall was found by the GPR survey on the west side of the entrance gate. The work to repair the stepped access to the moat in the north conducted by EFEO in the north, and the joined Italian-Cambodian[794] team in the southern part did not reveal any type of wall. The structural features N5 and S5 are possible preceding walls or additions to G4W on the western side, indicating a redesign of the complete area. This means that there is no evidence that the walls passed under the gallery, suggesting that the gallery, or a preceding structure, represented some kind of border for the structures. The connection of the features with the enclosure wall and with the main causeway could indeed reveal more information but remains unclear at this stage. Excavation would be required to test if the wall continues below the central causeway or below G4W.

Chronological Placement

From all the information gathered a preliminary conclusion can be drawn. Several construction and destruction periods highlight the importance of the western entrance to Angkor Wat over several centuries. Compared to the towers of the main temple the top of the G4W towers was most likely never completed, as the majority of the sandstone blocks have remained crude. This supports the hypothesis that the western *gopura* was built in a late stage of the construction period of Angkor Wat as part of the completion of the temple. This could therefore mean that the quincunx structure was still in existence at the time when the main temple was being built, and was removed when G4W was constructed.

When Angkor Wat was finished, the two so called "elephant gates" north and south of G4W had become the only entrances for oxcarts or elephants to enter the compound. This had not always been the case. Over a period of time, breaches[795] existed in the southern and northern and eastern enclosure wall, that were in alignment with the roads leading to the wall from the staircases of the main temple's fourth enclosure. These breaches may have been left open from the beginning of the construction, or were cut into the wall at a later period. The breaches were later filled irregularly with laterite and partly carved sandstone blocks that show aspects of the Angkor Wat style or a subsequent style - therefore certainly in a later stage. The construction process was of low quality and some of the fills have collapsed. Considering the amount of construction material which had to be brought into the enclosure, it was presumed, that the moat might have been left unfinished in the period of construction or been bridged to reach the breaches in order to have space for the hundreds of workmen to enter the compound. After inspecting the breaches however, Pottier[796] has argued with regard to the connection of the material filling the breach and the wall that the breaches did not exist initially but were cut into the wall at a later stage, since some laterite parts were broken. From that point of view, the breaches had no purpose as construction gates. When analysing the outlines of other temple enclosures that preceded as well as succeeded Angkor Wat, it appears that the main and largest entrances are generally in line with the main axis of the temple. The configuration of Gopura 4

West with its “elephant gates” at the northern and southern side is therefore unique. This could indicate that the central area was at that time occupied by the *quincunx* structure, which was removed when the central part of G4W was built.

There are rectangular holes facing south and north on the eastern side of the extended towers of Gopura 4 West, see Fig. [72]. Since they were cut into the carvings of the walls, they are certainly later additions, and related to wooden beams that may have supported wooden pavilions in this area. They could be related to the stone columns at the eastern side of G4W. The masonry laterite column bases excavated in the 1920s and removed in the 1950s do not seem to have stood in relation to the tower bases, but had possibly been erected in connection with pavilions in front of the northern and southern tower, similar to the pavilion at Gopura East. They could have been constructed some time after the destruction of the additional towers, when the sandstone additions were put in place.

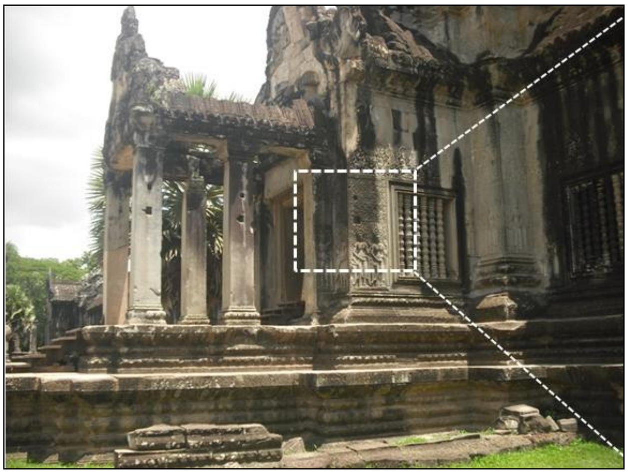


FIG. [72]: HOLES IN THE TOWERS OF GOPURA 4 WEST INDICATE TEMPORARY STRUCTURES.

Ideas to the Design of the Towers

From the information gathered we can outline what the feature would have looked like. There is no evidence that the stone bases initially supported major holding masonry towers. Pottier has argued that the platforms might have been the base for wooden pavilions or towers, and not masonry. Wood was used in the construction of several of the larger monuments and palaces, particularly in the form of internal buttresses and external pavilions,[797] which would have been very common in the vicinity of the temples, as shown by Cunin at Banteay Chhmar.[798]

The Appearance of Angkor Wat in the 17th Century

The *stupa*, the superstructure of the pillars and the superstructure of the quincunx configuration could not have been contemporaneous. The construction of the *stupa* would represent the latest addition to the entrance gate, done sometimes after the 16th century, and according to Marchal’s interpretation of the swords possibly even in the 19th century.

Besides the information from the various surveys, and while the construction period of the stupas cannot be securely estimated, there is another source that provide information about the appearance of Angkor Wat and especially G4W in the 17th century. A drawing in a Japanese travel report published as *A plan of Jetavana and Angkor Wat* in the EFEO edition of 1923, is supposed to be the oldest depiction of Angkor Wat from the 17th century, see Fig. [73]. Due to the title long time believed to depict an Indian temple[799] it was rediscovered and analysed in the early 20th century.[800] Noel Peri believed the plan to be a purely Japanese creation, as the buildings displayed do not show any foreign influence.[801] The existing version of the map, drawn in ink on a 70cm x 66cm size Japanese paper and dated to the year 1715, was seen as a modified copy of the original plan from the 1620s or 1630s.[802] The Japanese style buildings display the understanding of a population that had lived for several generations in a country which excluded any connections to the outside world.[803]

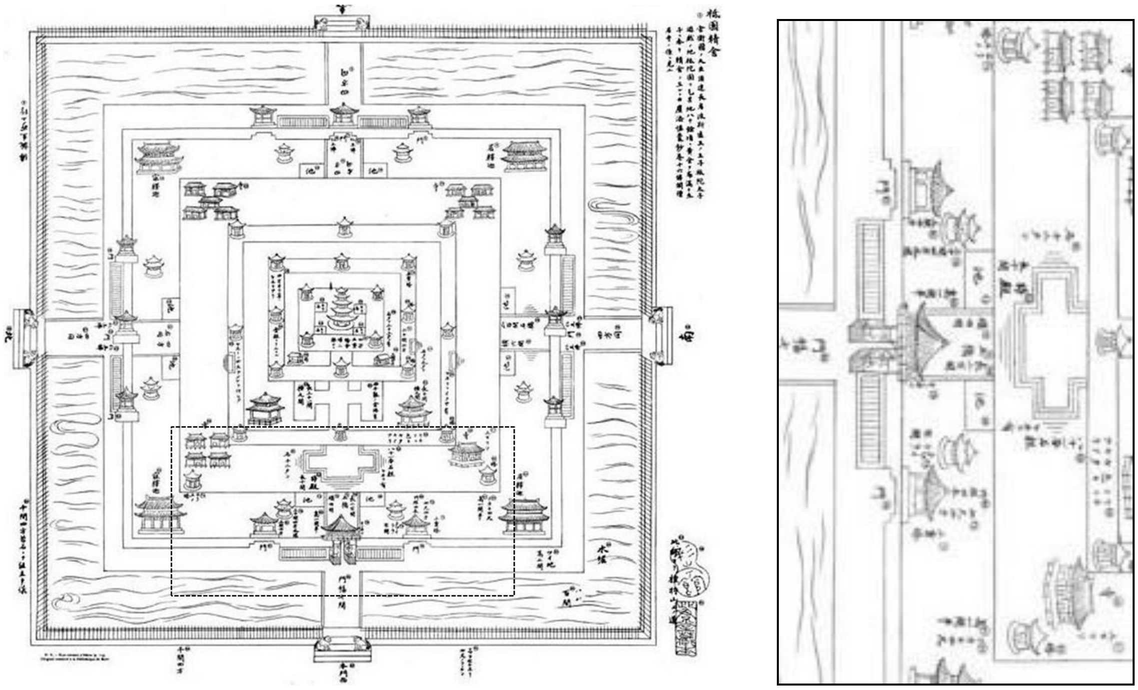


FIG. [73]: DEPICTION OF ANGKOR WAT IN A 17TH CENTURY JAPANESE PLAN (ORIENTED NORTH) AND CLOSE UP OF AREA AROUND GOPURA 4 WEST (SOURCE: PERI, 1923).

In addition to the plan there are Japanese inscriptions inside the main temple of Angkor Wat that were dated by Kuroita to 1632.[804] The person responsible, Morimoto Kazufosa, recounts his travel over China and India where he visited the Jetavana temple as well.[805] Bernard and Tientsin[806] proposed therefore in 1940 that the geographic misplacement of the plan referring to India had rather happened in the transcription in Japan. A geographical error of this scale by a Japanese traveller would be unlikely, as Van der Kraan describes a large Japanese community that lived in Ayutthaya and Udong and close trading relations with Japan in the 17th century.[807] The plan is important for the study, as it does not display any additional structures east of the G4W between the entrance gate and buildings that seem to represent the libraries, which would mean that in the 17th century, the outline had been demolished already, and neither did the *stupa* exist. Nevertheless, several of the buildings displayed on the plan do not correspond to any existing or known remains of a building; therefore the plan needs to be understood conditionally.

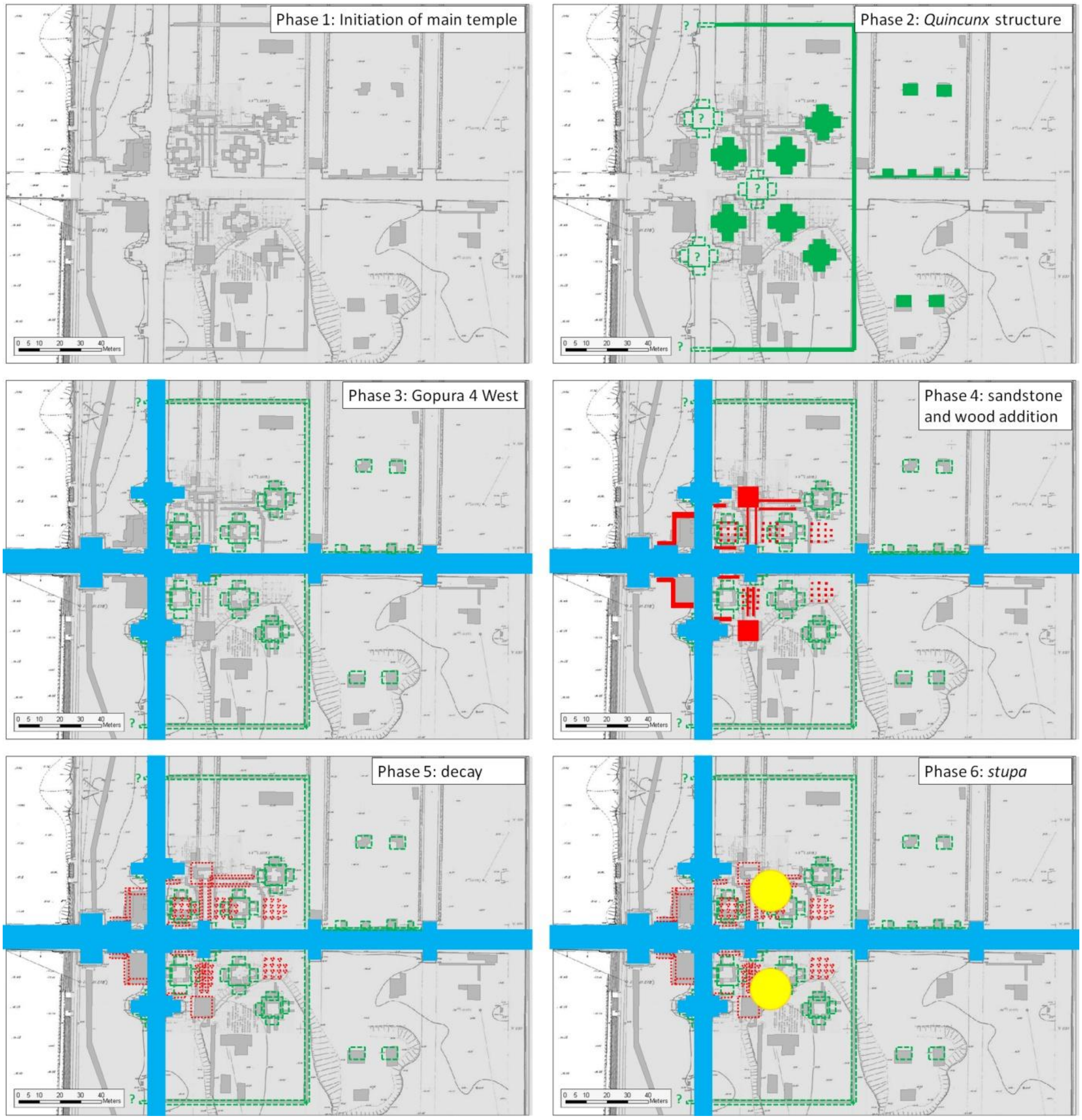


FIG. [74]: PROPOSED PHASES OF CONSTRUCTION IN THE AREA OF GOPURA 4 WEST (BASE PLAN: POTTIER)

CONCLUSION

Interpretation of the results concerning shrines and temples is reasonably straightforward. Masonry foundations of stone and brick in a soil matrix were amongst the clearest of the categorized GPR anomalies to identify. Sufficient differences between the electromagnetic properties of buried structural features and the surrounding subsurface due to strong signal reflections from the masonry allowed clear identification of structures. The penetration depth here was usually not of concern, since most architectural remains were not far under the surface. Time slices of the GPR grids were searched for foundation remains; outline, depth and size of the detected underground structured were mapped and extracted into GIS, where they could be compared to available excavation plans and historic records.

The GPR surveys around the Gopura 4 West of Angkor Wat and the discovery and mapping of the six tower bases and additional features resulted in the most comprehensive collection of data of any of the GPR target areas at Angkor. The additional surveys at the other *gopura* were helpful in concluding that the structure at G4W was unique. The combined effort of field survey, literature research, and targeted small scale excavations with the analysis of findings, provided information on the potential construction periods in the area of G4W, as displayed in Fig. [74]. From the evidence it has been concluded that the proposed *quincunx* structure was probably built within the time of the construction period of Angkor Wat. The ceramic finds make the structures unlikely to be of earlier origin than Angkor Wat. Therefore probably they were constructed and might have worked as a preliminary sanctuary until the main temple was finished. Its existence may have influenced the construction of Gopura 4 West but was then redundant. G4W later received additional possibly wooden pavilions that were built on laterite columns. The two *stupa* could really be, as it was proposed by Parmentier and Marchal, very late additions from the 19th century. The GPR data gathered from shrines and temples revealed a number of unknown buried structures. By measuring and mapping them, the study contributed with additional information to the structural history of those archaeological sites.

CHAPTER (6) ENCLOSURES IN THE PERIPHERY

> *'How many acres of ground?' said the White Queen. 'You mustn't leave out so many things.' (LG, IX)*

The often densely forested interior of enclosures is easily identifiable from aerial images, as the delimited space inside the enclosure wall is noticeably separated from the surrounding. Angkorian enclosures generally consist of a central monument or space enclosed by a rectangular wall. Depending on the importance and size of a monument, the number and combination of walls, moats and embankments enclosing the central space varies. Angkor Wat, for example, consists of six separable enclosure limits.[808] The furthest limit from the centre is often the moat. Many enclosures have entrance gates or *gopura*, doorways or at least breaches through earthen embankments that are aligned with the central axis running roughly east to west with an additional north to south axis.

Little is known about the area between the entry gates and the central temple. The extensive remote sensing and ground-based topographic mapping campaigns,[809] focused on the vast deforested areas of Angkor, have shown that the landscape surrounding the temples was heavily exploited. Given the sometimes substantial central monuments, one might expect structural remains that should be identifiable through a detailed survey. It was expected that the subsurface conceals structural remains, which could not be identified by measuring changes in topography. For this reason the GPR research was concentrated on a series of enclosures and the area in their vicinity. Large grids were laid out inside, to improve the knowledge on potential use of the interior, and to map additional buildings associated with the enclosure as well as non-structural archaeological features adjacent to monuments, such as former *trapeang* (artificial ponds) and moats, now filled with deposit. Due to the enclosures' large dimensions, limited funds, time and manpower available, the focus of the survey had to be on cleared and easily accessible areas.

Three types of enclosures were chosen as target sites for major GPR surveys: the enclosure around the hilltop temple Chau Srei Vibol, the enclosure of Banteay Sra which simply contains open space, and additional surveys targeted the *asrama* Prasat Kamnap and Muong Bong.[810] The *asrama* were not enclosed by masonry walls but surrounded by rectangular embankments.

(a) PREVIOUS MAPPING CAMPAIGNS FOCUSSING ON ENCLOSURES

The majority of temple enclosures at Angkor have not been archaeologically investigated, many having only been cleared of shrubs and undergrowth. The knowledge about the interior of some enclosures is in some ways comparable to the "terra incognita" of 16th century European cartography where unknown regions were simply left blank. An example of this is the 1:10000 plan of Angkor Wat,[811] displaying temple and masonry structures in the highest architectural detail, while the outer area of the temple enclosure was left off the map.[812]

The *stelae* of Ta Prohm[813] and Preah Khan,[814] dated to the reign of Jayavarman VII, mention a great quantity of people associated with the temples in the major enclosures. Earlier interpretations understood the enclosures as densely populated cities with walls.[815] Pottier and Fletcher[816] propose, based on a low density urban settlement theory, that only a small percentage of the main population, elites such as priests and monks and their direct associates, lived within enclosure walls, while the majority had settled in the surrounding area. Whether the enclosures were initially planned as confined spaces, and the outer walls of the large enclosures of Preah Khan and Ta Prohm were built in the initial construction phase, was disputed by Jacques and Freeman.[817] To understand their configuration and use, it is important to map the confined spaces of enclosures. This has been done in the few existing accurate topographic and descriptive maps of enclosures, see Fig. [75]. The most prominent example is an architectural landscape plan of Angkor Thom, conducted as a thorough and highly successful effort under J. Gaucher.[818] To map the complete interior, the 3x3km² area was divided into squares. Straight survey trails were cut through the dense forest dividing the enclosure like a chessboard, from which the topography was measured. The results from those surveys display a strong variation in topography as a result of a network of former roads and canals, secondary masonry structures, and a large number of ponds that made up the occupation pattern of Angkor Thom. Another example is the temple enclosure of Preah Khan which was mapped by Chan Chamroeun[819] under direction of the *World Monument Fund* in the 1990s.[820] The map displays several canals, ponds and a confined space surrounded by a moat that was thought to represent a potential palace of Jayavarman VII.[821] The surveys indicate that the enclosures, especially from the mid period of the Khmer empire onwards, played an important part in the Khmer urban development.

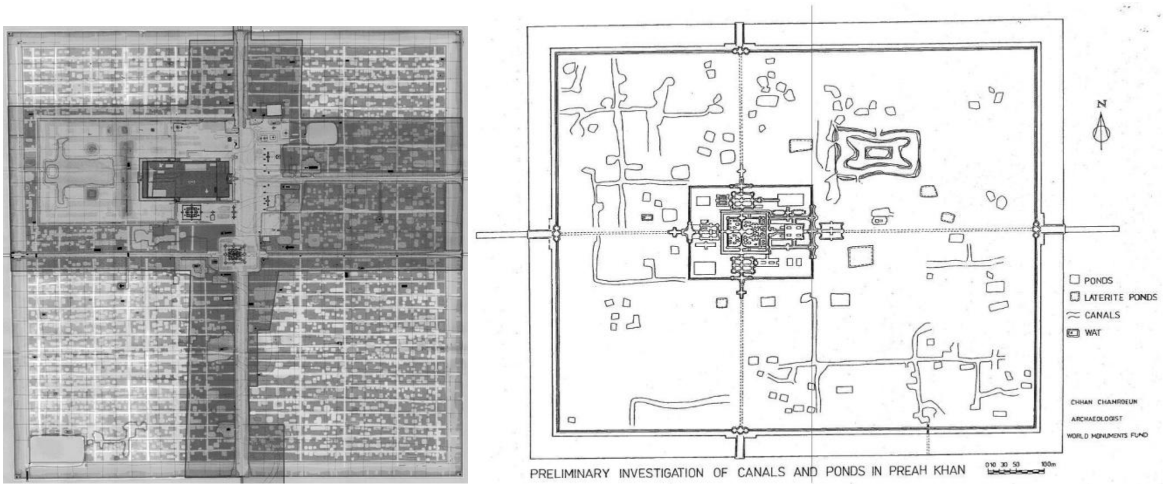


FIG. [75]: ARCHAEOLOGICAL PLANS OF ENCLOSURES: ANGKOR THOM (GAUCHER, 2004) AND PREAH KHAN AT ANGKOR (WMF, 2000).

(b) MASONRY CAUSEWAYS

To recognize causeways that are associated to Angkorian temples using GPR is one of the simpler tasks of surveying. They run between the central enclosure and the entrance gate and are predominantly covered or aligned with stones and therefore had a special status in the classification of Angkorian roads.[822] Examples can be found at many large Angkorian temples and are well known and visible e.g. at the central causeway of Angkor Wat, between the main temple and Gopura 4 West, Banteay Samré, the causeway towards a *trapeang* to the east, and at Beng Mealea, which runs east towards the *baray*.

At other monuments, the masonry causeways are only partial or are missing completely. The following surveys serve as examples of how missing key elements of Angkorian architecture, that still exist in other places, can be traced by GPR. Several GPR surveys were conducted by the author at Banteay Srei, Banteay Chhmar. These were designed to measure linear anomalies in alignment with the temple axis where the remaining structure was no longer evident on the surface.

i. Banteay Srei

The modern road that passes the temple of Banteay Srei runs on an east-west alignment and then turns about 100m east of the entrance gate towards the north. A slightly raised earthen embankment, about one metre high, continues several hundred meters towards the east in the direction of Phnom Dei, until it reaches the bypassing modern road, see Fig. [76]. GPR transects and an additional grid, conducted in collaboration with the *Swiss Banteay Srei Conservation Project (BSCP)*[823] about 350m from the temple entrance were able to display strong linear anomalies in alignment with the axis, that were interpreted as masonry, either indicating a paved causeway or the border of a former road that continued eastwards. Excavations which were conducted by the *BSCP* at the site after the GPR discovery revealed a masonry laterite surface supporting the results from the survey.[824]

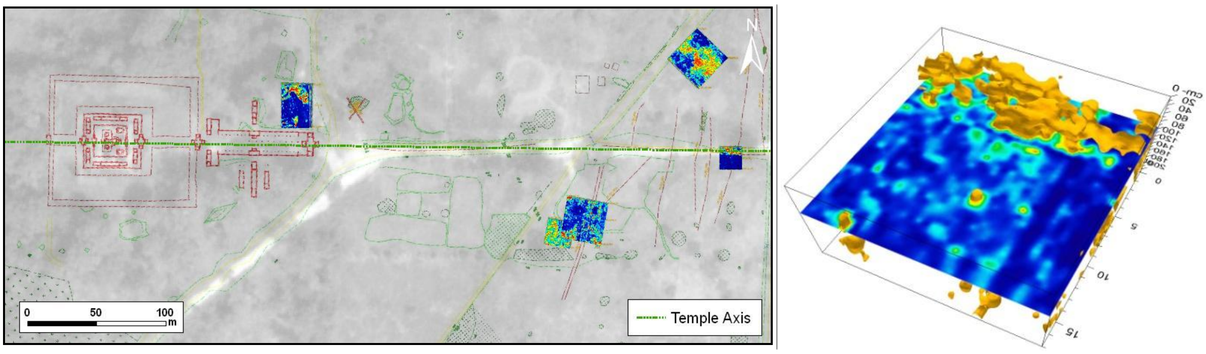


Fig. [76]: Banteay Srei temple axis and GPR results of Causeway (Background: BSCP/Finnmap).

ii. Banteay Chhmar

There is no visible evidence of a masonry causeway on the main east-west axis between the eastern *gopura* inside the moated enclosure and the main temple of Banteay Chhmar in Banteay Meanchey province. The area, about 50cm lower than the temple platform, was in use for rice cultivation at the time of the survey, while the modern earthen road runs about 10m away, parallel to the temple axis.

Four GPR transects,[825] conducted from south to north to cross the main axis, displayed repeated strong linear anomalies of 7m width that are in line with the temple axis; see Fig. [77]. The strength of the reflection indicates, that a causeway likely existed there and at least part of it once was covered by masonry. The anomaly is not continuously strong and sometimes not detectable, indicating that part of the masonry has been removed and in some areas only the compacted soil remains.[826]

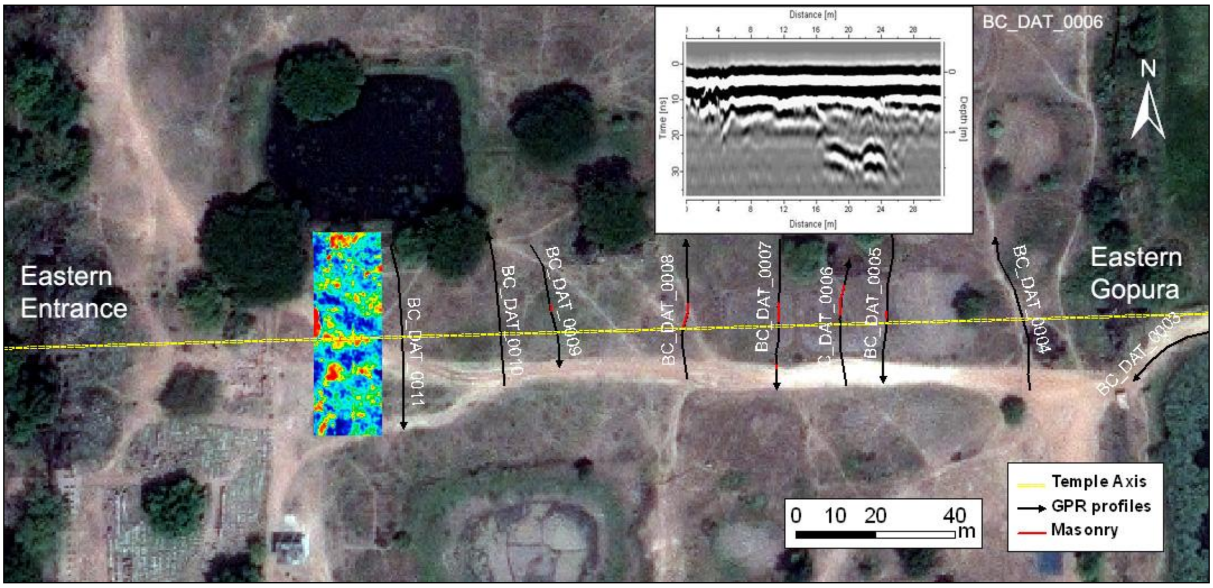


FIG. [77]: GPR RESULTS OF CAUSEWAYS: BANTEAY CHHMAR, BC_DAT_0006 WITH ANOMALY AT 17M TO 25M (BACKGROUND: GEOEYE/ COURTESY EVANS).

(c) ENCLOSURES

The most curious part to the thing was that the trees and other things around them never changed their places at all: however fast they went, they never seemed to pass anything. (LG, II)

While the centre of Angkor has been the target for research for more than a century, some archaeological sites in the periphery have not been investigated. Two outlying enclosures, specifically surveyed in this thesis, Chau Srei Vibol to the east of Angkor and Banteay Sra in the west, lie on the periphery of the rural-urban sprawl of the historic Angkor within a day's walking distance from the centre. Recently demined areas, as in the case of Chau Srei Vibol, can be assumed as largely undisturbed, and no previous excavations have been reported.

i. CHAU SREI VIBOL

'How very odd to find trees growing here!' (LG, V)

Chau Srei Vibol (site register MH456) is a small hilltop temple situated 30 km east of the centre of Angkor. A bean-shaped hill of andesitic rock, gently sloping up towards the west to about 30 meters height with an abrupt cliff to the east, was chosen for the location of a temple site, see Fig. [78]. The natural form of the hill directed the construction. The central temple structure was built on the peak of the hill on its eastern side. The cliff on the east side of the mound was overbuilt with a pyramidal structure, representing a broad staircase that reaches the central terrace. The natural topography, used and reshaped by masonry makes it look like an artificial mound and stands as a unique feature in Angkorian architecture. At the foot of the pyramidal structure east of the hill the remains of the eastern *gopura*, the main entrance, are to be found, today largely destroyed. Masonry staircases lead down the hill to the northern, southern and western *gopura*, much smaller in size than the eastern counterpart. Outcrops of rocks were partly removed to construct a staircase from the west. As the south part of the hill is concave it opens to a level field in the southwest where another temple is located directly south of the central structure, a rectangular monument consisting of four elements aligned in a square. This structure faces an excavated and masonry-lined reservoir, 66m long and 44m wide and about 4m deep in the centre. At its eastern side are the collapsed remains of a small platform. The entire hill is surrounded by a rectangular enclosure wall with dimensions of 220m by 320m. The surrounding outer enclosure (1090m x 635m) extends further to the east and is bounded by an embankment-moat-embankment combination. The width of the moat is 150m at the northern and southern sides and up to 190m in the east and west, and is only exceeded in width by the moat of Angkor Wat. Large earthen dikes separate the northern and southern moat that connected Chau Srei Vibol with a road to Angkor in the west and to Beng Mealea in the east.

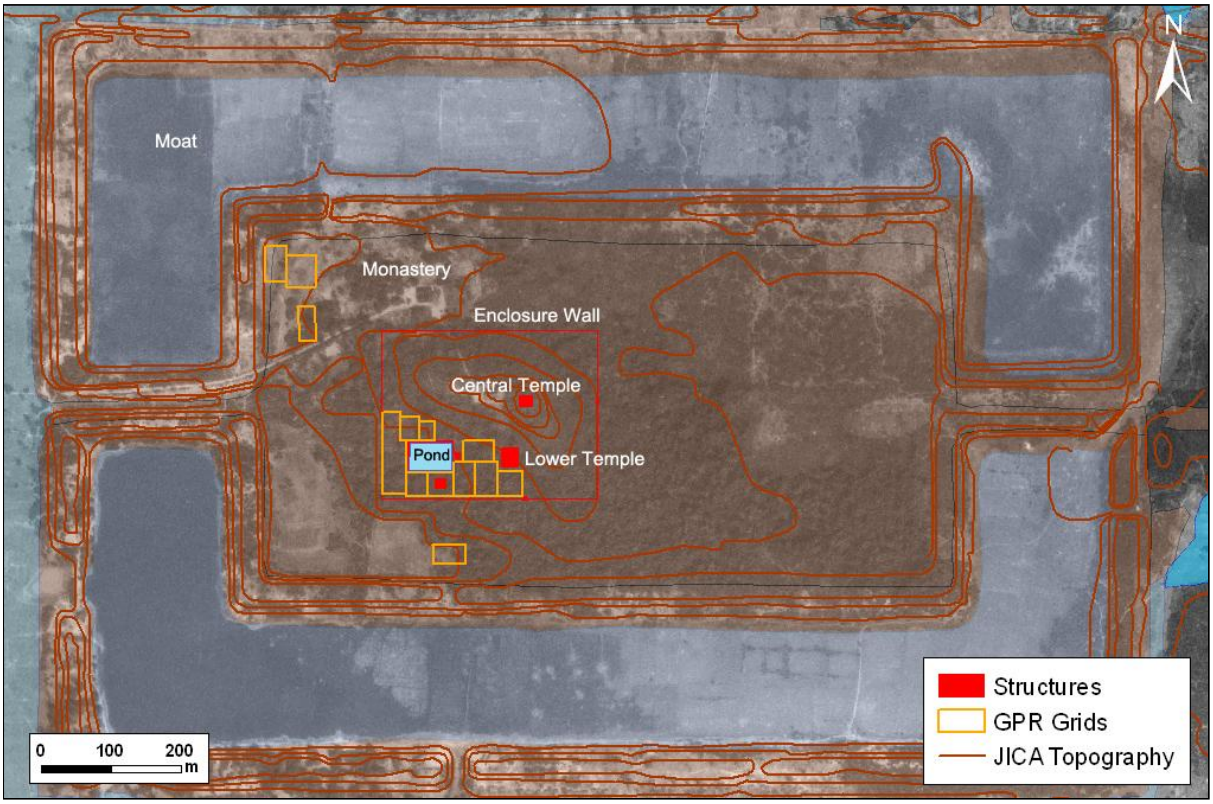


FIG. [78]: OVERVIEW OF SURVEY AREAS AT CHAU SREI VIBOL (BACKGROUND: JICA/IKONOS/POTTIER).

The "Fortress in the Woods"

Only a few publications include a description of Chau Srei Vibol - apart from several early visits by EFEO archaeologists - the temple site attracted little interest. No *stelae* or any kind of inscription have been found in the compound so far,[827] and therefore its period of construction could only be based on iconography and architectural style, which is still under discussion. Etienne Aymonier published information about *Yos Kèr* for the first time in 1901, by then also known as Bantéai Préi which means the *"fortress in the woods,"* and offered a short description of the situation of the temple, which he described as already in ruins.[828] This was supported by Lunet de Lajonquière in his travel records,[829] see Fig. [79] who named the temple "*Temple of Lord Chei Vibol*".[830] The explorer did not mention any resemblance to any other temple in the centre of Angkor, but associated the central temple with Siva. In the temple plan he added the masonry reservoir in the flat south-east part of the enclosure to the ensemble.[831] Henri Marchal mentioned and sketched the inner enclosure in his personal diary in the 1920s, adding a modern shrine that was constructed on top of the hill west of the central temple and still exists.[832] The EFEO map of 1940, see Fig. [79], displays the enclosure in its correct dimensions. Since then no more detailed plan of the architectural outline has been published. Pottier[833] concentrated on the earthworks, while JICA mapped the topography of this region, including the moat and the hill.

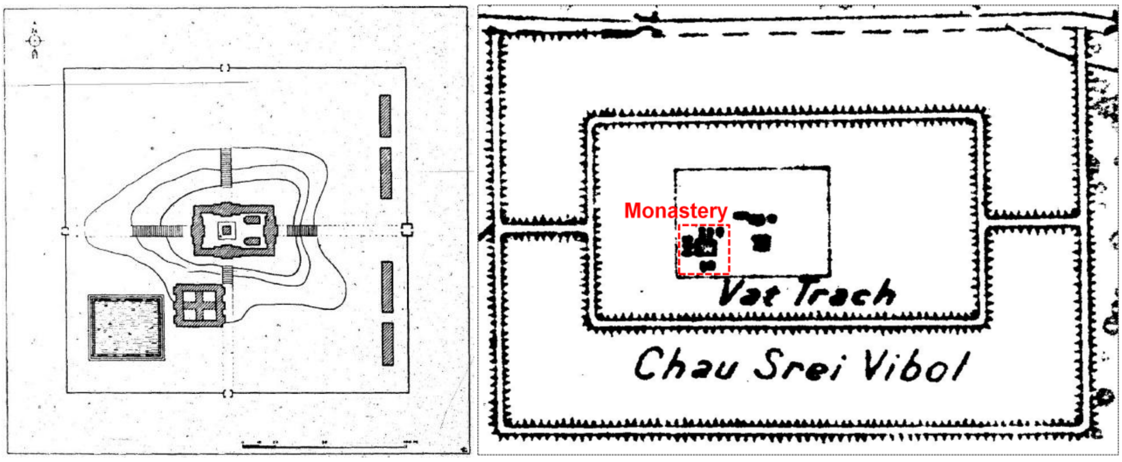


FIG. [79]: PLANS OF CHAU SREI VIBOL BY LUNET DE LAJONQUIÈRE, 1911, P.289, AND EFEO, 1930.

The most recent obstacle to investigation results from Cambodia's modern history. Chau Srei Vibol was used as a stronghold of the Vietnamese army in the 1980s against the Khmer Rouge who had entrenched themselves in the Kulen. Heavy artillery was used in both directions. Until recently the area was mined and littered with unexploded ordinance, and was therefore rather inaccessible. Several bunker-like structures of reused laterite blocks around the hill are remains of the recent conflict. The central enclosure was demined in 2008 and has since been opened to the public, while the outer enclosure, covering the vast area east of the temple, is still mined and only a few paths lead through the bushes. Since the demining campaign the complex has received more attention from a variety of researchers,[834] whose results have yet to be published.

The GPR Survey

The GPR survey was primarily conducted in the south-western flat part of the inner enclosure around the large rectangular reservoir. As the area was initially expected to be largely undisturbed by Post-Angkorian use, the goal was to seek more information about the configuration of buried structures within enclosures including a search for Angkorian settlement features.

FIG. [80]: CHAU SREI VIBOL - CLOCKWISE: (1) CENTRAL SHRINE (2) MASONRY REMAINS IN SURVEY AREA (3) MOAT (4) POND.

This area was divided into 9 rectangular grids. The survey, performed with a 250MHz antenna, covered an area of approximately 13098 m^2 or over 1.3 hectares. The ground was even and flat over most of the terrain, only areas close to the hill contained topographic obstacles. The north-western area was covered with small trees and bushes. While they hindered the survey path, the interpretation of results was only influenced to a small degree. The rest of the survey area had been cleared of small vegetation and only large trees remain. Several small structures were visible on the surface, see Fig. [80]. Masonry features of reused laterite blocks in the west (CSV1) and in the southwest (CSV2) were defined as staircases, south of the reservoir was a low rectangular platform surrounded by irregularly aligned laterite blocks (CSV3), see Fig. [81]. The survey left out areas too close to the partly collapsed enclosure wall. Several "Vietnamese bunkers",[835] which were located in the area, had to be bypassed in the survey. The masonry obstacles, termite mounds as well as large trees, which existed over the complete compound, were mapped within the outline of the grids to facilitate interpretation. Additional surveys were performed outside the enclosure walls, which are described in Chapter (3) regarding living patterns.

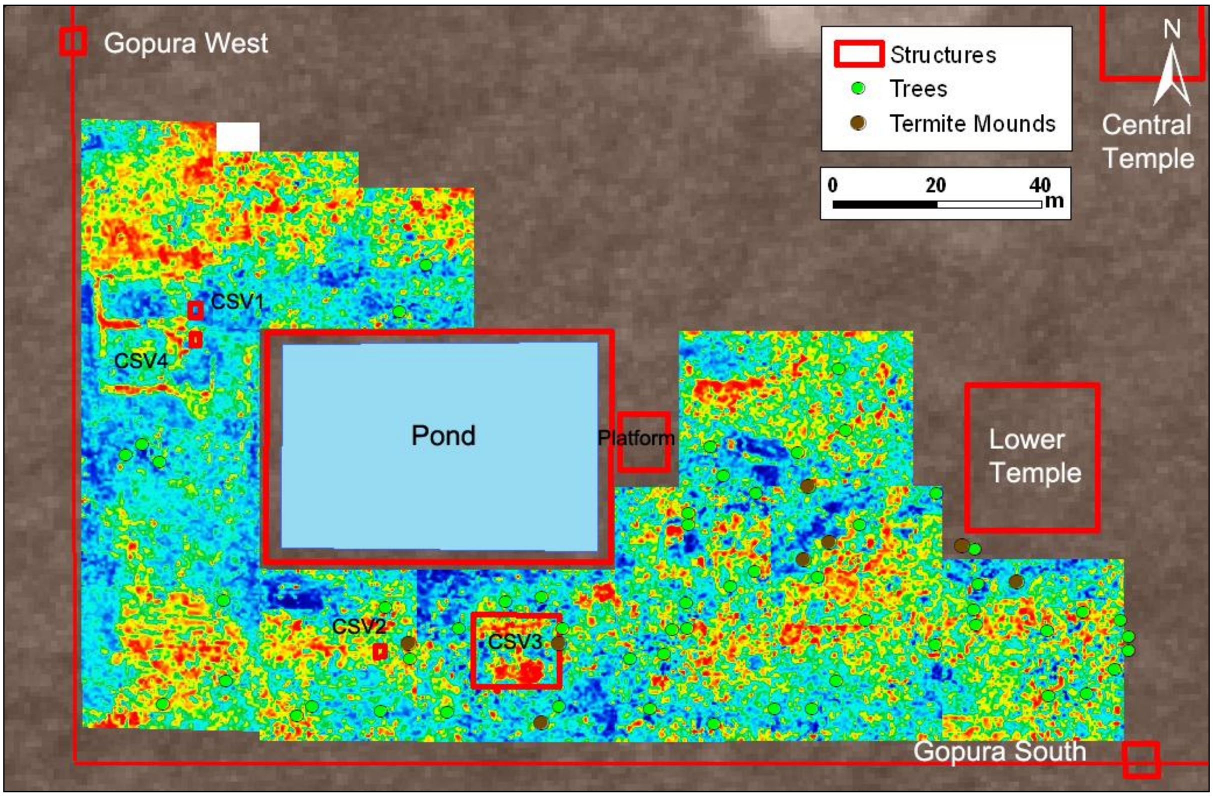


FIG. [81]: GPR SURVEY CHAU SREI VIBOL, ~50CM DEPTH.

GPR Results and Interpretation

The survey area consists of mainly unconsolidated soil, providing a decent signal depth. Near the hill, the soil covers the natural andesitic rocks, which appear in the results as bright red non-geometrical anomalies that should not to be mistaken for structural remains. The most striking results were detected close to the surface at the western end next to the remains of stairs. Here several rectangular anomalies, only visible in the topsoil (CSV4), clearly indicate the remains of structures. The anomalies form a fork-shaped outline of 26m x 19m, opening towards the enclosure wall in the west attached to a stronger rectangular anomaly further south. Possibly other structural remains were also detected in the south-western corner. Local APSARA personal associated the laterite staircases and the discoveries, with a pagoda, that had been at this location approximately until the 1960s, when the buildings were moved from inside the enclosure to the north, where now a large pagoda is situated.[836] The early descriptions by Aymonier, Lunet de Lajonquière showed no structure in the southwest corner, nor did any of the French researchers mention a modern pagoda in the enclosure. In his sketch, Marchal labelled the area in the southwest bonzerie, an old French word for monastery. The EFEO map of 1939 displays in the southern area inside the enclosure several buildings surrounding the trapeang, naming it Vat Trach; see Fig. [79]. It is likely that this wat was fairly modern was and had existed at this location only for a few decades before it was moved to the north of the compound. Those anomalies detected with the GPR are possibly the remains of this monastery and could be associated with the reused laterite blocks in this area that were used as staircases.

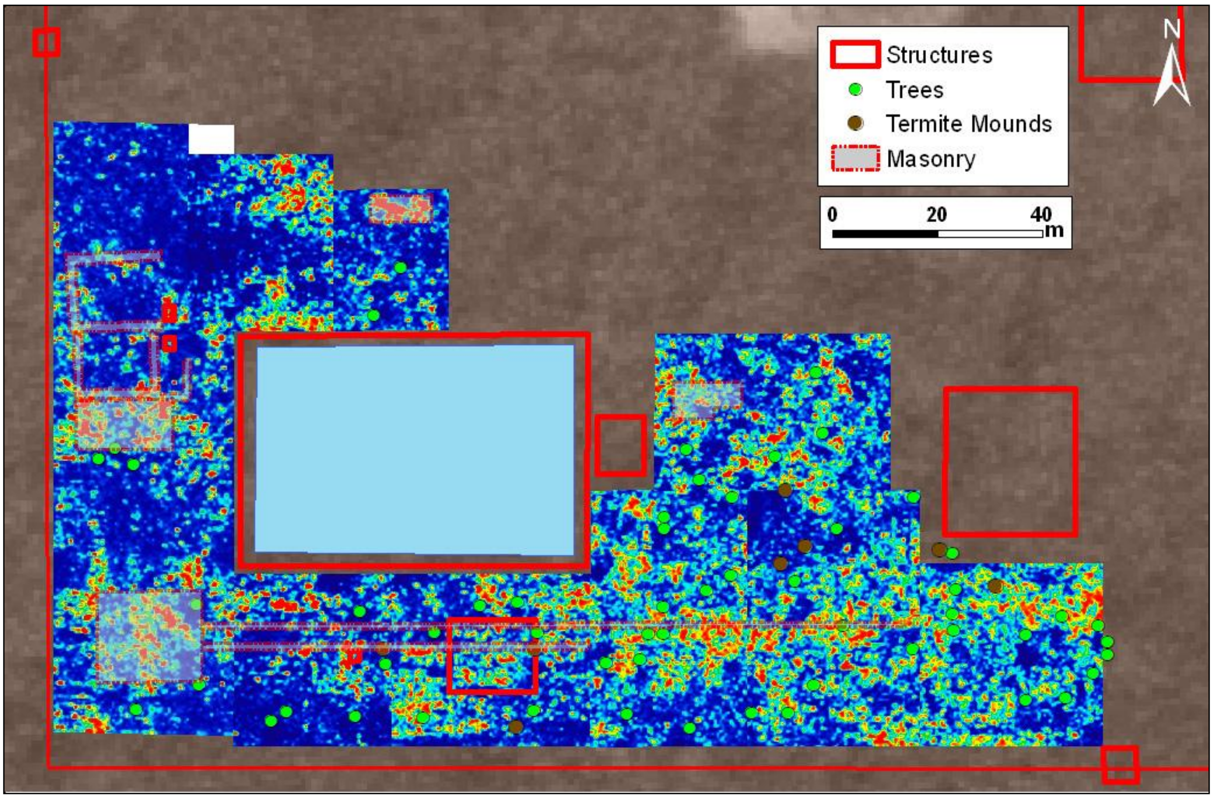


FIG. [82]: GPR SURVEY AT CHAU SREI VIBOL, ~100CM DEPTH AND INTERPRETATION OF RESULTS.

Other stronger anomalies in the upper layers are either too small or in an irregular form to be clearly distinguishable as structural or masonry foundations. Some refer to the modern bunkers that were built from reused laterite stones. It is questionable if areas with more anomalies could refer to areas of more frequent use or deposited material. The subsurface of the area displayed very little evidence for Angkorian activity, see Fig. [82]. No connection, such as a linear feature referring to masonry, between the rectangular temple and the platform to its west was detected. Neither was there a linear feature between the rectangular temple and the southern *gopura*. Below calculated 100cm depth, the GPR returned a more chaotic signal that perhaps refers to bedrock, especially close to the hill.

The anomalies associated with the recently removed modern structures at Chau Srei Vibol complicate the interpretation of results. The features in the topsoil are possibly of modern origin, while evidence from the Angkorian period was detected at greater depth. There is, however, no clearly identifiable structural anomaly between the surface features and the potential natural rock formation, which means that remains have perished or simply did not exist. The investigation of Chau Srei Vibol can serve as a reminder to consider also the post-Angkorian and modern history of Angkor in the GPR surveys. The unexpected survey results show the importance of additional knowledge for the interpretation of findings and displays re-occupation of the temple area and abandonment in modern times. A search for settlement patterns should be started in the densely forested area within the moat on the east side of the inner enclosure, once it has been demined.

ii. BANTEAY SRA

The "Fortress of the Wine"

The enclosure of Banteay Sra (site register: IK653, CP89) is located about 7km northeast of the West Baray, and just outside the modern town of Puok in the province of the same name. The modern Khmer name of the temple Banteay Sra is translated as the "Fortress of Wine." The Angkorian road going westwards towards the medieval temple of Sdok Kok Thom[837] passes north of the enclosure. 600m north of the northeast enclosure corner an Angkorian bridge once crossed the river Stung Preah Srok and now stands beside the river. Banteay Sra is similar in size to enclosures that are lined up both on the road to the west and on the road to Phimai, whose purpose is not known.[838]

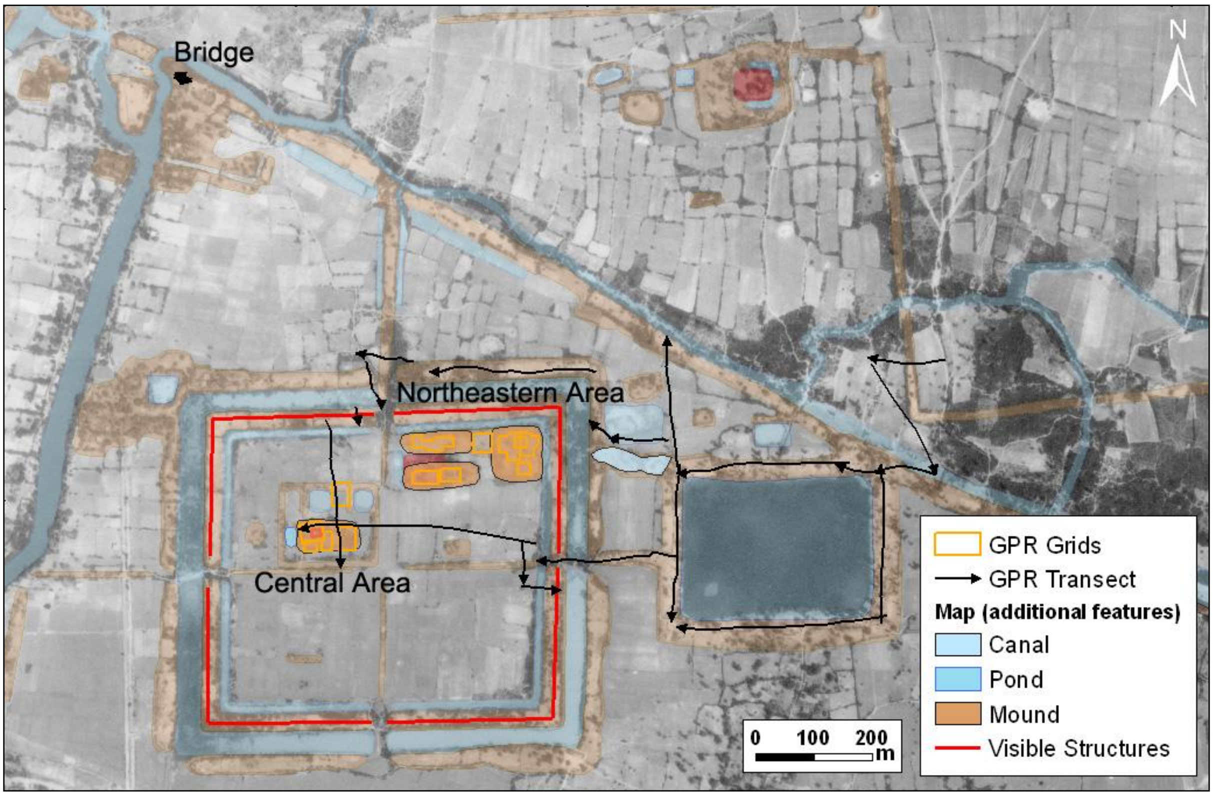


FIG. [83]: OVERVIEW OF BANTEAY SRA (BACKGROUND: FINNMAP/ ARCHAEOLOGICAL MAP: EVANS).

Even compared to the sparse literature available for Chau Srei Vibol, little has been published about the enclosure of Banteay Sra. Most publications that referred to it, mention the archaeological site in connection with the pre-Angkorian "circular" site of Lovea, 2.5km to the northeast of the enclosure.[839] The enclosure was first mapped in detail by Pottier[840] as a moated, roughly rectangular enclosure oriented east to west, bordered by a large reservoir to the east. In all four directions there are gaps through the centre of the embankments providing access into the enclosure, while slightly raised earthen causeways cross the large outer moat. The causeways continue, mainly covered with bushes, to the centre of the enclosure from all four sides. No trace of structures is visible in the low-lying central part of the area, see Fig. [83]. The outer moat varies between 25m and 40m width, while a 10m wide channel runs along the inner side of the main embankment. On top of the embankment, two parallel lines of laterite blocks almost completely surround the enclosure. Only in the northeast corner does the original height reach about 2m. Over almost the entire length of the embankment only the base remains of the wall. If the entire enclosure wall had once existed to its full height, there is no evidence today what happened to the vast majority of the now missing laterite blocks.

Fig. [84]: Banteay Sra Clockwise: (1) remaining enclosure wall (2) interior (3) reservoir (4) ceramics.

Besides the wall no other masonry structure is visible inside the enclosure that could confidently be identified as of Angkorian origin. The vast empty area inside the enclosure today is used for agriculture, predominantly rice and cattle farming. Three slightly elevated areas are situated in the northern half of the enclosure, the highest rising to a height comparable to the embankment of about three meters. The area in the north-western quadrant close to the centre includes a rectangular 15m x 20m wide earthen platform enclosed by laterite blocks. The irregular alignment of the blocks indicates, however, that it was built of used laterite block. This may perhaps be some of the material from the enclosure wall. Additional laterite blocks were detected east of the platform, one group appeared to be *in situ*. The surrounding elevated area is bounded to the north by two ponds. Another small reservoir is located to the east. Along with the stronger border vegetation and slightly higher elevation on its side the whole group forms an enclosed rectangle. The north-western quadrant displays the highest elevation within Banteay Sra. Three small hills form a 240m x 100m rectangle with two hills stretched out east to west, divided by a small depression, bordering the third in the northeast corner. Sparse vegetation exists primarily on the elevated areas, only the embankment is densely covered with bushes. In all elevated areas there is a high concentration of ceramic sherds, indicating long term settlement, see Fig. [84]. Small depressions scattered over the elevated areas in the centre may indicate looting pits.

The Survey

The enclosure of Banteay Sra and the potential pre-Angkorian "circular" site of Lovea to the north were chosen as one of the Terra-SAR-X sample sites because of the barely forested landscape, and there are only few more mapped archaeological features. Studying the compatibility of TerraSAR-X and GPR data was limited to Banteay Sra, as the GPR survey concentrated solely on the enclosure and its surrounding landscape. The elevated areas in the northwest corner of the quadrant close to the centre and in the northeast quadrant were chosen as primary targets for the GPR survey. Those locations provided the highest potential for buried structural features since most of the enclosure was inundated part time of the year, and no structural remains were expected in the flooded areas. Additional transects were conducted over the embankments of the reservoir and the surrounding landscape.

Results and Interpretation

The Central Part

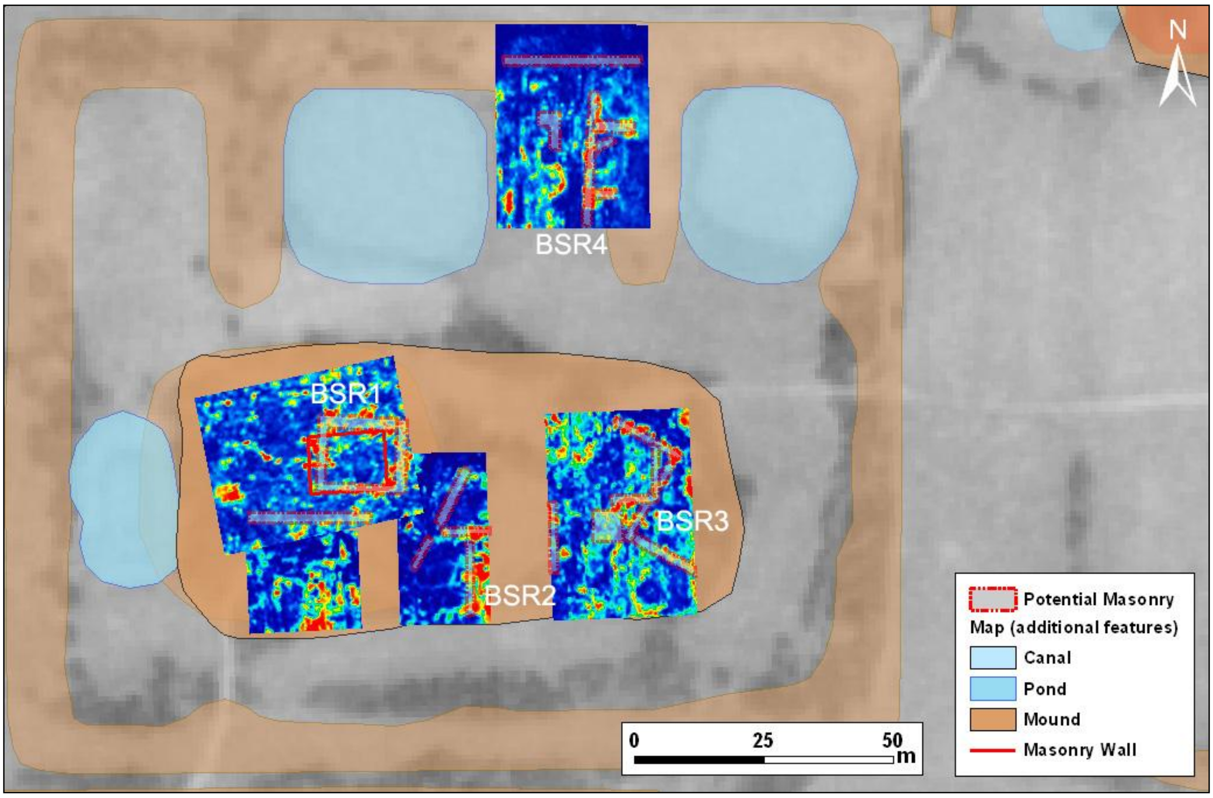


FIG. [85]: GPR SURVEY AND INTERPRETATIONS OF THE CENTRE OF BANTEAY SRA (BACKGROUND: EVANS /FINNMAP).

The survey in the central mound, see Fig. [85], concentrated on the area in the vicinity of the laterite enclosed platform and between the two northern ponds, to search for a possible link between the site and the northern entrance. The mapped configuration of landscape features indicates a significant role for this area within Banteay Sra that includes the highest potential for buried structural remains. There is no indication for additional remains around the mentioned laterite enclosed platform (BSR1), which supports the assumption that it was made of reused laterite blocks and not constructed contemporary to the enclosure. At least two additional groups of linear and potentially masonry features, not aligned with each other and therefore possibly of different construction phases, were detected. One group is oriented north-south east-west (BSR2), similar to the enclosure, while another group seems to be aligned 45 degrees to the side (BSR3). The area in the south has been excavated, which left a round crater like structure of 7m diameter. Between the two ponds the GPR results display two linear structures (BSR4) perpendicular to each other. The northern one is aligned east to west, which also corresponds to the topographic rise in this area. This could possibly have corresponded to an “enclosure” wall of the central part, surrounding the elevated area in this quadrant. There is no indication in the GPR results that a temple size structure ever existed in this area. However, the central part, where the four causeways meet and where the main shrine is located in the most enclosures, was left out of the survey due to its low-lying base. The annual flooding of the whole area makes the construction of a monument in this area unlikely.

The Three Mounds

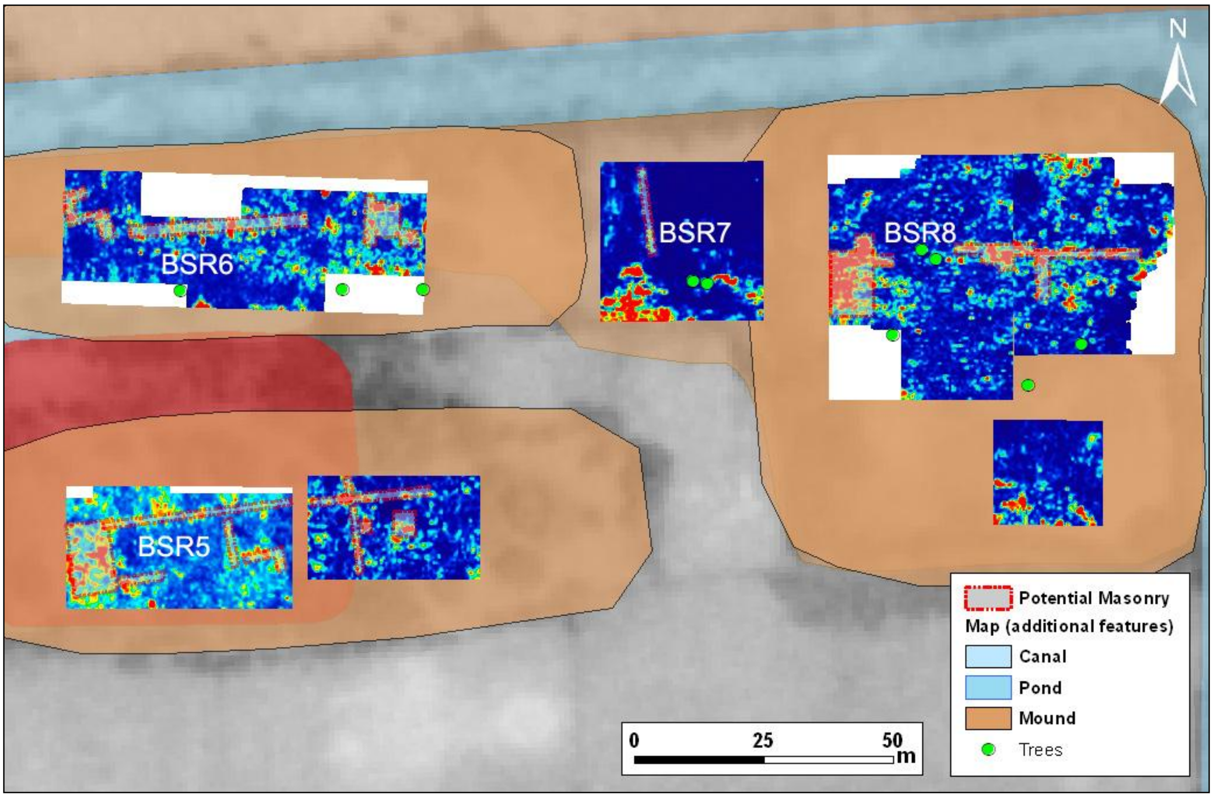


FIG. [86]: GPR SURVEY AND INTERPRETATION OF THE THREE MOUNDS IN THE NORTH-WESTERN QUADRANT (BACKGROUND: FINNMAP/EVANS)

All three mounds located in the north-eastern quadrant seemed relatively undisturbed by looting, the even ground was covered in the centre with patches of grass which were surrounded by denser vegetation on either side. The grids were laid out predominantly over areas that were free of shrubs and bushes, see Fig. [86]. Two parallel linear features (BSR5) were detected on the south-western side of the three mounds, covering nearly the complete grid. The anomalies are nearly 50m long, and about 10m apart, starting from a more solid rectangle in the east and extend in two lines to the west. This most likely represents some kind of settlement structure, potentially the foundations of a long building. The north-western mound displayed traces of linear features similar to the mound further to the south (BSR6), but not as clearly identifiable as structural remains. Another wall-like subsurface feature (BSR7), roughly oriented north-south was detected further east on a raised area located within the three mounds. The orientation of all mentioned anomalies in this area was almost the same and similar to the enclosure walls, roughly oriented east to west. This indicates that they were built in relation to each other as well as to the enclosure. The strongest signal return at Banteay Sra was obtained on top of the highest mound of the enclosure in the north-east corner (BSR8). Potentially this represents a broad platform that was connected to a thick wall running further to the east. Aligned perfectly east to west, the features have a different orientation than the anomalies on the more western mounds. The thick vegetation in this area prohibited the search for similar wall structures further to the north or east, while the low-lying southern part did not reveal any structures. Overall the subsurface of the raised area is rich with anomalies that possibly result from human action and constructions. While predominantly aligned east-west, the features are not easily identifiable as remains of structures. Their varying angles of orientation indicate several phases of settlement in this area.

The Surrounding

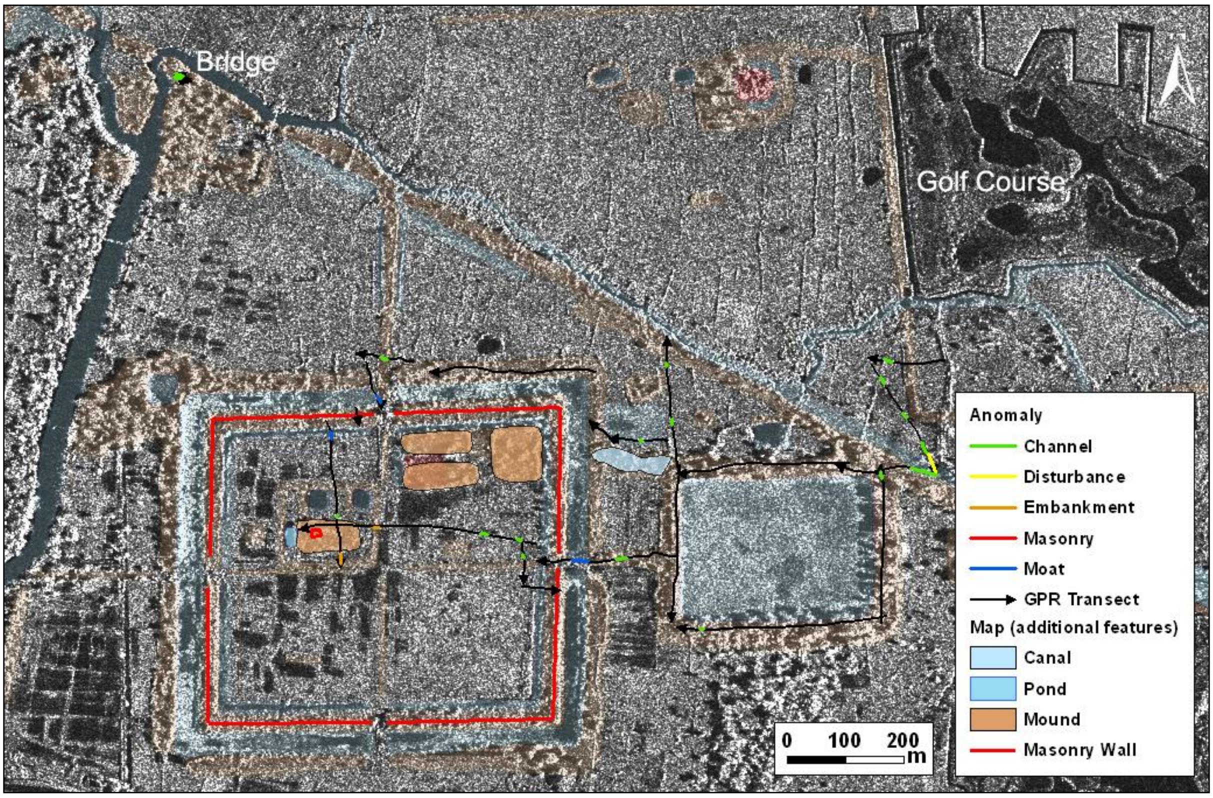


FIG. [87]: BANTEAY SRA AREA COMPARISON OF GPR AND TERRASAR-X (ARCHAEOLOGICAL MAP: EVANS).

Regarding the usefulness of TerraSAR-X data at Banteay Sra, only few additional features have been identified that had not already been mapped by aerial surveys or GPR. The structural features detected in the GPR grids are too small for the coarse resolution provided by the TerraSAR-X data. The GPR profiles conducted around and inside the enclosure of Banteay Sra revealed several depressions, anomalies representing possibly channels or ponds, see Fig. [87].

Outside the enclosures, the main anomalies corresponded with the mapped remote sensing data, in case of the channel next to the road or the partially silted moats. The anomalies correspond generally with the dark reflections that are displayed in the TerraSAR-X data as reflections from moist surfaces and partially flooded areas.

Spean Thma Stung Preah Srok

Six GPR profiles to map a former water channel were taken beside the bridge of Spean Thma Stung Preah Srok, which once connected the Angkorian road to the north east of Banteay Sra. The top of the bridge was covered with brushes, and the river passes the bridge on the western side, so surveys were only possible parallel to the bridge on the southern side. Here the GPR survey displayed the extent and depth of the original riverbed, see Fig. [88], which is now located further to the west than its original channel. The TerraSAR-X image displays the current course of the river, but does not indicate the original flow.

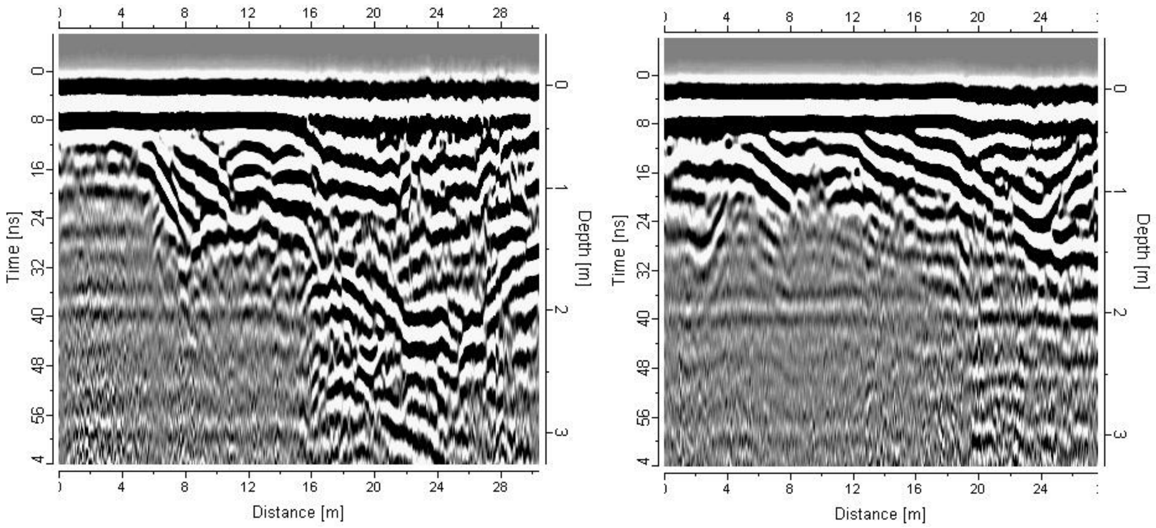


FIG. [88]: PROFILES BA_DAT_0001_1 AND BA_DAT_0001_3 CONDUCTED ALONGSIDE BRIDGE SHOW ANOMALIES RESULTING FROM FORMER RIVER BED.

iii. ASRAMA

The Hermitages of Angkor

Three similar inscriptions associated with small *stela* pavilions located to the south of the Yasodharatataka were translated by Cœdès,[841] who classified the sites as *asrama*. Due to the religious purpose of the sanctuaries, dedicated to Brahma, Vishnu and Buddha, the term *asrama* is generally translated as "hermitage", [842] a type of sanctuary associated with King Yasovarman (AD889-919). He is mentioned as the founder of a total of 100 *asrama* distributed over the whole Khmer kingdom. The inscriptions provide information about "*the operation of each āçrama, their common rules, procedures and some of their differences.*"[843] Pottier, from aerial images, measured the extent of the visible earthen features that were associated with the *stela* buildings, regarded the temple of Pre Rup as possibly covering the area of one destroyed *asrama,* and identified a fifth one to the north of the *baray*.[844] The *asrama* display several similarities. All *asrama* are orientated east to west and the average size is about 375 metres[845] long and 100-120 metres wide. The enclosed space is divided into three sections,[846] two squared areas of same size, and a third of half the size; the function of this arrangement is unknown.

Most *asrama* are made of irregular earthen mounds alternating with lower areas, which are today used as rice fields. The eastern partition houses in its geometrical centre a small laterite pavilion which originally sheltered the *stela*. In the case of Prasat Komnap, the stela K. 701 displays information about the use, the rules and religious procedures of the *asrama*. Some *asrama* have in addition to the *stela* pavilion a linear masonry building situated at its south-western side. In the case of Prasat Prei 720, the structure was cleared by Trouvé who then wrote an architectural study of this *asrama*.[847] To the east of the *asrama* a small *trapeang* completed the ensemble. The location of most of the *asrama* outside of Angkor remains unknown, but the recent detection of previously unidentified *asrama* has drawn new attention to them again.[848]

The region south of the East Baray was originally an even floodplain, and any raised areas indicated human built mounds. The archaeological sites that were surveyed, Prasat Komnap 747 (associated to stela K.747) and Prasat Oung Mong 349, are two of the five archaeological sites in vicinity to the Yasodharatataka that have been identified as *asrama*.[849] The primary survey site Prasat Komnap 747 was only covered by shrubs; the *stela* pavilion had been excavated earlier on, but had not been reconstructed. The area of Prasat Oung Mong 349 in the vicinity to Sra Srang is in comparison relatively densely occupied, and buildings around the repaired stela building leave little space for a survey. Although not fully qualifying for the definition of an “enclosure”, in the sense that *asrama* are not surrounded by a masonry wall the rectangular earthen embankment around the site encloses a clearly defined space. The distinct topography, with generally no visible structural and masonry elements, gave reason for a large scale GPR survey.

Prasat Komnap

The lower parts of Prasat Komnap (site register: MH747) as well as its surroundings have in recent times been used as rice fields and feeding ground for livestock, while the raised embankments and potential occupation mounds, are covered with a low vegetation of scrub and small trees. The actual survey area consists mainly of rice fields and bush land that had to be cleared before the survey. Since the aerial image was taken (Fig. [89], and subsequent figures), a fruit plantation had been planted in the south-eastern part of the *asrama*. Several wired fences close off this area. Around the collapsed and looted centre, where the remains of the stela pavilion are situated, several laterite blocks were moved to the side. From an earlier excavation the laterite roof top has been reconstructed to the west of the remains of the structure. From the aerial image and the archaeological mapping by Pottier[850] there are obvious topographic differences between the three sections. The archaeological map, as displayed in Fig. [89] and Fig. [90], differed slightly from the topography encountered on the ground. This and the fact, that the archaeological map was shifted when transformed into a GIS environment, was the reason for choosing the precise JICA topographic and street data to newly orientate the aerial images and the archaeological map.

The goal of the survey at Prasat Komnap was to cover as many varying areas as possible of the *asrama* to get a full understanding of subsurface features. While part of the area was cleared from shrubs, grids were laid out at the same time in open areas. The twelve grids covered an area of about 2.7ha. Obstacles, such as modern buildings, the remains of the stela pavilion, larger trees and termite mounts were mapped and later included into the map. While the trees at this archaeological site did not have a large impact on the survey due to small size, the number and density of the termite mounds have a heavy impact on data recording, which influenced the overall interpretation. Although the termite mounds were partly destroyed for the survey, the remains appear as dark blue areas especially in the deeper reflections (marked as brown dots in the images), which indicate that they are nearly impenetrable with the GPR.

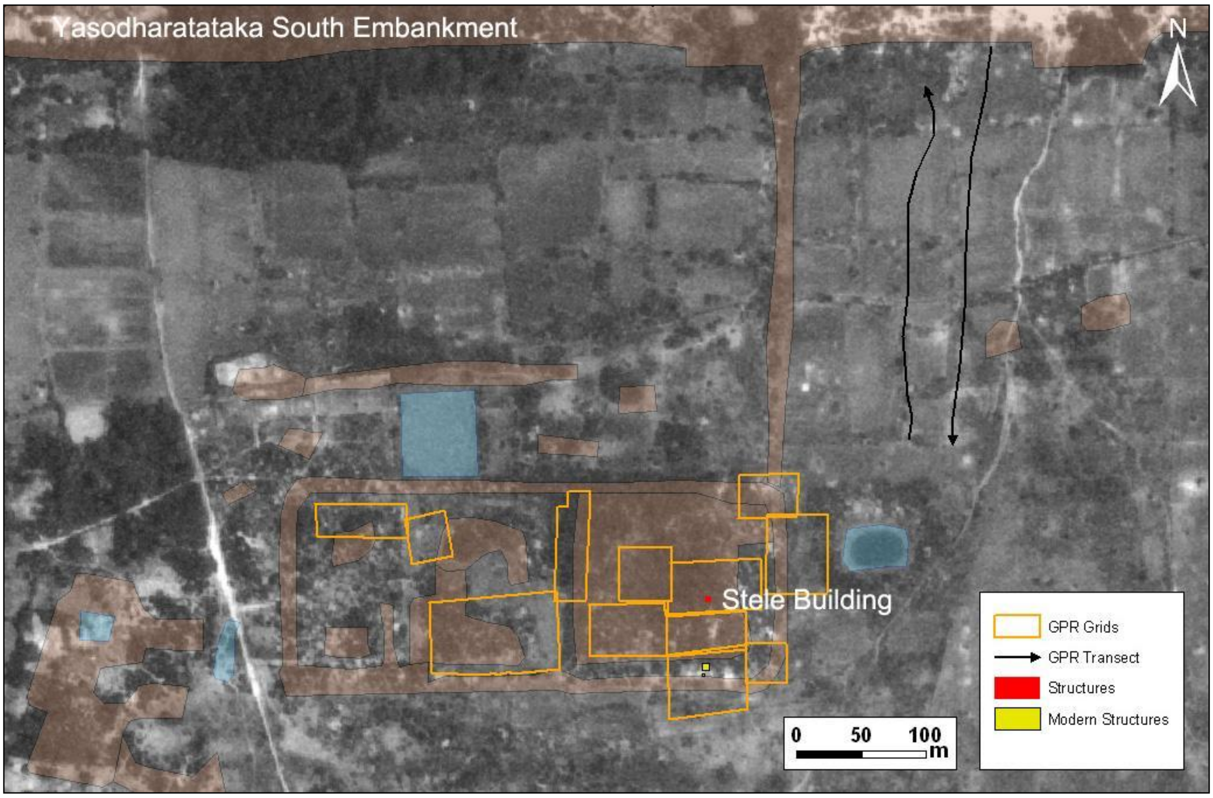


FIG. [89]: SURVEY AREA OF PRASAT KOMNAP (BACKGROUND: POTTIER/ FINNMAP).

Surveys in the central part of the eastern partition around the pavilion of the *asrama* were conducted to identify the connection of the eastern and the central partition. Southwest of the pavilion a masonry sub-surface structure was detected (APK1). Separated by two fence lines, only the combination of the grids revealed its complete outline. The total structure is about 34m long and 15m wide. Oriented east to west, its walls corresponded in size and location to the long laterite building found in a similar location at other *asrama*, e.g. Prasat Prei. While two 2-3m wide linear features possibly represented the outer wall, two narrower linear features were detected parallel to it, further south (APK2). There are several irregular, possibly masonry remains to the west of the structure which might not have a relation with the ensemble (APK3). Another strong anomaly ran north to south about 40m to the west of the feature and is potentially a masonry enclosure wall. A similar anomaly was detected to the east of the pavilion (APK4) as well. Other areas of potential masonry were difficult to interpret due to the concentration of termite mounds. The area connecting the central and the eastern partition may have a high potential for additional laterite structures (AKP5). The largest grid, which covered the southern area of the central partition, a mound surrounded by rice fields, does not show any clearly identifiable anomalies. Since roof tiles were found in the area, it warrants further investigation. The rice fields, due to the saturated earth, dispersed the radar signal and returned a chaotic image in the upper slices, displayed as a light red colour. Probably due to the scatter of the signal, parts of the rice fields are displayed deeper down as strong red anomalies. A survey to the east of the embankment, to identify possible connections between the small pond, the *asrama* and the causeway leading to the north to the *baray*, displayed the earthen embankment around the enclosure. Due to its low penetration depth it is displayed in dark blue colours. Between the pond and *asrama* are two linear features (APK6) that appear modern because of their length and orientation. At 140-150cm depth there is a feature seen before at other locations, nearly rectangular and about 20m wide and long, which could indicate the remains of an enclosed living space, as discussed in Chapter (3) see Fig. [25].

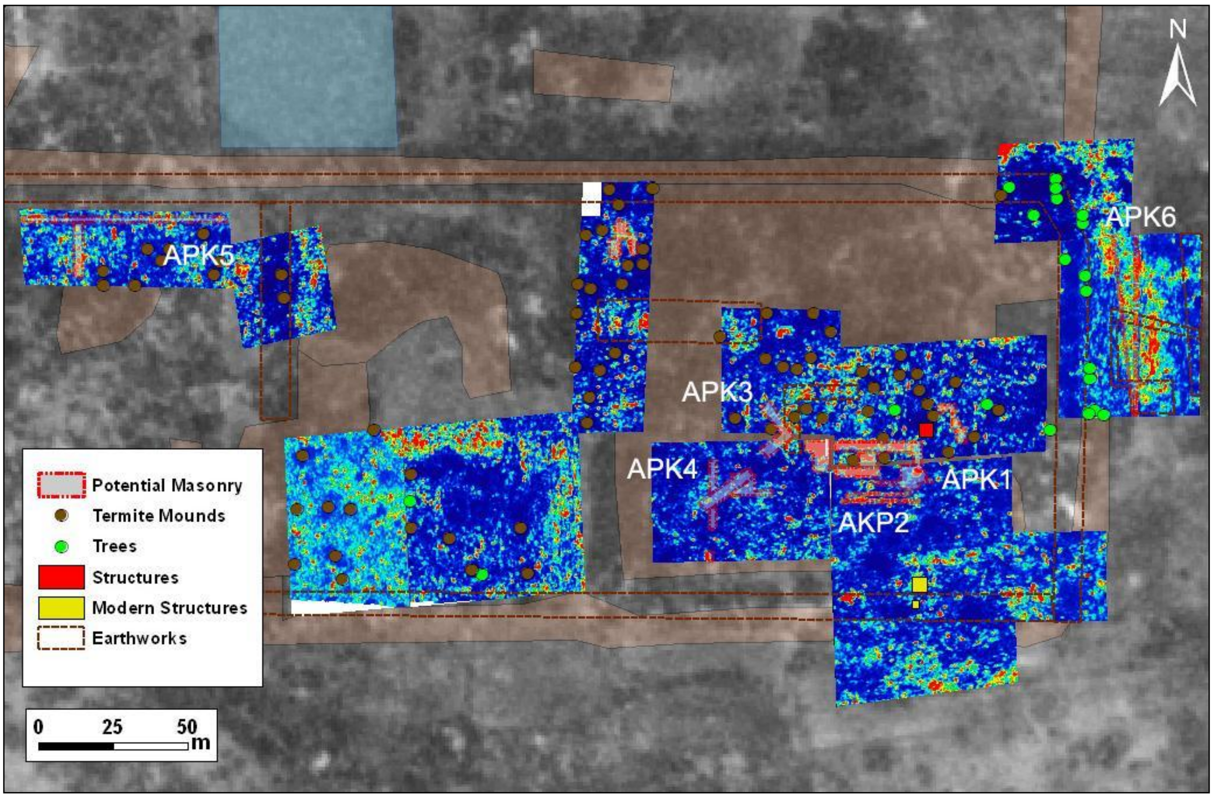


FIG. [90]: GPR SURVEY AT PRASAT KOMNAP CP175 (BACKGROUND: POTTIER, 1999).

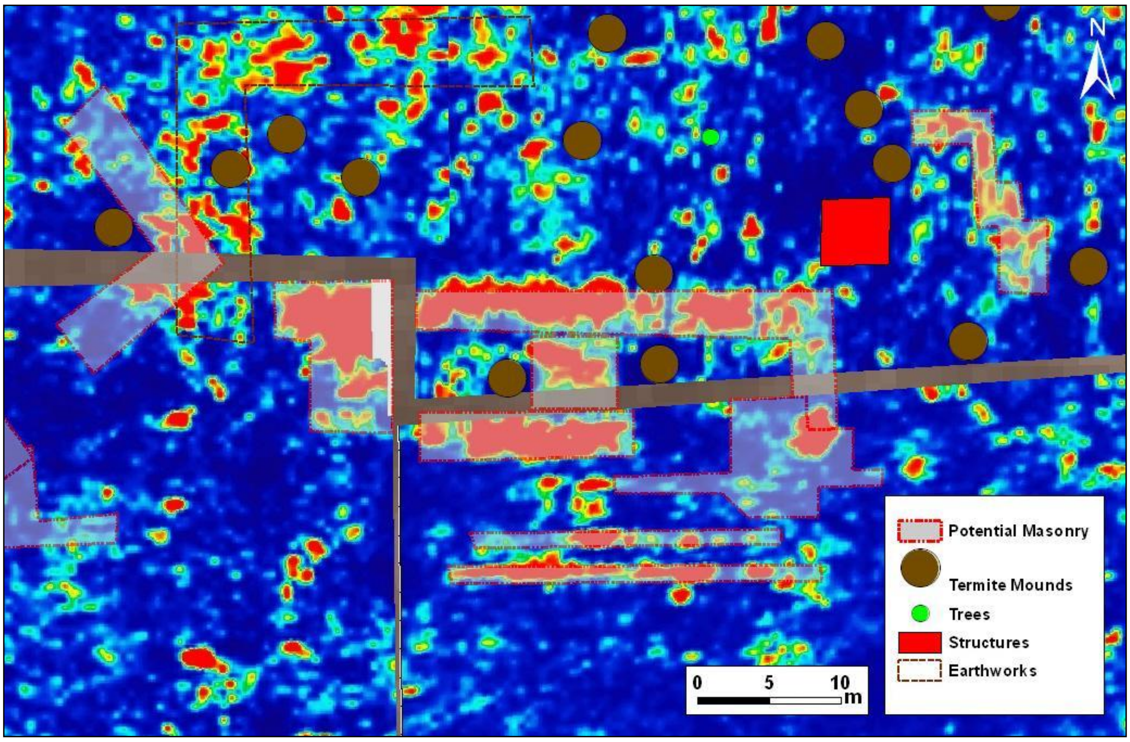
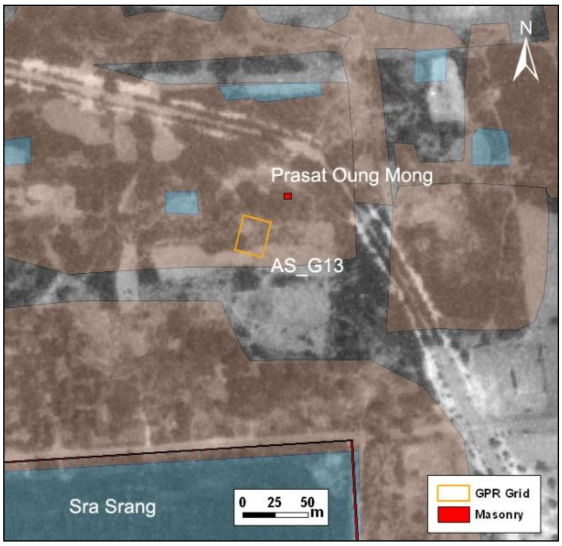


FIG. [91]: CENTRAL PART OF THE GPR SURVEY AT PRASAT KOMNAP.

Prasat Oung Mong

After the discovery of the linear subsurface structure at Prasat Komnap a survey was conducted to test for the possible existence of a similar structure at Prasat Oung Mong. Since the area is densely occupied, only a small grid was conducted southwest of the *stela* pavilion. A strong anomaly of rectangular shape was mapped at the western side of the survey area. The results were initially not interpretable, because of the small area covered. However, when oriented correctly the mapped anomaly possibly indicated the western end of a masonry structure, in its location would resemble, the situation at the pavilion of Prasat Komnap, see Fig. [92]



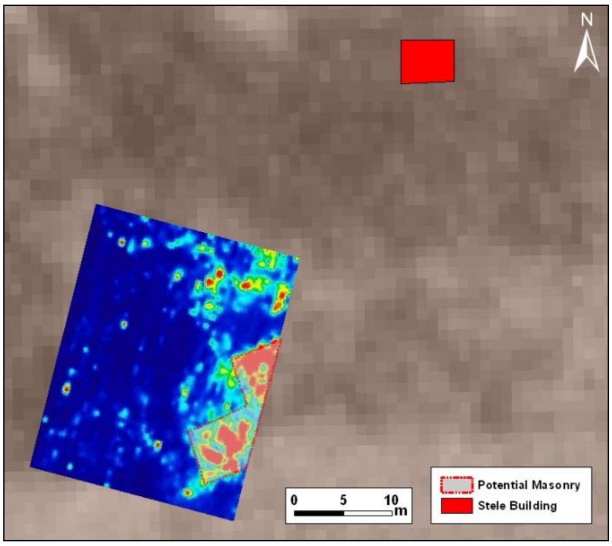


FIG. [92]: AREA AND GPR SURVEY AT PRASAT OUNG MONG (BACKGROUND: POTTIER/FINNMAP).

CONCLUSION

A variety of areas inside enclosures, from forest covered landscapes as at Chau Srei Vibol, the open spaces at Banteay Sra, through to the dense bush land as at the *asrama*, have revealed the possibilities and problems concerning the coverage of large areas by GPR grids at Angkor.

The linear features detected on the shallow mounds at Banteay Sra indicate a series of buildings inside the enclosures, which should be further investigated. The anomalies measured at Chau Srei Vibol show recent use of the enclosure, but display little evidence for additional masonry construction from the Angkorian period. The foundations to the south of the *stela* shrine at Prasat Komnap, and to some extent the anomalies measured at Prasat Oung Mong are analogous to known structures at other *asrama.*

All three targets contribute GPR-information from the subsurface for the interpretation of space at Angkor: empty areas searched for signs of earlier use, raised mounds and areas associated to known structures surveyed for additional structural remains by following Angkorian principles of construction alignment and use of space.

CHAPTER (7) RESERVOIRS AND INFRASTRUCTURE

'All round the town?' he said. 'That's a good long way. Did you go by the old bridge [...]? (LG, VII)

The overall extent and complexity of the transport and water management network of Angkor were eventually discovered by remote sensing. Construction and maintenance of the system, consisting of mainly raised linear earthworks, has been regarded since B.P. Groslier as a major factor in the development and decline of Angkor.[851] Its purpose, especially the association of the four large reservoirs with the network of channels and banks, however, has been fiercely discussed over the last 30 years. The importance of those *baray*, displayed in Fig. [93], as irrigation devices was questioned, and missing evidence of exit channels favoured the concept of a purely ceremonial function of the reservoirs. GPR surveys were carried out to search for and measure such traces within the canal system. The presence and function of the *baray* inlets and outlets in the embankments of the reservoirs are of special interest for the water management network.

(a) THE *BARAY* AT ANGKOR

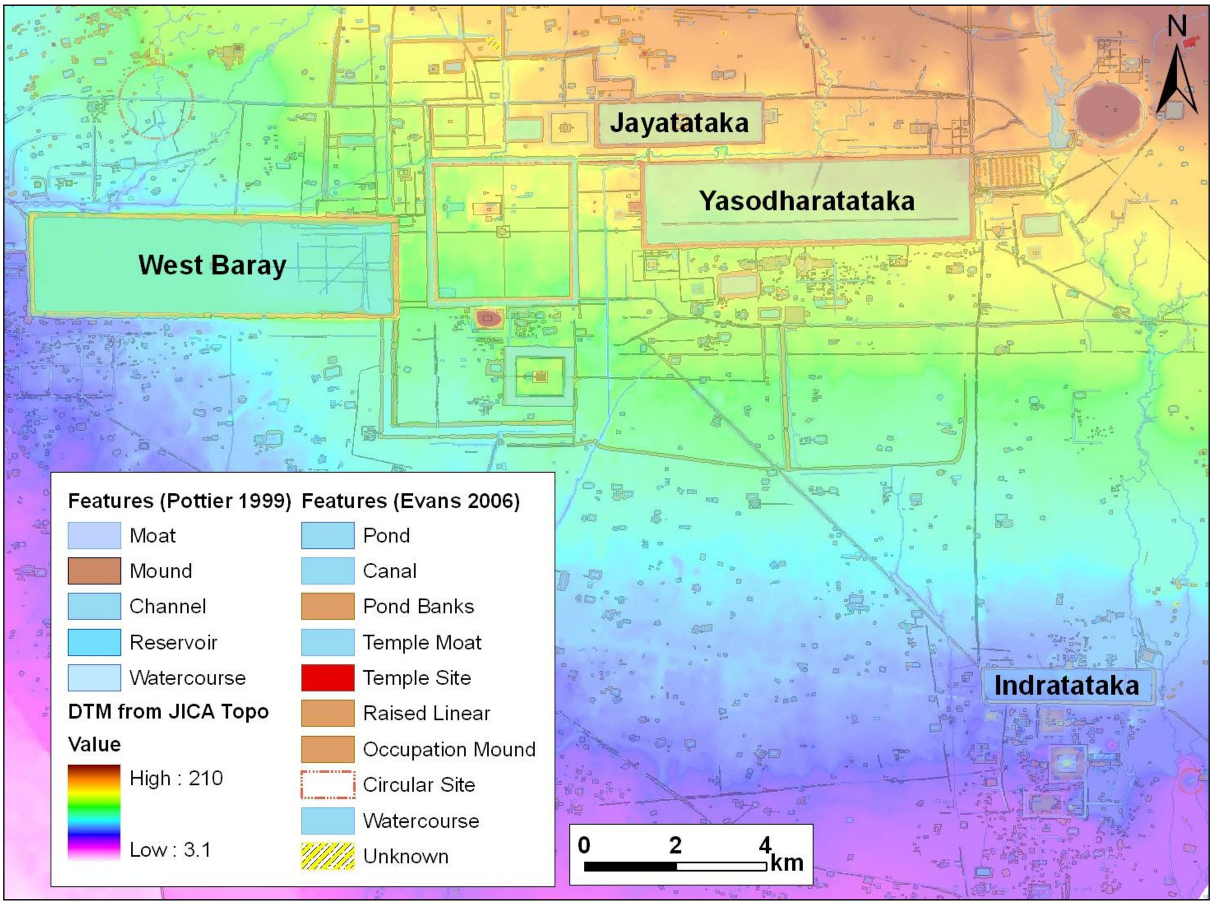


FIG. [93]: THE *BARAY* AND TOPOGRAPHY OF ANGKOR (DTM FROM JICA DATA)

i. THE YASODHARATATAKA

The Yasodharatataka, also commonly known as the East Baray, see Fig. [94], was the second great reservoir of Angkor, built after the Indratataka at Hariharalaya. It was constructed under Yasovarman (AD915-923), and the East Mebon, a temple placed in its centre, was consecrated in the year AD953 by Rajendravarman (AD944-968). The rectangular reservoir measures 7250m x 1844m.[852] The highest point inside the reservoir lies in the northeast corner at 28.75m above mean sea level (AMSL), sloping down to the southwest to about 23.8m AMSL.[853] The embankments surrounding the *baray* have an average height of about 30m AMSL. The lowest laterite platform of the East Mebon lies at 31.9m AMSL.[854] According to Dumarçay & Royère the *baray* had several phases of development. They propose:

> *"The East Baray must have rapidly given indications of insufficiency and doubtless the sedimentation was considerable. It was therefore initially abandoned and several smaller reservoirs were constructed downstream, including Sras Srang and that at Bat Chum. But work on the Eastern Baray was resumed and a vast refashioning was begun. At first the north, east and west dykes were raised; the southern dyke was displaced and rebuilt to the same height as the others."*[855]

Dumarçay & Royère's idea of a later remodelling was based on a linear embankment that crosses the complete *baray* south of the East Mebon and a channel running parallel to it, and the notion that the stelae were moved from there to the new location.[856] There are two reasons that make a remodelling of this kind unlikely.

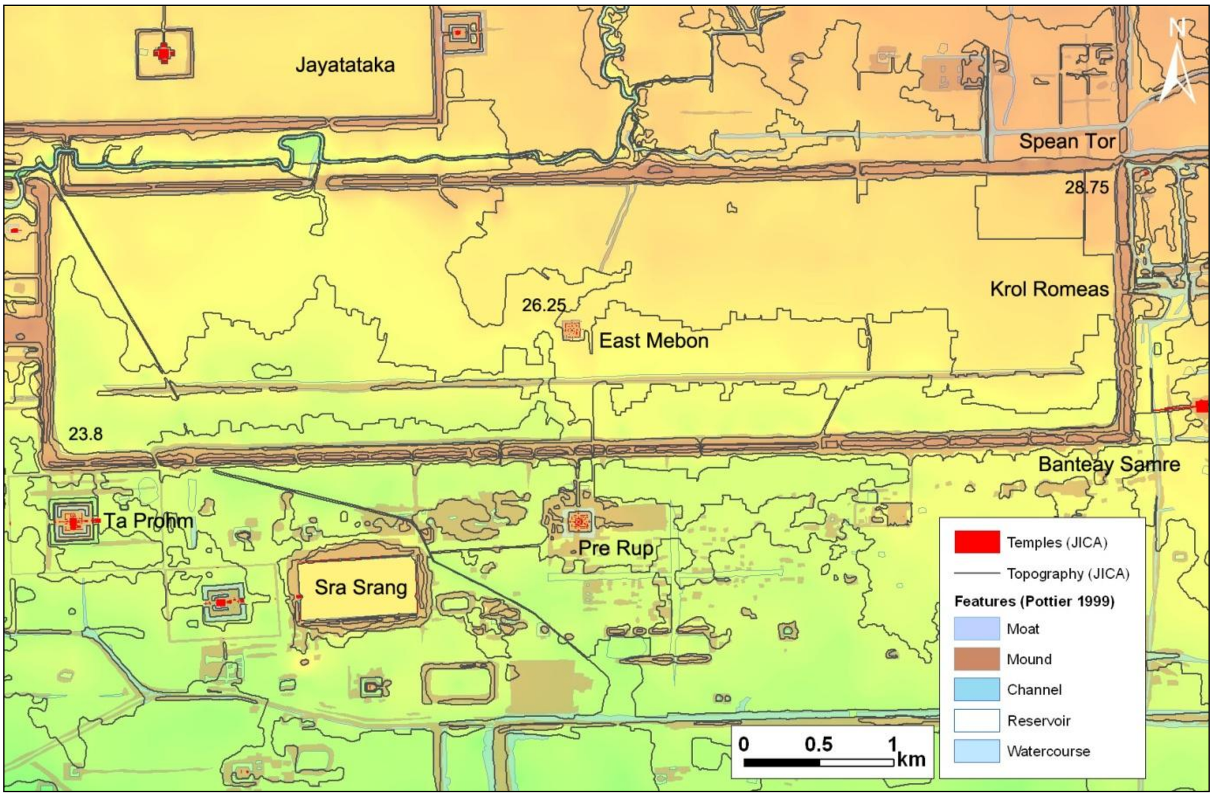


FIG. [94]: THE YASODHARATATAKA - OVERVIEW (BACKGROUND: DTM FROM JICA DATA).

The linear embankment today only lies about 50cm over the surrounding *baray* floor; its demolition would have been a major task; a new interpretation is that this embankment succeeded the construction of the *baray* and was raised in association with a reduced water flow to channel the remaining water.[857] Besides that, the construction of the reservoir is mentioned on *stelae* that were located in pavilions in the corners of the *baray*,[858] which are still in place.[859]

Previous Archaeological Work at the Outlet at Krol Romeas

Since the 1930s it is known that Yasodharatataka actually had an outlet structure in the east embankment. Near the centre of the axis of the *baray*, G. Trouvé mapped a gap in the embankment at the location of Krol Romeas,[860] see Fig. [95]. On the east side of the embankment, Pottier mapped large earthworks, which run in parallel lines away from the *baray*.[861]

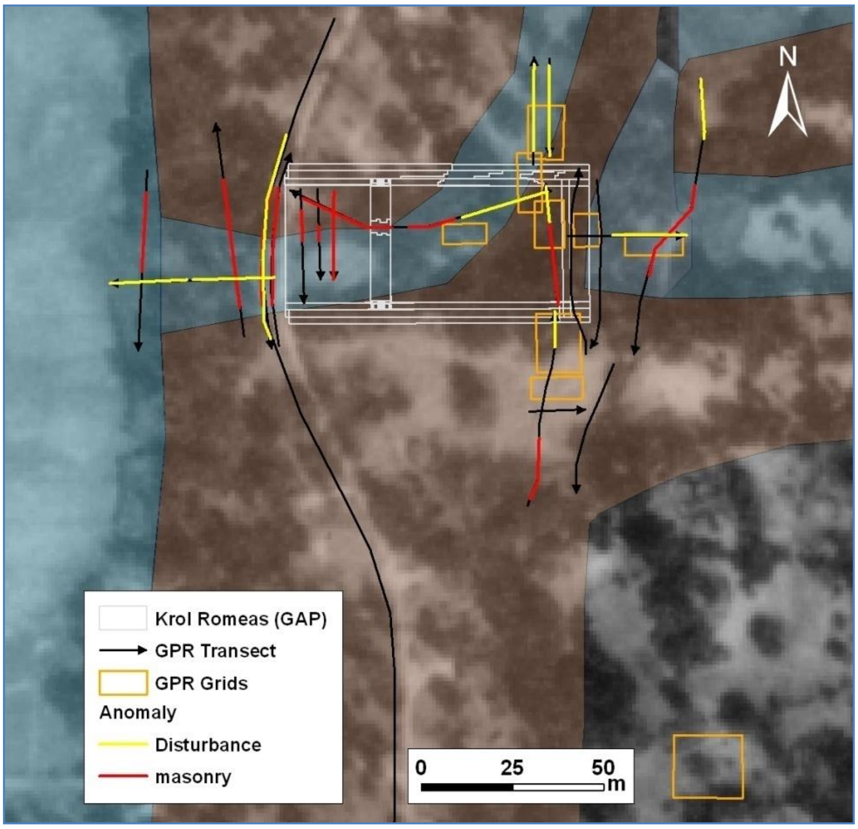


FIG. [95]: SURVEY AREA OF KROL ROMEAS (MODEL: WILSON/GAP, BACKGROUND POTTIER/FINNMAP).

Recent clearing of the area and excavations by GAP provided more information.[862] The structure consists of two parallel three-meter-high laterite walls of 40m length that divide the east embankment. The four-meter thick walls of several rows of finely crafted laterite blocks run parallel 20m apart to each other from east to west, supporting the sand embankments to the outside, while the interior is mostly paved.[863] Connecting the north and south walls via a pair of finely carved staircases is a three-meter wide laterite causeway lower than the outer wall, which has been broken, leaving a three meter wide gap in its centre. Small holes in the sidewalls potentially indicate the presence of a wooden structural addition. There is a large gap at the east corner of the northern wall, where the laterite blocks were completely removed. The eastern side of Krol Romeas is closed by a laterite wall of only one row of irregular blocks, shown in the

2008 excavations, supported from the east by an earthen built up, that was possibly later raised to withstand the water pressure from the inside.

The analysis of the structure by GAP archaeologists[864] led to the conclusion that Krol Romeas was indeed initially an outlet which was later remodelled to change its purpose. At first the water was channelled out to the southeast in between the two carved parallel walls, with the causeway constructed at a later stage.[865] For some reason - it could be speculated that the inlet in the northeast corner of the *baray* might not have provided enough water flow - the water was directed alongside the reservoir from the north, through the bridge of Spean Tor. Krol Romeas was hence converted into an inlet: the northern wall was knocked down on the eastern side of the embankment[866] to bring the water through the gap into the reservoir, while the east side was closed off by a simple masonry wall.[867] The interpretation of Krol Romeas as an outlet towards the east, therefore close to the proposed inlet in the northeast corner, however does not solve the question if the *baray* served as water storage for the rice fields: as the east side is elevated compared to the rest of the reservoir, most water that was stored in the *baray* could not be directed out in the dry season. Yet, water stored by embankments further upstream may repeatedly have filled the *baray*.[868] With the structure converted into an inlet, it also left the question unanswered where the new outlet had been or if there was a new outlet at all, and if similar water channelling devices had been in place for the other *baray*.

GPR Surveys to detect Infrastructure

Following the initial archaeological survey by GAP at Krol Romeas,[869] GPR surveys were conducted over the embankments of all four *baray* at Angkor to test if this configuration existed at other reservoirs. To detect evidence of outlets, and to search for additional water management infrastructure, such as inlets, bridges, canals, long GPR transects were conducted to produce vertical profiles of the landscape. Areas were chosen based on the highest potential for outlets, using C. Pottier's archaeological map,[870] accurate topographic JICA GIS data of the region[871] and additional remote sensing information. GPR transects were conducted mainly on straight roads and footpaths to receive long, continuous profiles, preferably on the *baray* embankments with additional transects parallel on either side. If the high content of compacted clay or dense vegetation especially on the large *baray* embankments reduced the penetration depth of the signal and limited the outcome of results, the surveys were conducted parallel to the embankments. If the area where detected anomalies were identified was suitable, a more detailed gridding survey was completed. The surveys to the south of the structure were followed by targeted excavations.

GPR Survey at Krol Romeas

Previous surveys and excavations have revealed the potential construction history of Krol Romeas in the eastern embankment of the Yasodharatataka. According to current interpretation by GAP[872] the last phase of construction of Krol Romeas closed the exit to the east, allowing water to enter the *baray* through the northern breach, leaving open for answer, where the water exited the reservoir, if at all, and how the *baray* would have functioned at that point in time.

20 transects with a total of 1570m length and eight grids were conducted inside and in the surrounding of Krol Romeas, to detect the extent of the masonry floor and to find connections with the surrounding earthworks. At the south-eastern side of Krol Romeas, where the southern

wall ends about one meter before reaching the eastern wall, see Fig. [96], GPR results displayed two parallel linear masonry structures (KR1), one meter apart and about 20m long, buried under the embankment material. The anomalies begin at the small gap of the south wall of Krol Romeas and continue towards the south. In an additional grid 25m from the south wall, a linear anomaly perpendicular to the other structures and significantly deeper was detected (KR2). Another linear anomaly aligned north-west-south-east was detected below 2m depth (KR3). The direction of the feature, running parallel to the *baray* embankment to the south, indicates an important structural addition to Krol Romeas which could solve the problem of a missing outlet at the time of the blockage of the eastern end of Krol Romeas.

The grids and especially the single transects between the walls displayed the extent of the laterite floor, and showed that it extended further out from between the walls (Fig. [95], in red), and from where it had been removed in the northwest corner (Feature KR5, made visible as yellow disturbances in Fig [95]). The results at KR4 show the possible extent of the laterite pavement east of the walls.

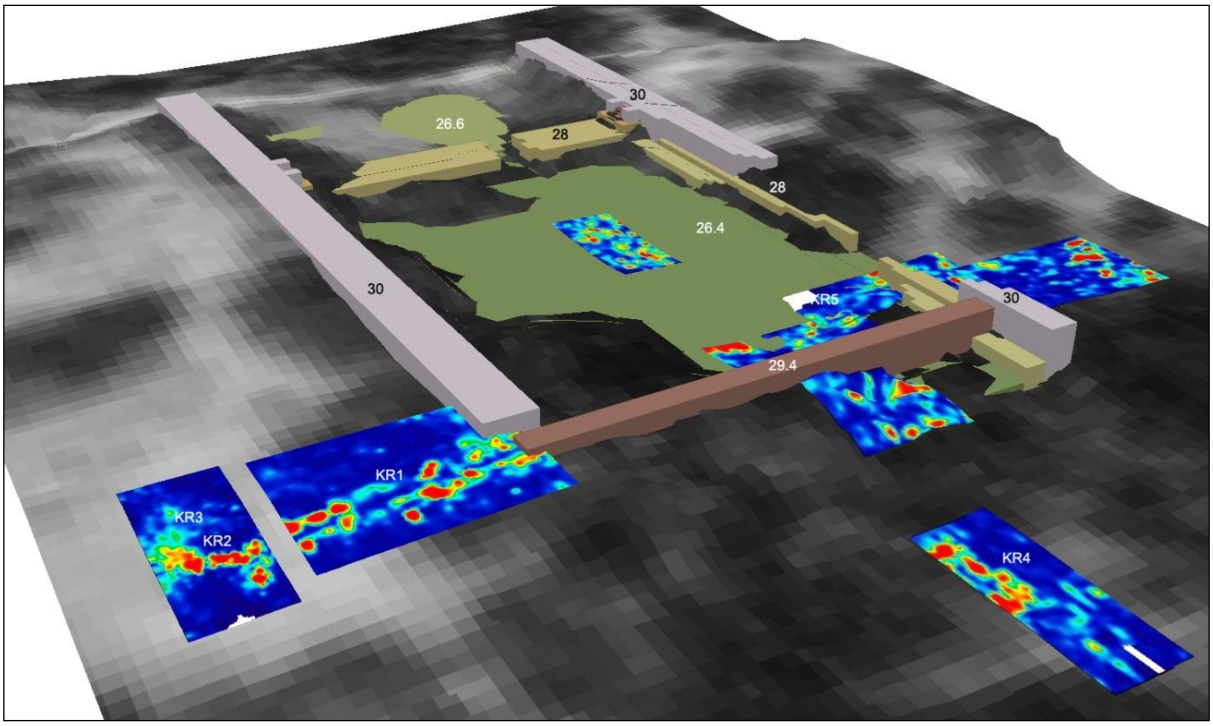


FIG. [96]: THE GPR SURVEY AT KROL ROMEAS, VIEW FROM SOUTHEAST (MODEL AND DTM CREATED FROM GAP DATA/FINNMAP).

Excavation of Features Identified through GPR

Four targeted excavations were initiated to further study the linear features KR1, KR2 and KR3.[873] Trench21 (named as in GAP report) was laid out in the corner of the southern wall and eastern wall of Krol Romeas with an extent of approx. 4 x 4.5m, to examine the relation of the anomalies with the visible masonry structures. Three additional trenches were laid out south to the southern wall of Krol Romeas: Trench22 about 2m south in east-west direction (initially 3m x 1m and later extended to 3m x 3m to cover both anomalies); Trench23 (5.5m x 1m) was laid out approximately 8m south of the wall perpendicular to the linear feature in east-west direction to excavate the linear feature further to the south; Trench 24 (4.5m x 1m) was laid out 17.5m from the south wall as well in east west direction, to cover the angled linear feature.

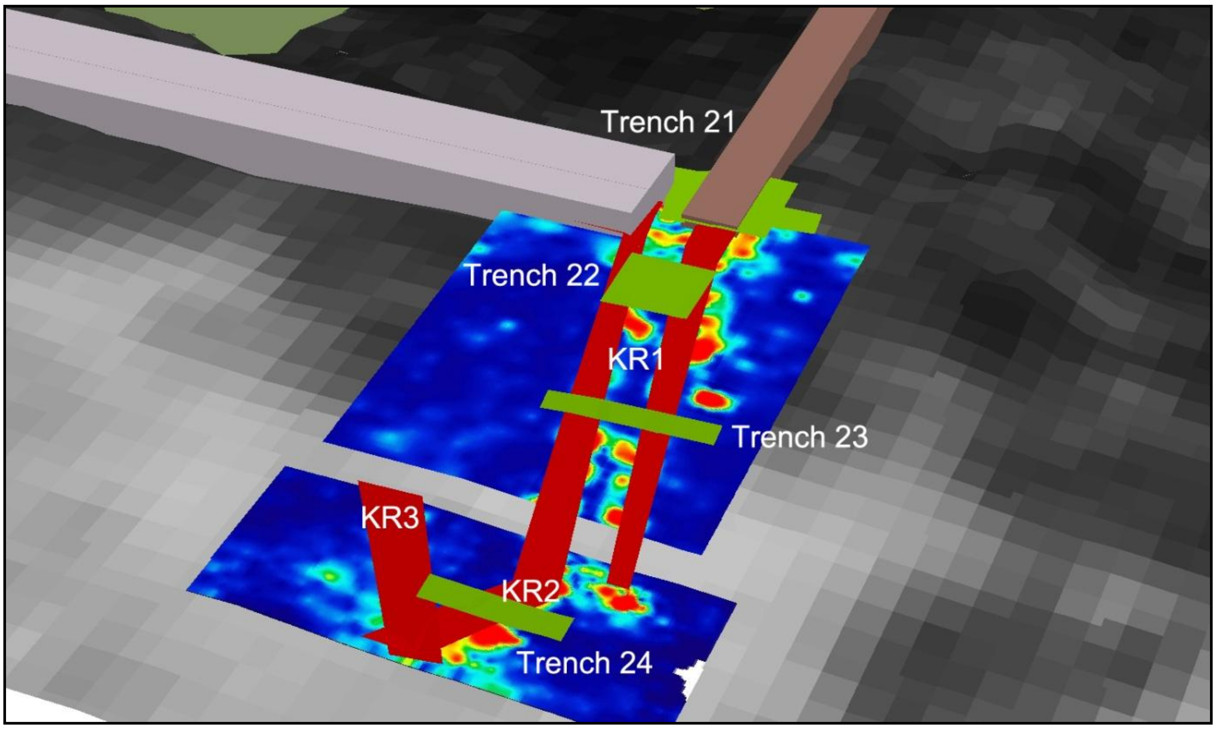


FIG. [97]: LOCATION OF THE EXCAVATION TRENCHES IN RELATION TO GPR SURVEY (BACKGROUND: WILSON/GAP/IKONOS).

While the top surface at the excavations consisted of a shallow layer of soil, further below the excavation revealed only sand without any additional finds. Trench21 displayed that the eastern wall continues through the gap towards the south without interruption. The construction material differs to that of the south wall of Krol Romeas; the masonry consists of smaller, irregular blocks similar to that used in the eastern wall. Where the south wall of Krol Romeas ends, another wall runs in about 90 degrees angle to the south, parallel to the continuation of the eastern wall and made of similar material. The masonry floor inside the structure was broken; some stones had been removed; see Fig. [98.1].

The excavations of Trenches 22 and 23 revealed two parallel laterite walls that are in line with the gap, the top surface barely covered by sand. The uppermost part of the walls is about 50cm thick. The side surfaces of the walls facing each other are smooth and vertical. A masonry floor was excavated at 170cm depth that is paved smoothly with laterite. The width of the side walls increases to the outside with depth, like an irregular staircase; see Fig. [98.3]. The side walls include several laterite blocks carved in an L-shape. This type of masonry blocks were used for the uppermost layer on the north wall of Krol Romeas to secure the wall. A similar layer on top of the south wall is apparently missing. This indicates that at least some of the stones were possibly reused in the newly discovered masonry walls. No clear stratigraphic changes measured inside the channel. The pure sand that filled the interior could indicate that the canal structure was filled artificially, blocking this channel at some point.

Trench 24 over KR2 revealed a masonry wall of four layers of laterite blocks at 3m depth oriented in a 70 degree angle to KR1, the wall structure running in north-south direction, without an apparent structural relation between them, see Fig. [98.4]. The wall is inclined towards the *baray* embankment. Several other irregular laterite blocks were found on the base of the wall. The anomaly detected further below in this grid would have been under this masonry wall. Probing inside the western part of the trench identified a compact material further below, possibly additional laterite blocks; the trench was however not extended due to safety concerns.

FIG. [98]: RESULTS FROM EXCAVATIONS (CLOCKWISE): (1) T21 - GAP IN THE KROL ROMEAS SOUTH WALL. (2) T22 - VIEW ALONG THE CHANNEL. (4) T23 - SUPPORT FROM THE OUTSIDE. (4) T24 - WALL ANGLED TO CHANNEL FROM NORTH.

Other Potential outlets of the Yasodharatataka

Several breaches are visible along the southern embankment of the Yasodharatataka. They are however irregularly cut through the banks and there is no evidence of the use of masonry found at Krol Romeas. Some of the breaches are nowadays used by locals to pass through the large embankment while others channel water out of the lower parts of the *baray*. Currently, no evidence of outlets in the southern embankment has been identified to support the presence of formalised sluice gate devices. The large gaps are probably modern or post-Angkorian, as permanent breaches of that size would have rendered the *baray* incapable of retaining water - they are topographically at the lowest point of the reservoir. In the 1930s Trouvé discovered a breach he identified in as "*the old outlet*" [874] in the western embankment of the Yasodharataka. He described it as "*a very definite gap with paving*" (named GT78),[875] in alignment with the axis of the "Gate of the Dead" of Angkor Thom. In the EFEO map of 1940 a linear connection is displayed to the Gate of the Dead, see Fig. [99]. This breach is similarly described by Dumarçay,[876] as the outlet of the 3rd construction stage. Its continuation was drawn as a double embanked channel in between the Yasodharatataka and Angkor Thom, on both sides of the Siem Reap River, and was located by the author of this study on the western side of the river. Pottier reports that there had been a problem locating this breach due to the dense forest - the map shows it north of the axis of the Gate of the Dead.[877] A survey by the author could only find a breach 400m from the southeast corner with masonry paving on the southern side on top of the western embankment - it possibly corresponds to a feature ("*sans nom*") which was mapped 50m further south of GT78, on the map displayed as "Baray Oriental (Exutoire)," see Fig. [99]. This breach is in alignment with the Gate of the Dead of Angkor Thom and with an embankment mapped by Pottier. A GPR survey passing through the breach did not detect any anomalies indicative of a masonry structure, and the masonry more likely are remains of a platform on top of the embankment, not an outlet. A detailed topographic survey is needed in this area to fully understand the southwest corner of the Yasodharatataka in relation to water management.

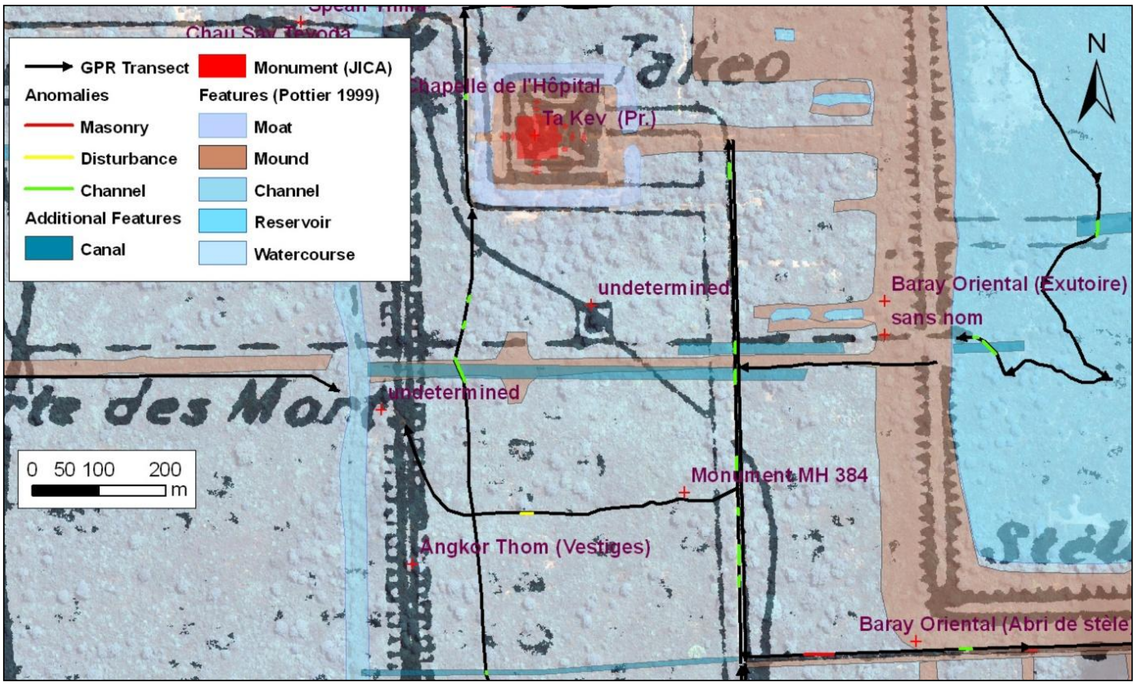


FIG. [99]: SOUTH-WESTERN CORNER OF THE YASODHARATATAKA (BACKGROUND EFEO-MAP, 1940/POTTIER/ IKONOS).

Spean Tor

Spean Tor, a known but buried bridge, was chosen as a sample site. It served to classify and interpret GPR signals reflected by buried masonry infrastructure on *baray* and canal embankments. Located east of the northeast corner of the Yasodharatataka, Spean Tor is now completely covered by the earthen embankment that runs in east-west direction, and today functions as a local road. The structure was cleared in the 1930s as part of the excavation of the temple of Prasat Tor (IK543) further to the south, under supervision of George A. Trouvé. He described the bridge as a construction of six corbelled arches, he describes as 10.65m in length and 5.80m in width, elevated to approximately 3m over the ground[878] (possibly meaning the central part of the bridge; see photo in Fig. [100]). The photo, taken after the clearance of the structure and published in 1935,[879] shows that the bridge has partially collapsed. Trouvé interpreted the large gap as the result of a removed or collapsed pillar. According to Dumarçay the bridge originally allowed water to pass under it towards the south.[880] He classified it as a "*dam-bridge*",[881] which makes it a Khmer water management device for the storage of water within some type of catchment northeast of the Yasodharatataka;[882] see Fig. [100]. Dumarçay does not mention how the bridge would have worked as a blocking device.

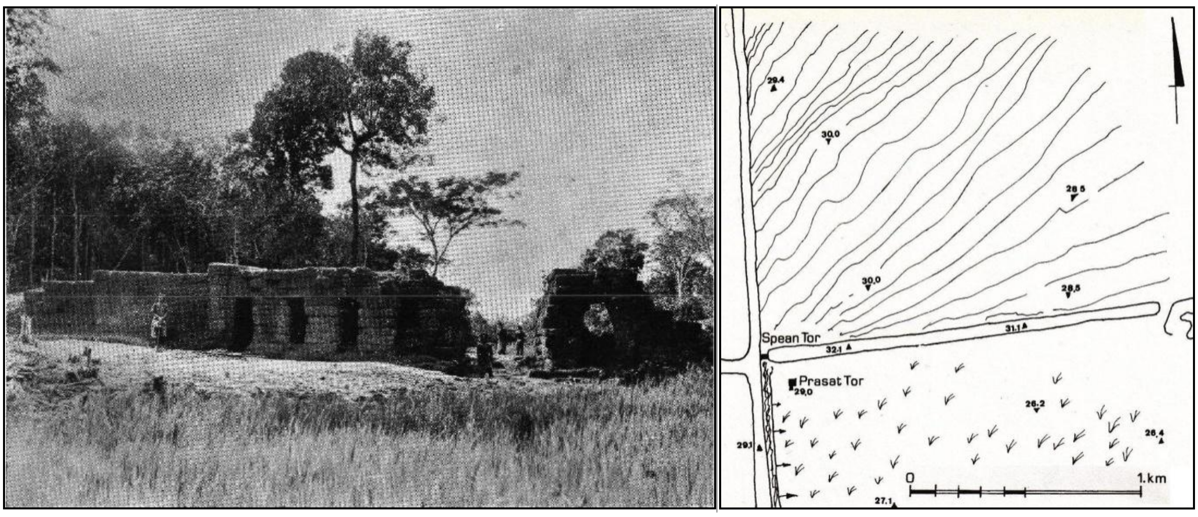


FIG. [100]: PHOTO OF THE BRIDGE SPEAN TOR BY TROUVÉ, 1935, AND INTERPRETATION BY DUMARÇAY, 2003, P. 60.

The dirt road that covers the bridge today provided a smooth surface for the GPR survey. Four transects were conducted to map the extent of the bridge and the inlet, revealing a strong anomaly at the proposed site of the bridge. A 35m x 7m grid was subsequently surveyed to cover the entire road, see Fig. [101].

The GPR results show a strong and layered anomaly 25m in length and detectable over the complete width of the 7m-wide grid. The radar profiles here display more information than the slices. The anomaly is flat, in the centre only 30cm under the surface and about 100cm strong, pointing downwards on its edges that can be seen to 250cm depth, giving the impression of a large arch. A second such "arch-like" feature starts to the west side of the anomaly.

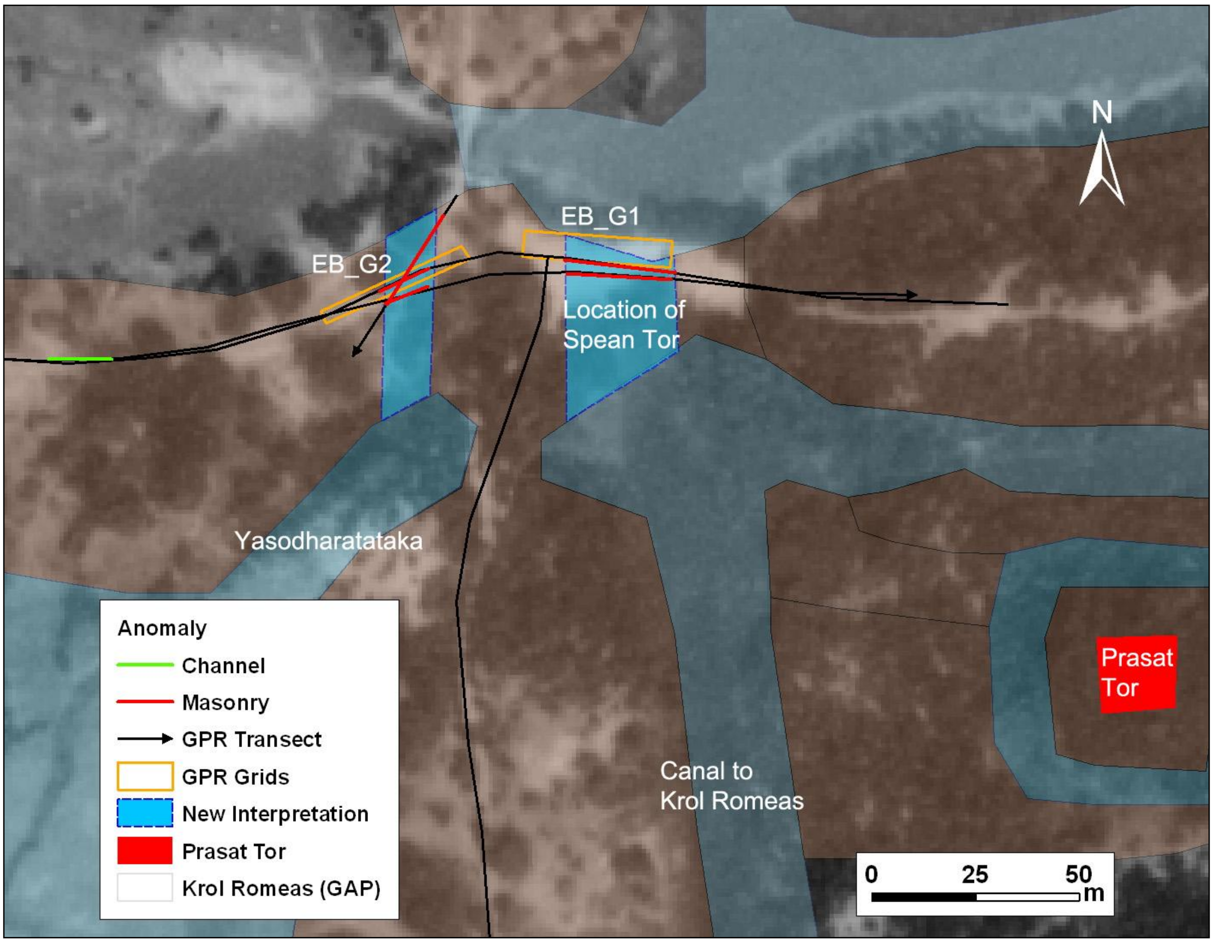


FIG. [101]: GPR SURVEYS IN THE NORTHEAST CORNER OF THE YASODHARATATAKA (BACKGROUND: POTTIER/FINNMAP).

The central part of the anomaly, about 10m wide, possibly refers to the top of the larger section of the bridge, as visible on the photo, while the one western anomaly could refer to the smaller part that spans only one arch, as there is a an area filled with strong reflecting material in between, possibly referring to the gap, see Fig. [102]. The signal only reveals the top part of the structures or possibly the layers of sand covering them. The much smaller corbelled arches of the bridge, as seen on the photo, were not detected, possibly due to the ferrous laterite blocks dispersing the signal.

Evidence for an Inlet

Further west, 40m from the northeast corner of the *baray*, see Fig. [101], the northern reservoir embankment displays an unusually thin and shallow bottleneck. In the results of the GPR transects a strong reflection of 14m width and calculated 300cm depth (60ns) was detected, corresponding to ground level in this area. An additional narrow grid confirmed the findings over the complete width of the 4m.

The strength of the reflection indicates the remains of a laterite structure, possibly a floor. In concurrence with the topography, the anomaly was measured at about the same height as the *baray* floor; potentially providing evidence of an original inlet to the baray,[883] see Fig. [102]. An inlet at this site would however mean that the water, coming from the east, at one point was directed past the site of the bridge into the *baray*. An inlet at this location is supported by the idea that the masonry bridge was probably a later addition, when the water needed to be channelled to the south. Area excavation is required to investigate this anomaly in greater detail.

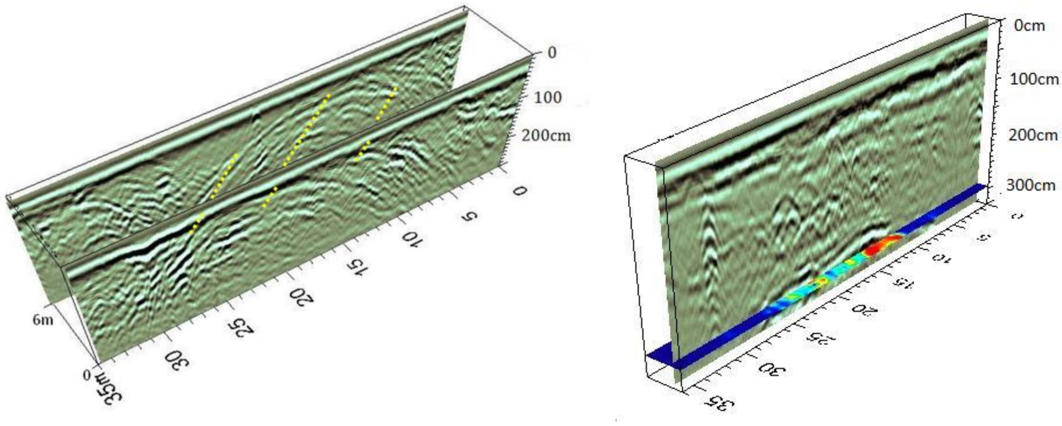


FIG. [102]: GPR RESULTS OF SPEAN TOR (EB_G1, LEFT) AND OF POTENTIAL INLET (EB_G2).

Additional GPR surveys were conducted on the northern embankment of the Yasodharatataka to investigate the vicinity of other earthworks for potential inlets. However, the GPR profiles did not provide sufficient evidence of additional entry channels into the reservoir.

Implications for Krol Romeas and the Yasodharatataka

The laterite pavement at 26.44m AMSL[884] between the northern and southern wall of Krol Romeas was measured by GAP slightly below the interior of the *baray,* directly to the west at 26.5m.[885] The pavement displays the initial potential height of the water level in the *baray*. This configuration,[886] with the exit open to the east, would not have filled up the reservoir completely, and barely covered the surrounding of the East Mebon (at about 26.25m AMSL[887]) with an outermost laterite wall at about 31.9m as displayed in the interpretation of the topographic survey; see Fig. [94]. This could have been one reason that the central causeway was built. Closing the gap in its centre raised the water level temporarily to 28m AMSL.

Regarding its structural attributes, the small masonry channel was made possibly at the same time the east side was blocked off. The bottom laterite floor of the newly discovered masonry channel lies at 26.89m AMSL. The channel is therefore slightly elevated relative to the interior floor of the main structure of Krol Romeas, and slopes downward towards the south, making it the new exit channel mean to direct water, as an overflow, into a channel parallel to the eastern embankment and towards the south.

For further interpretation additional topographic data from JICA is needed: (1) the height of the *baray* embankment varies between 30-32m AMSL; (2) the top of the masonry walls at Krol Romeas were measured at 30m AMSL. Both are higher than (3) the most elevated part of the *baray* interior in the northeast corner at 28.75m AMSL, which was the highest water level the *baray* could have reached when the structure was closed off to the east side. With the eastern side closed off permanently, leaving an opening only to the south, a sluice gate closing the small exit channel could have filled up the *baray* to a new level, reaching the base of the East Mebon without flooding it. A water level of 170cm, the height difference between floor and walls, could have been managed. The thick walls of the channel demonstrate that it could have directed large amounts of water fast out of the *baray* into the channel running along the east embankment towards the south. The archaeological excavations of the channel did not show any evidence of gaps in the walls that could have been closed off to block the water. Nevertheless, the GPR survey may have detected the first sluice structure in Angkor, that of its small size could easily to be shut and opened depending on the water level in the *baray*.

ii. THE INDRATATAKA

The identification of Krol Romeas as a masonry outlet/inlet structure encouraged the search for unknown structural features related to water management at other *baray,* to get to a better understanding of their functions, and of their construction histories. Easy access to the site and relatively low embankments gave reason to start the search for inlets and outlets at the Indratataka.

Commonly regarded as the oldest *baray*[888] in the Angkor region, the Indratataka is situated to the north of the enclosures of Hariharalaya and is attributed to the reign of King Indravarman I (AD877-886/889).[889] Jacques and Freeman assume that the initial outline of the reservoir consisted of three embankments that were open upslope to the north and worked as a water catchment.[890] This first outline was, according to Dumarçay, influenced by the configuration of dams that can still be found in the Kulen,[891] located near the capital of Indravarman I's predecessor Jayavarman II, who is regarded as the first king of Angkor.[892] Lolei temple was constructed near the centre of the *baray*[893] by Yasovarman I (AD889-about 910)[894] to commemorate his father Indravarman. By adding the Lolei to the ensemble, the reservoir was officially transformed into a spiritual place that modelled the Hindu universe, in which the *mebon* was interpreted as Mount Meru, the sacred Hindu mountain surrounded by the world ocean.[895] Dumarçay argues that at some point in time the existing embankments were raised and the construction of an additional embankment further to the north closed off the reservoir, which explains its displaced central E-W axis.[896]

Description of the Indratataka

The Indratataka is distinguishable from preceding pre-Angkorian temple ponds at e.g. Sambor Prei Kuk by its tremendous size. According to Groslier, the finished reservoir, 3760m in length and 760m in width,[897] exceeded any water management structure ever built in Cambodia.[898] This scale was made possible by raising the earthen embankments instead of excavating the reservoir's interior. The water source for the Indratataka and Hariharalaya was a river running south from Phnom Bok reaching the northeast corner of the *baray*. Today the Roluos River has again meandered out of its bed, and passes about 200m east of the reservoir. Pottier mentions that he came across a masonry structure in the northern embankment, possibly indicating an inlet, that is displayed on the map as CP758.[899] The modern outlet of the mainly dry Indratataka is in the southeast corner, at the lowest point of the interior of the *baray*. National Road 6 (NR-6), which covers the complete southern embankment of the *baray,* runs over a concrete bridge. Any evidence of a potential former outlet at this side of the reservoir would have been removed when this bridge was constructed.

The GPR Survey

GPR transects were conducted over the complete western,[900] and the less than 2m high northern embankment.[901] Additional surveys were conducted on the dirt road to the east of the eastern and partly on the southern embankment over NR-6. To the north of the northeast corner of the reservoir a series several canals possibly associated with Roluos River and the existence of some form of distribution system.[902] The results from the GPR transects (e. g. IB_DAT_0161_12-55m) show evidence of a channel that is directed south-west towards the northern embankment, displayed as a light blue line in Fig. [103]. In the embankment the GPR survey found at least one inlet and evidence for several others that could have been in subsequent use.

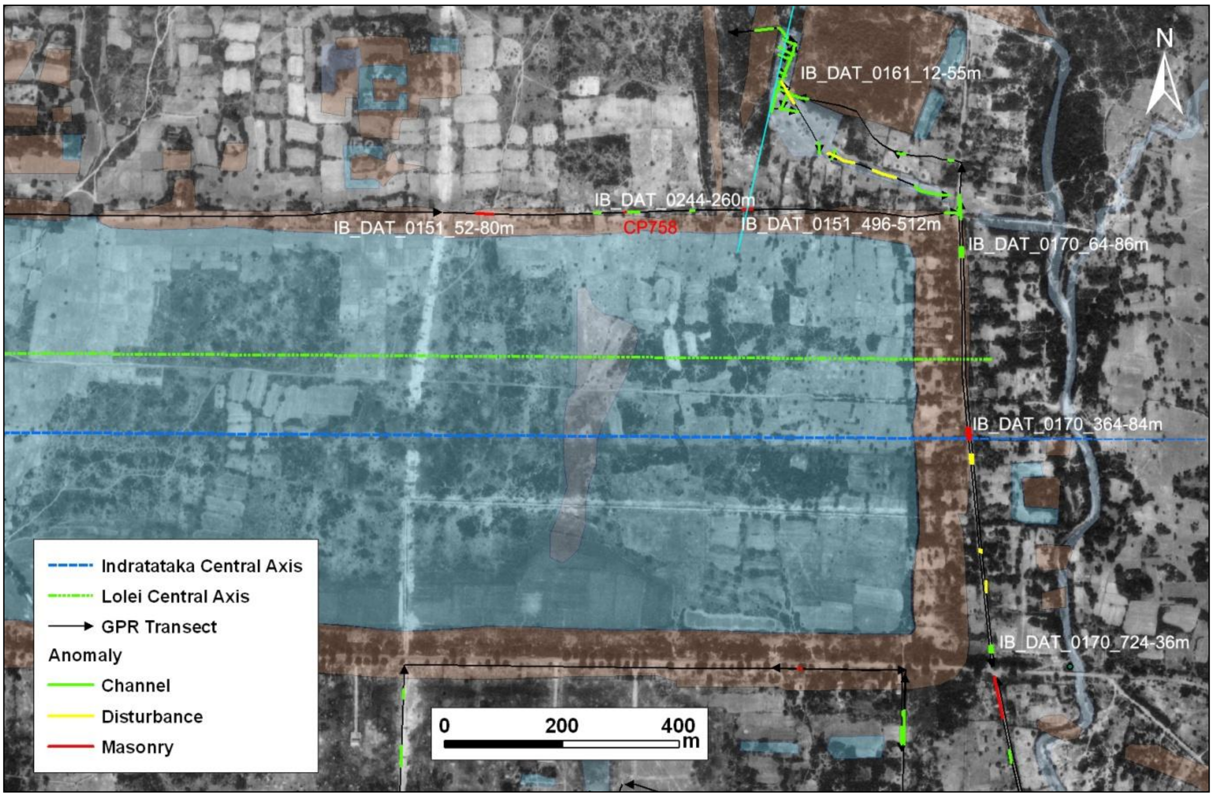


FIG. [103]: THE GPR SURVEY AROUND INDRATATAKA, POTENTIAL INLETS AND OUTLETS (BACKGROUND POTTIER/FINNMAP).

Inlets

Anomaly IB_DAT_0151_496-512m shows a very strong signal reflection, see Fig. [104], indicating an approximately 16m wide masonry structure. Similar to the signal from the covered bridge at Spean Tor, the anomaly has the form of an arch. Below the structure a small channel or gap is visible. The anomaly's location corresponds to an embankment that reaches the *baray* from the northeast. Pottier mapped a masonry structure CP758 inside the embankment, and assured that it is located on the western side of the dike.[903] Therefore it is unlikely that the mapped structure, located 200m further to the east on the eastern side of the dike, is associated with it. CP758 is possibly related to another mapped anomaly, IB_DAT_0151_296-304m, or IB_DAT_0151_244-260m, see Fig. [104], however it is not clearly recognizable as a masonry structure by GPR. Another long linear feature was detected at IB_DAT_0151_52-80m. Other anomalies might be related to natural features or breaches in the embankment, e. g. anomaly IB_DAT_0149_420-472m, a deep channel detected in a depression or breach of the embankment. At this point in the rainy season a small natural stream runs slowly into the *baray* - it can already be found on the EFEO map of 1940.[904]

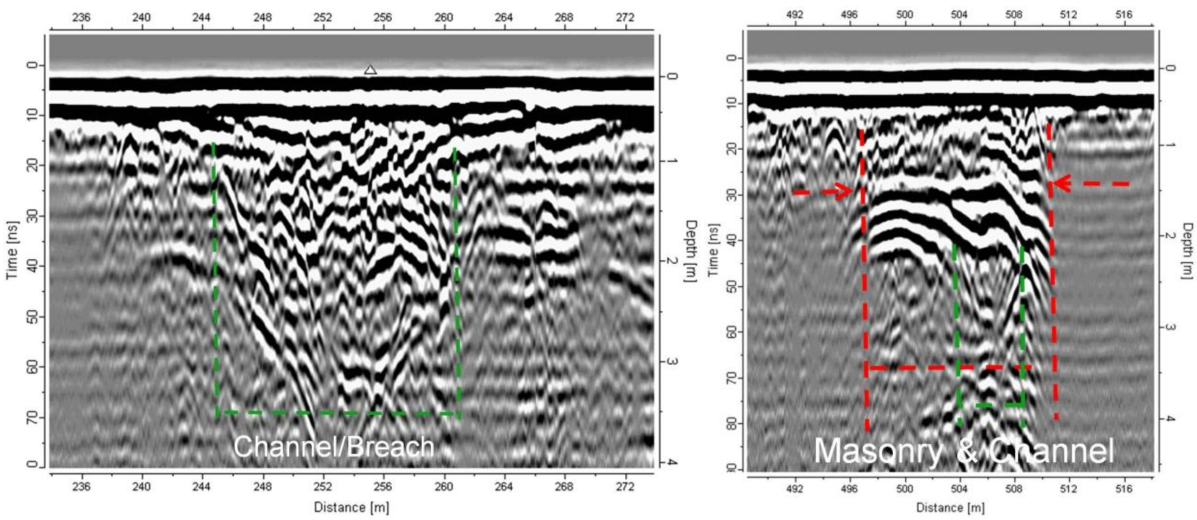


FIG. [104]: THE POTENTIAL INDRATATAKA INLET IB_DAT_0151_244-260M & MASONRY AT 496-512M.

Potential Outlets in the Eastern Embankment

GPR surveys on the road which runs about 50m parallel east of the reservoir's east embankment, detected several anomalies worth mentioning. Anomaly IB_DAT_0170_64-86m in the northeast corner displays a very clear channel feature of several sedimentary layers in between 200-250cm depth, see Fig. [105]. It corresponds to a topographic depression that is potentially a canal overseen by remote sensing - it is visible from the road running in E-W direction toward the River Roluos. In analogy with the assumed construction history of Krol Romeas, its position on the east side could even make it a former outlet; the proximity to the north-eastern corner however suggests it was used as an inlet. An excavation conducted by GAP that crossed the channel N-S found evidence for a channel.[905]

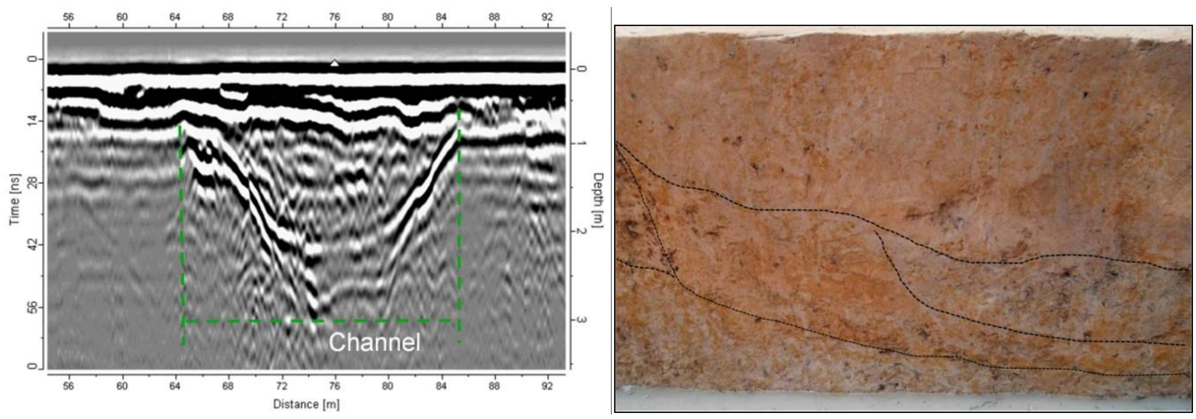


FIG. [105]: GPR RESULT IB_DAT_0170_64-86M AND EDGE OF THE CHANNEL REVEALED IN EXCAVATION (IMAGE: GAP/PLAYER).

A very strong signal response was received from an approximately 20m wide massive linear anomaly (IB_DAT_0170_364-384m, see Fig. [106]). The anomaly is visible on two radargrams that were taken about 5 m apart in N-S and S-N direction on both sides of the modern dirt road, see Fig. [106]. It appears at 30 ns depths (approximately 150cm) and ends below 40ns (approximately 200cm). Measurements using JICA 2003 GIS topographic data revealed that the discovered anomaly is directly in alignment with the centre axis of the *baray* embankment, and that there is a gap in the embankment at this location. The virtual extension of the central axis of Lolei temple passes the eastern embankment further north of the anomaly, and is therefore not in alignment with the outlet. In regard to the other *baray*, see further below, this could be an indication that the *mebon* and outlet were not contemporary constructions.

Following the discovery of the anomaly with GPR, the excavations by the GAP[906] revealed a flat 20 m wide lateritic masonry surface with clearly defined border stones at the western and eastern ends. An additional field survey in a sand quarry, conducted by GAP to the east of the excavation, detected a chaotic cluster of laterite blocks within the alignment of the laterite pavement excavated at the road. This led to the assumption that the laterite platform had originally continued all the way to the river bed, and the eastern part had afterwards been destroyed by flood water. The displacement of a laterite pavement due to strong flooding is not uncommon in Angkor as there is evidence at Bam Phean Reach[907] and Koh Ker.[908] This again would imply that water had been running over the platform, and supports the idea that the laterite floor is part of a former outlet. Its alignment with the central *baray* axis indicates that it was constructed contemporary to or later than the enlargement of the *baray*.

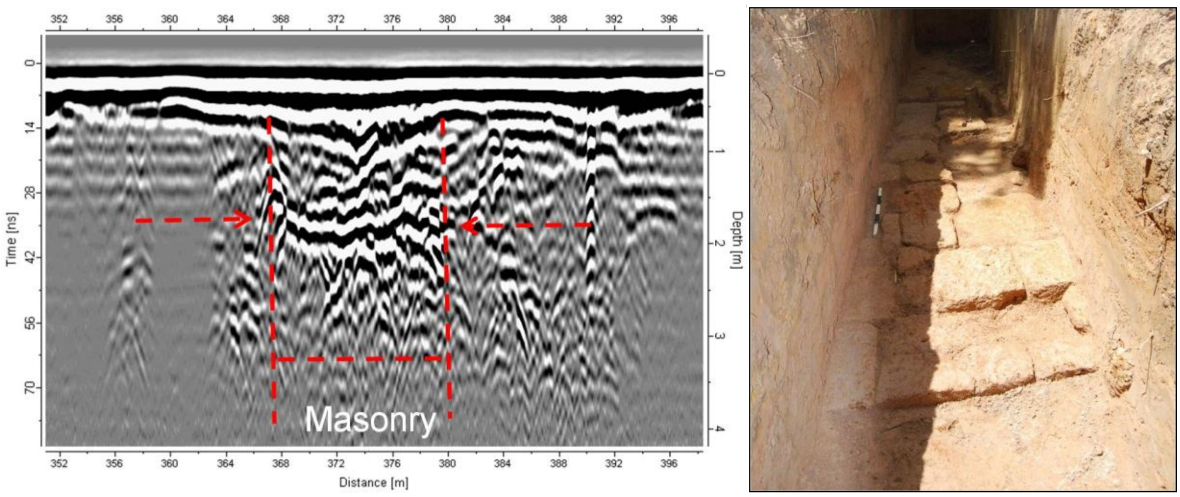


Fig. [106]: GPR result IB_DAT_0170_364-384m, indicating masonry, and following excavation of masonry pavement (Image: GAP/Player).

Additionally, IB_DAT_0170_724-736m, an anomaly close to the south-eastern corner along NR 6 showed evidence of a channel with potential of a masonry pavement. As the modern road runs in an angle to the embankment, the anomaly lies 100m to the east of the embankment, and could indicate just a channel unrelated to the *baray*.

The combined GPR and excavation results from the Indratataka show that it had potentially several inlets and outlets to adjust the flow into the reservoir. The fact that the masonry floor in the eastern embankment of the Indratataka is in a similar position to that of Krol Romeas, displays continuity in hydraulic engineering, and with regard to the earlier construction of the Indratataka this may have been a structure pre-dating Krol Romeas.

iii. THE WEST BARAY

The West Baray is the largest reservoir constructed by the Khmer. The massive embankments surround an area 7950m in length and 2080m in width.[909] A modern canal, built by the French protectorate in the 20th century, directs water through a concrete bridge into the *baray*, while a modern sluice gate in the southern embankment regulates the water level. The reconstruction and modern utilization of the embankments as roads have also covered any breaches of original inlets and outlets. Since no inscriptions have been associated with the West Baray, its date of construction, as well as reasons for the necessity of another giant reservoir at Angkor, have been under discussion. Jacques and Freeman associate construction or extension of the reservoir with Suryavarman I (AD1002-1050)[910] which would put it into the early to mid 11th century.[911] As for possible reasons, Groslier argued that *"it is not out of the question that Yaśodharatatāka has already been partly silted up at the beginning of the eleventh century* [,]*"*[912] while Dumarçay & Royère suggest that "*neither the enlarging nor the raising of the dykes [of the Yasodharatataka] changed anything."*[913] A complete dysfunction of the Yasodharatataka as a reason was ruled out by Jacques & Freeman:

> *"It has often been stated that this vast lake had to be created because the East Baray had completely dried out. This is a dubious assertion, since Jayavarman V had built a terrace to the east of his palace not long beforehand, and the landing stage leading to the temple of Ta Keo would also have been useless if it did not look out over the waters of the East Baray. There is also an inscription of the thirteenth century which mentions it as still functioning."*[914]

It was suspected by R. Fletcher that the construction of the West Baray started as an extension of a causeway that potentially reached from Yasodharapura to the pre-Angkorian temple of Ak Yum.[915] A stela associated to the temple (K. 752) states the year AD1001,[916] indicating that at least the upper part of the temple was uncovered and in use at this time, and might have been until a raise of the embankment buried most of the temple in a later construction period of the *baray*. The West Mebon temple was placed into its centre either by Suryavarman I.[917] or his successor Udayadityavarman (AD1055-1066).[918] Following the re-use of the *baray* in modern times, in recent years the top part of some embankments of the West Baray, the largest rising up to 10m over the original surface, have been bulldozed, several meters from the top of the *baray* were removed and pushed to the side which has resulted in a wide platform used as a road, making the topographic survey of JICA inaccurate.

Aerial images of a dry West Baray reveal several smaller linear earthworks within the eastern part of the reservoir interpreted as distributor channels[919] about 600m south of the modern inlet, the so called "French canal." A 20m wide channel can be traced in parts running from the West Mebon to the eastern embankment. The channel widens in the east, where two small parallel earthworks, 150m apart and elevated to about 50-100cm, reach the eastern embankment close to the central axis of the reservoir. Those embankments gave reason to search for more evidence of an exit channel at the eastern embankment of the West Baray.

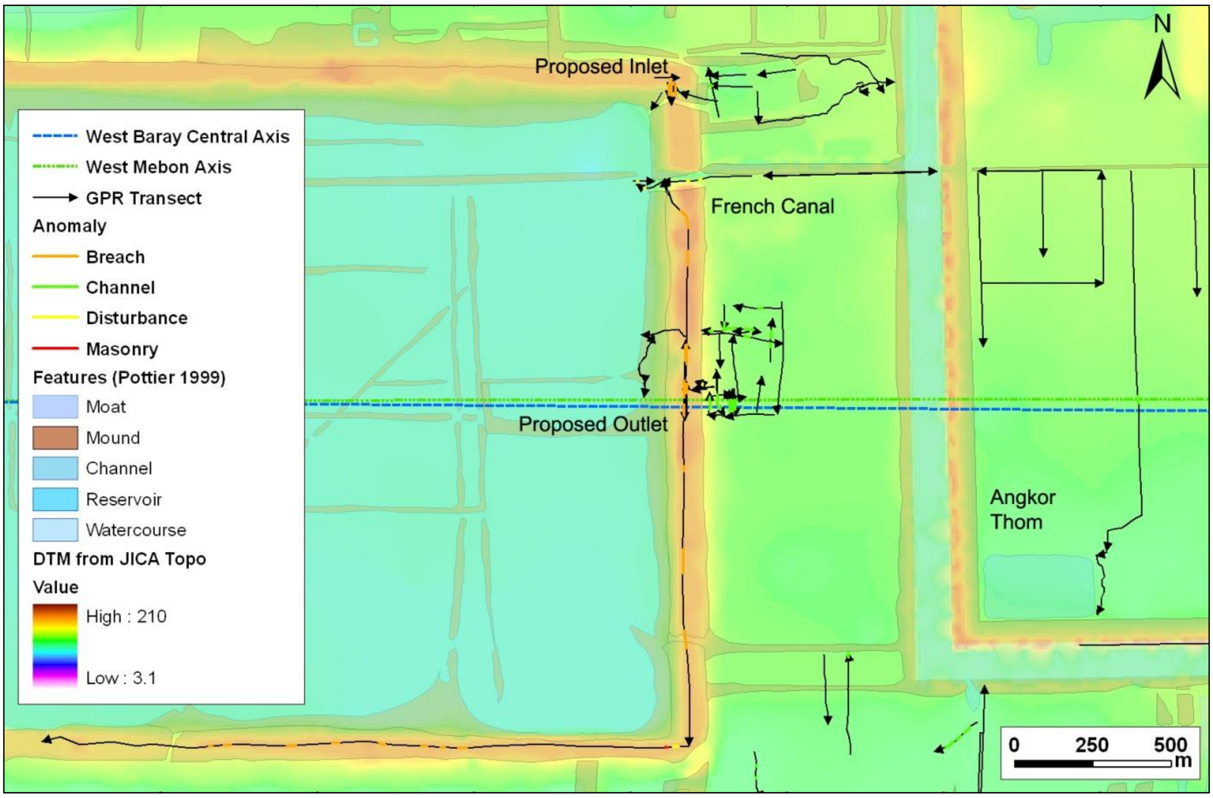


FIG. [107]: THE WEST BARAY SURVEY AREA (BACKGROUND: POTTIER/DTM FROM JICA DATA).

GPR and other Surveys

To search for former inlets or outlets at the West Baray, GPR transects were conducted around and over the north-east corner, over the east and partly over the south embankment, within the dry part of the reservoir parallel to the embankment; and because of the immense height of the reservoir a large number of N-S transects were conducted on the east side of the embankment, corresponding to the two parallel earthworks inside the *baray*.

Inlet

A breach in the north-eastern corner of the *baray* was indicated by Groslier[920] and later identified by Pottier as a potential inlet,[921] as it could be associated with earthen embankment outside the *baray* that were recognized as part of the canal network. The embankment at this location is relatively narrow and some material at the eastern side is removed forming a chasm. The GPR surveys in the area outside the *baray*, see Fig. [108], did not detect anomalies that referred to channels in association to the inlet. GPR profiles on top of the *baray* embankment, crossing the side of the breach, displayed a large anomaly representing presumably the sand-filled part of the breach.

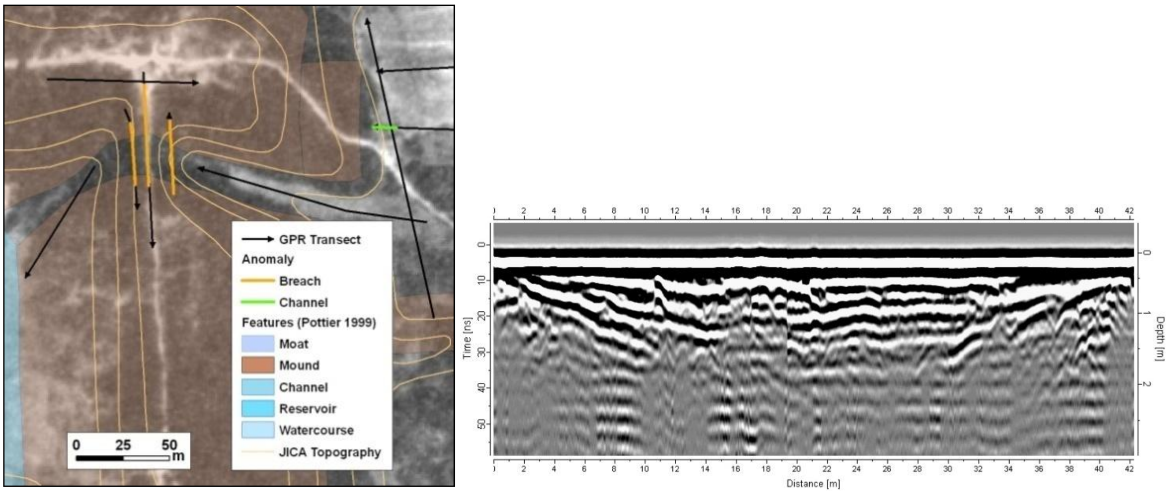


FIG. [108]: LOCATION AND GPR SIGNAL OF WEST BARAY INLET (BACKGROUND: FINNMAP).

Outlet

GPR surveys inside the reservoir between the two small embankments in the central part of the eastern embankment showed no evidence for a continuation of the channel from the West Mebon. Surveys on top of the *baray* embankment revealed large anomalies over the complete east embankment, possibly corresponding to breaches in the wall that had been refilled. The largest breaches were measured in this central area, fewer and smaller in the profile covering the eastern part of the southern embankment. The signal penetration depth of about 300cm did not, however, reach to the base of the *baray* embankment 10m below therefore hindering the search for potential outlets. Due to the embankment height and flooding inside the reservoir, the main focus was directed onto the east side of the embankment. Seven parallel north-south transects were conducted crossing the central axis of the *baray*. The majority reveal slightly dipping feature that could emphasise an about 40 m wide but shallow channel. This feature was measured independently from the rising slope of the embankment. Transects further north to this area reveal evidence of small distributor channels but no similar channel feature was detected.

An excavation[922] following the GPR survey did not discover masonry structures, however, a soil change was detected which is associated to the remains of a former outlet. Two excavation trenches that crossed the central axis of the baray further investigated this potential outlet. The excavation revealed the extent of a channel that dips down in the centre, corresponding to the results from the GPR survey. The construction had later been buried with sand deposits which are clearly different to the clayey sand of the embankment.[923]

When looking for the potential extension of an outlet at this location, aerial photos reveal a linear feature east of the modern road which runs parallel to the east embankment between the *baray* and Angkor Thom. GPR survey at this site was not possible due to too much vegetation, therefore GPR transects was conducted in the southwest quadrant of Angkor Thom. The only anomaly recognizable in the over 1.5km long transect is a channel feature in alignment with the central E-W axis of the West Baray. This could indicate the extension of the canal towards the east before construction of Angkor Thom. Arguably however, the inside of the massive enclosure was heavily transformed at the time of its construction, and is today difficult to interpret solely with GPR; see Chapter (8).

Further south Pottier mapped two parallel earthworks leaving the southwest corner of the West Baray towards Angkor Thom, which have the same width as the southern Angkor Thom moat, therefore apparently a later addition. Only one of the two GPR profiles crossing the connecting two embankments between the West Baray shows an anomaly (PB_DAT_0005_312-324m) that may refer to a small channel. Pottier also mapped 180m earthen ramps on the south of the western side of the southern embankment, and described them as potentially related to exit channels.[924] The southwest corner of the *baray* embankments was breached by Trouvé in the 1930s in an effort to empty the reservoir. The excavations also discovered large wooden posts inside the embankment that, according to Pottier may have been associated with water management,[925] but alternatively they may have had a supportive function for the baray embankment.

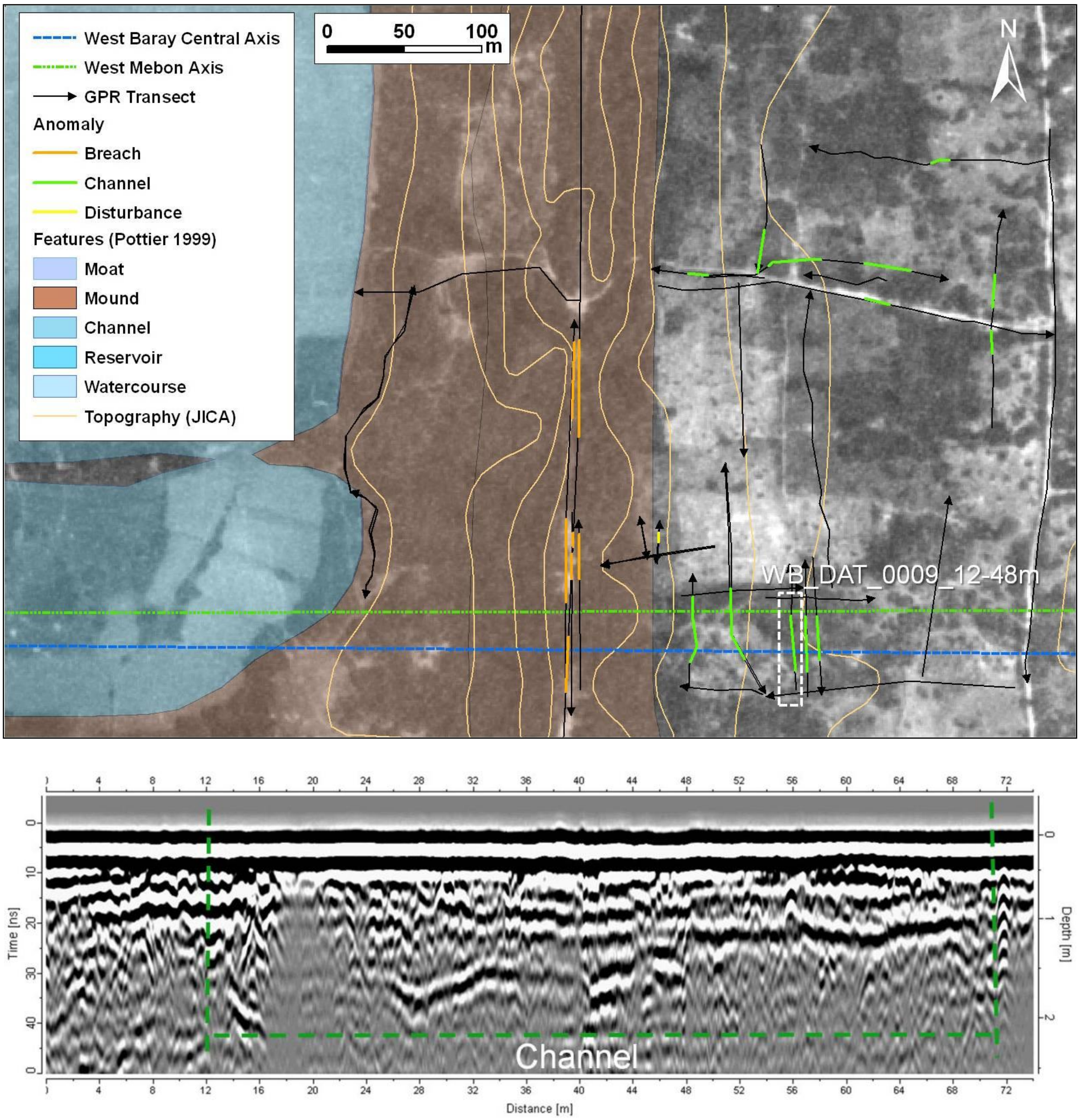


Fig. [109]: Location and GPR anomaly (WB_DAT_0109_12-48m) of potential West Baray outlet (Background: Finnmap).

iv. THE JAYATATAKA

The last of the giant reservoirs, the Jayatataka, was built under Jayavarman VII (AD1181 - ~1218)[926] to the north of the Yasodharatataka and east of the large monastery of Preah Khan (consecrated AD1191).[927] Neak Pean, the *mebon* in the centre of the reservoir, and the temple of Ta Som, have been linked with the same ruler.[928] Ta Som is located east of the eastern embankment and north of the central axis of the *baray*, its outline is slightly inclined to the *baray* embankment.[929] To address whether the last *baray* was ever finished and if and how long it was in use, Dumarçay quotes Zhou Daguan, who possibly described in AD1296 the temple of Neak Pean inside the Jayatataka: *"The northern lake is five li to the north of the walled city. In the middle is a square golden tower, and several dozen stone chambers."*[930]

The 3640m long and 960m wide reservoir is considerably smaller than its two predecessors, but is comparable in size to the Indratataka. The Jayatataka has recently been investigated further. Several excavations were conducted by APSARA at Neak Penh and the *baray*; from 2009 on the reservoir was filled again with water, which is directed through a modern concrete inlet in the northern embankment.

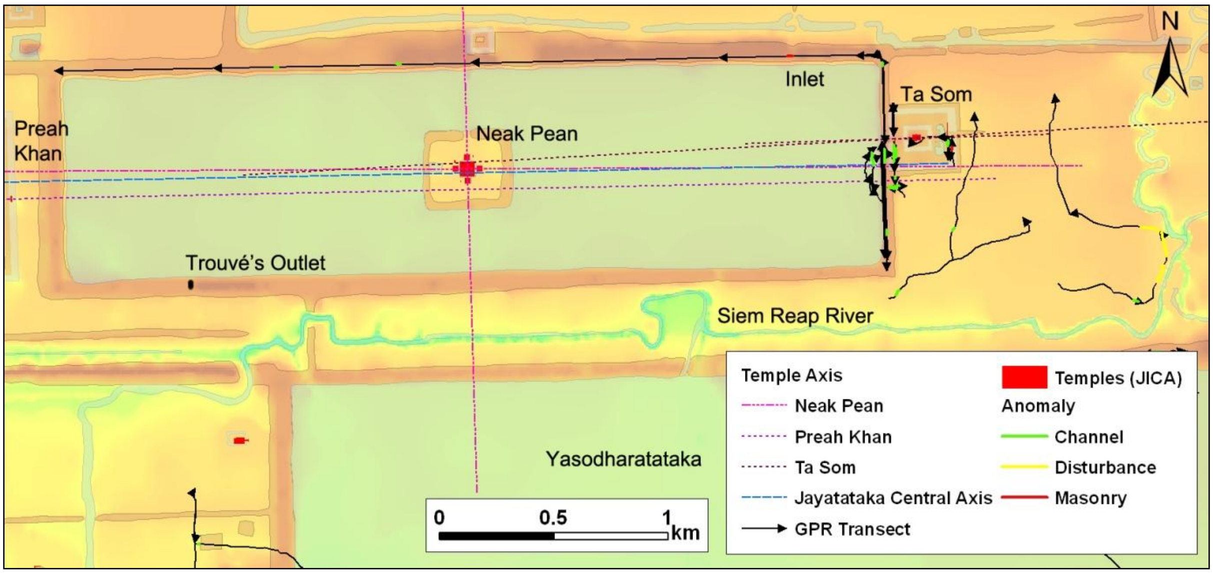


FIG. [110]: JAYATATAKA AND ASSOCIATED FEATURES (BACKGROUND: POTTIER/DTM FROM JICA TOPOGRAPHY).

The GPR Survey

Following the findings in the other reservoirs, GPR surveys were conducted on the road of the north and east embankment of the *Jayatataka* to look for additional inlets and outlets former of the reservoir. The survey concentrated on the area around Ta Som temple due to its location in relation to the *baray*.

Inlet

There is a known masonry inlet located about 400m to the west of the north-eastern corner of the reservoir,[931] see Fig. [111]. The central part is covered by the asphalt surface of the modern road; however the southern part of the structure is exposed, showing two parallel masonry walls of carved laterite blocks, about 2m apart, and a few laterite blocks are visible to the north.[932] The GPR survey over the road provides a clear signal of the outline of the structure below the surface. The resultant anomaly served as a sample signal to identify additional masonry inlets at the other reservoirs. Other anomalies that were measured over the complete length of the northern embankment by GPR could not be clearly identified as masonry structures or potential inlets.

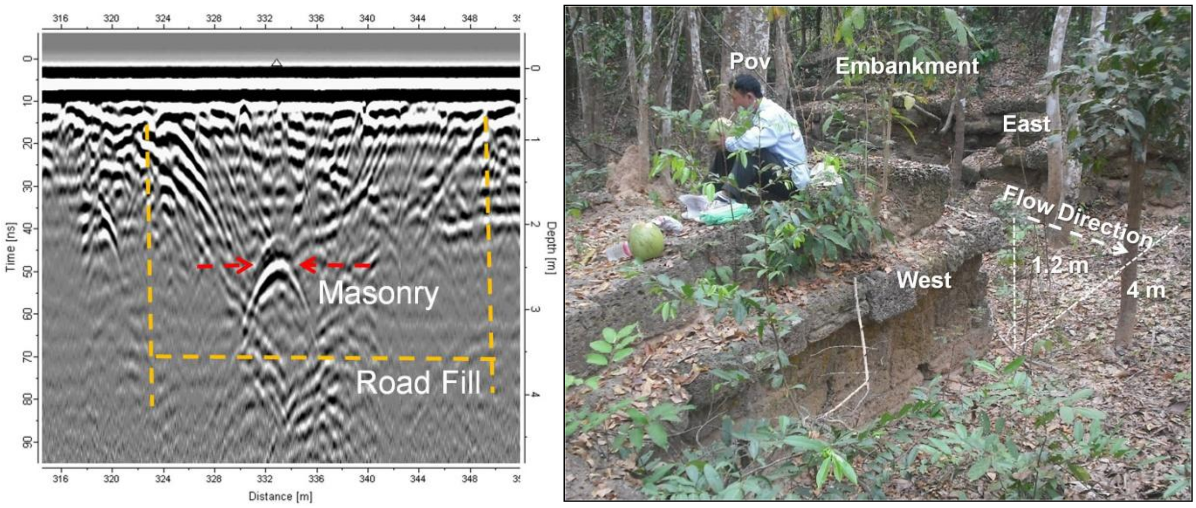


FIG. [111]: GPR ANOMALY OF JAYATATAKA INLET (JB_DAT_0043_ 324-342M) AND IMAGE OF SOUTH SIDE.

A Potential Outlet and Ta Som Temple

Trouvé described laterite remains near the western end of the south of the Jayatataka he interpreted as the former outlet of the *baray*, supported by the presence of a depression along the East West axis, a potential channel that might be related to the moat of Angkor Thom.[933] There is also a gap in the JICA topography data displayed 600m east of the south-western corner of the reservoir.[934]

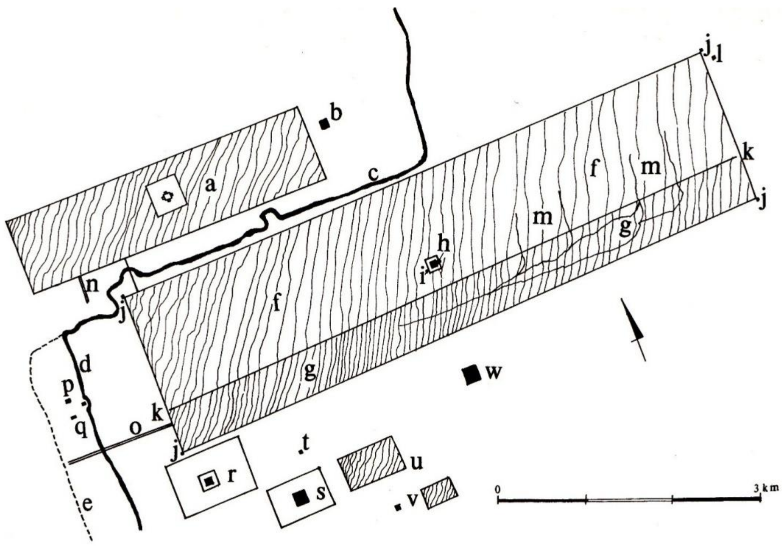


FIG. [112]: DUMARÇAY'S INTERPRETATION OF THE NORTH-EASTERN *BARAY*. K) ORIGINAL STELA LOCATION O) OUTLET YASODHARATATAKA N) OUTLET JAYATATAKA (SOURCE: DUMARÇAY, 2003, P.50).

In Dumarçay's model of the construction chronology of the *baray*, an outlet is displayed close to the south-western border on the southern embankment towards Siem Reap River; see Fig. [112].[935] Dumarçay saw it as a later addition to the *baray*.[936] The area was however not accessible for the GPR at the time of the survey.

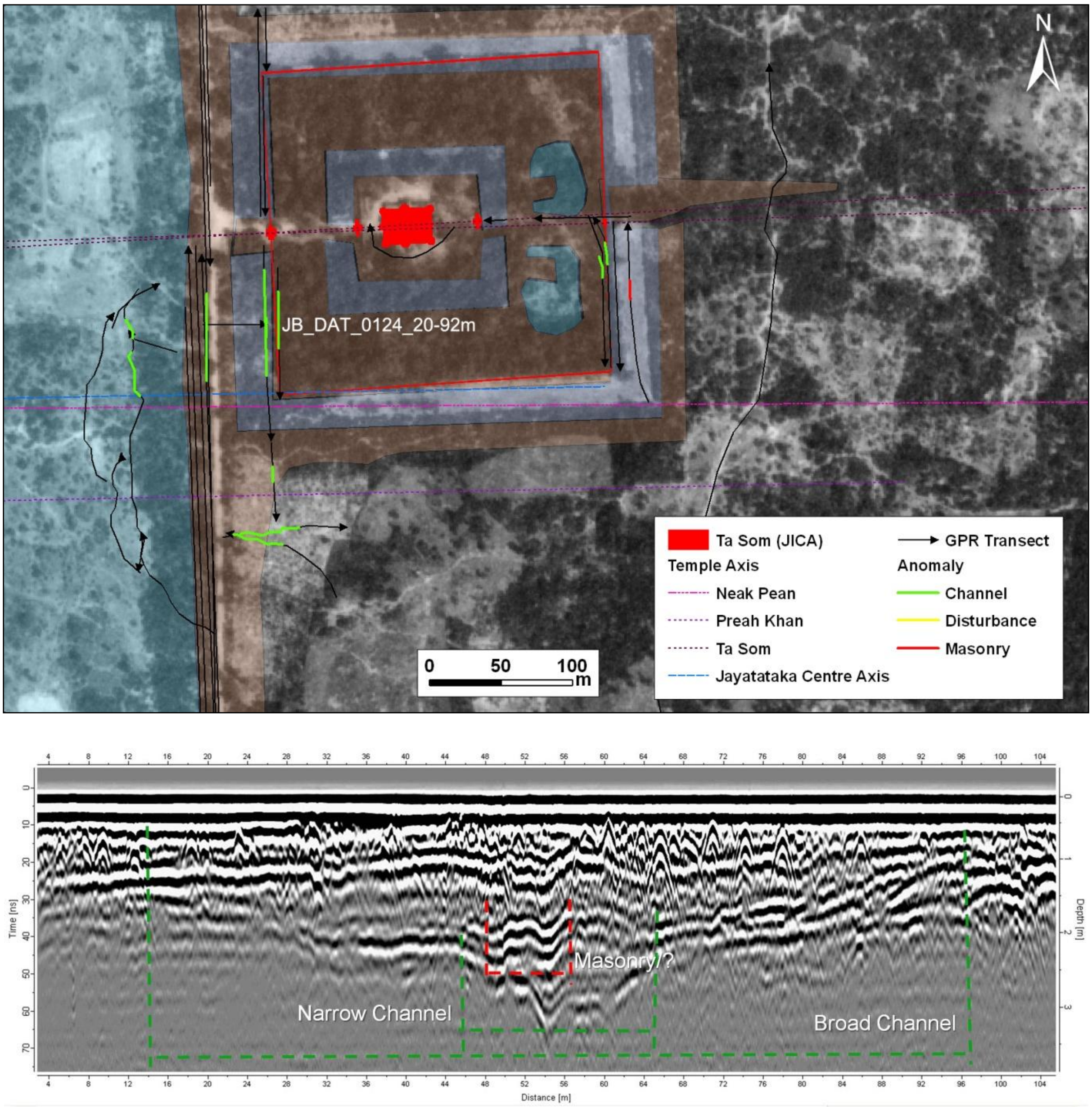


FIG. [113]: ANOMALIES DISPLAY POTENTIAL OUTLET AT TA SOM (BACKGROUND: POTTIER/FINNMAP), ANOMALY JB_DAT_0124-20-92M.

The search for a potential outlet was concentrated on the eastern side of the *baray*, see Fig. [113]. The GPR results give no evidence of a potential outlet associated to the central E-W axis of the *baray,* nor to the extended central E-W axis of Neak Pean, which both are in line with the southern moat of the Ta Som. However, GPR profiles in- and outside the southern part of the west wall of Ta Som display a 60m wide linear feature dipping towards the middle of the radargram with an approximately 15m wide channel feature in its centre at about 60ns depth (approximately 3m depth). Additionally a drill core down to the feature was taken in front of the southern wall at the slopes of the channel feature; the bottom of the core was a compact surface at about 150cm depth, approximately at the same depth as the recorded anomaly. The two profiles were not sufficient to determine either the direction or extent of the potential channel, but several additional N-S transects inside the *baray*, on the road, each parallel to transects at wall, showed similar anomalies that supported the hypothesis of an E-W outlet of the *Jayatataka* in this area.

GPR surveys to the east of Ta Som show no sign of any channel that could have directed the water to the Siem Reap River. However, if there had been a channel, it could have run beside the embankment to the south, thereby corresponding to the channels found at the Yasodharatataka and Indratataka. Evidence of a channel was revealed on an E-W transect south of Ta Som. The problematic issue however is that an outlet at this location would have run into the west wall of the outer end of Ta Som. The fact that it is situated in front of a temple, construction of which has been associated with the same ruler as the Jayatataka, makes the existence of a former outlet at this location unlikely. Presuming, however, it is a former outlet, it could be explained by assuming a different chronological order of construction:

- Ta Som temple was built after the *baray*, and the original outlet was moved to a different location, which has not been discovered. Several aligned laterite blocks next to the road south of the temple indicate other preceding constructions that were removed.
- The outer enclosure wall was built later than Ta Som temple[937] and the *baray*; the structure could have been used therefore as an outlet over a period of time. The southern part of the outer enclosure of Ta Som is lower than the rest of the enclosure, indicating that this could have been the original channel. The inclined angle of the moat compared to the *baray* and the location of the temple being off the centre axis, speak for a later addition compared to the temples of Preah Khan and Neak Pean, which align exactly with the *baray*.

Support for a later construction of the Ta Som comes from architectural comparison of the Bayon style monuments by Cunin[938] and magnetic susceptibility measurements on the sandstone by Uchida *et al*.,[939] who place Preah Khan (described by them as period: VIa and VIb) and Neak Pean (VIc), the two temples associated with the construction of the Jayatataka, into an earlier construction period than Ta Som (VIII). Only archaeological excavations could clarify the existence of a potential former outlet.

v. Implications Drawn from the GPR Survey

From the evidence presented several conclusions can be drawn about the *baray* as part of the water management system:

- Each of the baray has evidence of inlet/outlet structures. Several are masonry structures, and close to the northeast corner of the reservoir, which at Angkor are the most elevated point of the interior of the *baray* and the general topography. Some of the inlets have been known before.[940] All historic inlets were buried under embankments that serve now as roads, which might have been one of the reasons that they were sometimes not observed by other scholars.

- The geophysical survey and subsequent excavations have shown that at some point in time each *baray* had at least one exit channel in their eastern embankment. While the role of Krol Romeas in the construction history of the Yasodharatataka is now relatively well understood, the outlets in other *baray* are not as apparent. It seems to be quite clear however, that water was distributed from the *baray* to other locations when the reservoir was filled.
- The existence of inlets and outlets shows that the *baray* were embedded in a vast network of canals - originating from redirected former natural rivers, which channelled the water into the reservoirs, and reaching a high water level, directed the water out of the *baray* east and then southwards. Additional canals further down slope could have distributed water across the landscape or disposed it in the Tonle Sap.
- Most inlets and outlets were at some point in time covered by the embankment as the function of the reservoirs changed when they were disconnected from the water source and the water management system.

(b) OTHER WATER RESERVOIRS

i. IN THE ANGKOR REGION

Srah Srang

The smallest of the large reservoirs at Angkor is unusual not only in size (only 790m x 410m) but also in structure, sometimes described as a *baray* or *trapeang* as it displays structural features of both types. The whole interior of the reservoir was dug out and is below the surrounding ground surface; as a result it is filled with water all year round. In the 19th century, Bastian mentioned that in the centre of the reservoir, at that time the only one still filled with water, there were the remains of a pavilion.[941] Today, at the end of the dry season a shallow mound of stone blocks can be seen in the centre of Srah Srang that could be the remnants of the structure referred to by Bastian. The EFEO map of 1940 displays a channel that reaches the reservoir from the east. In 1964, within the archaeological survey at Srah Srang in which the Angkorian cemetery was excavated, Groslier discovered a small linear masonry channel that ran parallel to the western embankment for over 100m, but without a direct connection to the reservoir.[942] Groslier associated the channel construction with Jayavarman VII, who is also regarded responsible for the extension of the reservoir and its complete encasing with masonry.[943] A modern inlet is 120m north of the southeast corner. A large GPR grid was laid out in the mid 1990s by Y. Nishimura and D. Goodman in an area to the west of Srah Srang that detected a large linear feature which was interpreted as a wall associated to Banteay Kdei.[944]

The GPR Survey

A GPR transect conducted beside a modern canal passing Srah Srang on the eastern side detected a channel anomaly (PR_DAT_0005_372-420m) that could possibly correspond to the double dotted line that is featured on the EFEO map of 1940, likely representing a channel, which lies within the extension of the axis of Srah Srang, see Fig. [114]. However, the EFEO map displays several channels not corresponding to the results from recent mapping campaigns or identified in aerial imagery.[945] Several breaches, mapped by GPR, were associated with parts of the masonry embankment that had slumped to the inside.[946] The GPR signal penetration depth was however very shallow, not more than 50cm. To analyse the ground composition of the embankment, a core was drilled which revealed extremely hard clay of very fine particle size.[947] To conclude, the survey conducted on the embankments surrounding Srah Srang did not reveal any anomalies that could be evidence to former inlets or outlets. On the other hand the low ground surface of the excavated reservoir could have made an external water source for Srah Srang unnecessary as there was enough groundwater all year round.

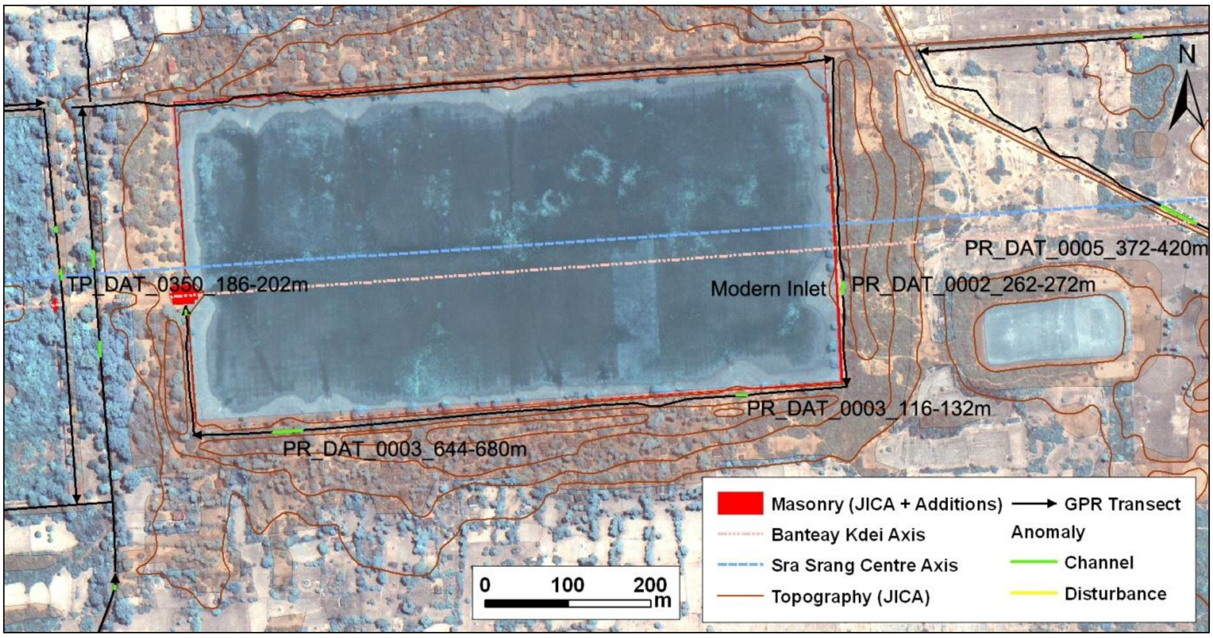


FIG. [114]: ANOMALIES ASSOCIATED WITH SRA SRANG (BACKGROUND: POTTIER/IKONOS).

Chau Srei Vibol

Traces of earthen embankments and linear canals in remote sensing images[948] give reason to consider the existence of a reservoir at the east side of Chau Srei Vibol. The rectangle that forms the outline of this potential *baray* has the same size as the outer moat of Chau Srei Vibol. Eastern and northern embankments are visible, while the existence of the southern and western embankment is uncertified and only traceable as a canal feature, see Fig. [115]

Evans mapped a pond and a small mount in the centre of this proposed enclosure.[949] Indication of a special status of this mound is the east road to Beng Mealea, which passes from the eastern gate of Chau Srei Vibol through the centre of the potential reservoir. After the central mound, the road becomes a double embanked canal that runs for about 5km to the east, before the embankments become one again and continue as a road. However, a field walk in this area did not reveal any remains of masonry structures or ceramics on the mound that could speak for particular importance of this area or use as a *mebon*.[950]

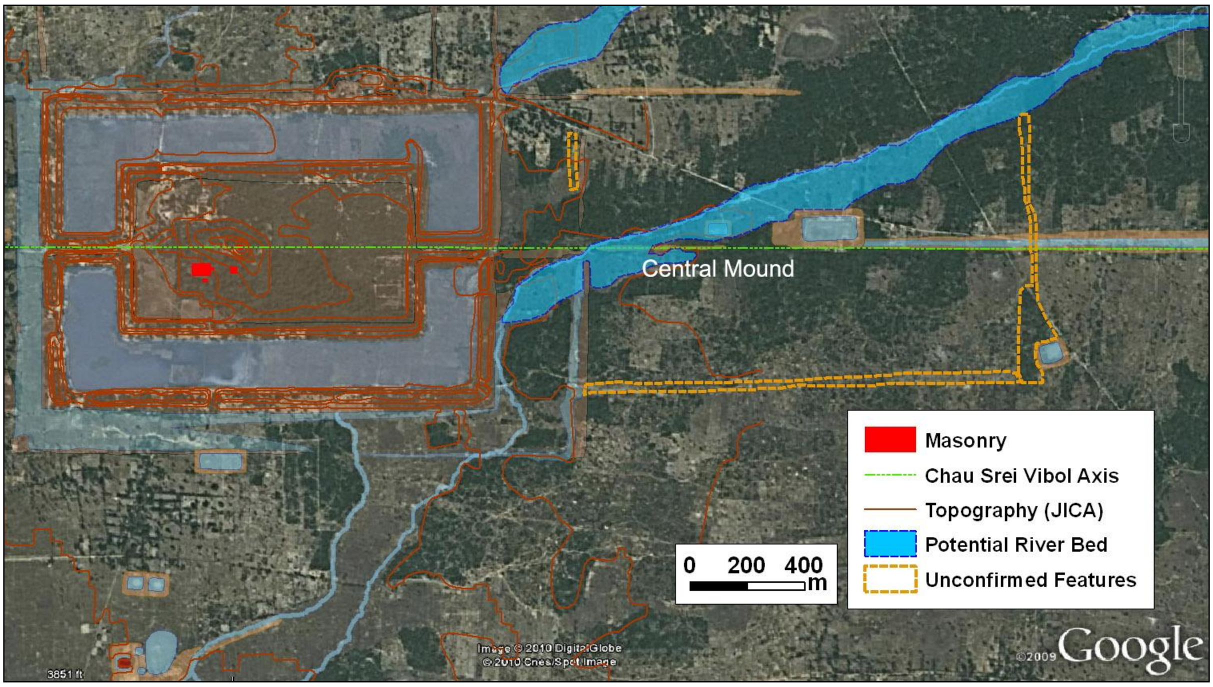


FIG. [115]: POTENTIAL RESERVOIR OF CHAU SREI VIBOL (BACKGROUND: POTTIER/EVANS/GOOGLE EARTH).

ii. RESERVOIRS BEYOND GREATER ANGKOR

Besides the *baray* at Angkor, several other large reservoirs were constructed in the Angkorian period at regional centres, such as the *Rahal* at Koh Ker *(*early 10th century), and the large reservoirs of Beng Mealea (ca. 1075),[951] Preah Khan of Kompong Svay (ca. 1170)[952] and Banteay Chhmar (associated to Jayavarman VII, late 11th to early 12th century). Not all *baray* are easily accessible, but some have recently been investigated by different research groups,[953] and were visited by the author, and to some parts examined by using GPR. Each of the reservoirs is a special case in relation to the topography of the landscape and their connection to a water source. The information gathered about their location and orientation, potential inlets and outlets from other *baray*, as and well can contribute to a better understanding of the possible functions of the reservoirs at Angkor. Dumarçay & Royère mention the problems involved when a functioning system is copied into a different landscape:

> *"At this time the baray system spread to the provinces and can be seen at Ben Melea and at the Preah Khan of Kompong Svay among other places; these were vast retaining areas comparable to those at Angkor, and must have created problems for their filling with water and maintaining them."*[954]

Koh Ker

The Rahal of Koh Ker is located southeast of the main complex of the temples and orientated in perpendicular to the main axis of the temple pyramid Prasat Thom.[955] While the construction date of the reservoir was credited to Jayavarman IV,[956] it has been argued by Dumarçay and Royère that it was constructed before Prasat Thom, which became state temple in AD928, and the temple complex was orientated in relation to the *baray*. The whole complex, unlike the orientation of the main E-W axes of Angkor, is angled to about 10 degrees to the north. The northern and western embankments of the *baray* are massive earthworks, and only a small part of the southern area has been excavated.[957] There is a slightly higher ground in the centre of the reservoir, see Fig. [116]. Neither GPR profiles conducted by the author nor a ground survey have however shown any evidence of structural remains of a *mebon*.[958]

Inlets and outlets

Survey evidence indicates there is no evidence of an artificial inlet into the *baray*.[959] The water probably accumulated naturally from rainwater, followed two small creeks into the reservoir from the southeast and east[960] or spilled over the natural embankments in the south.

There is a breach functioning as an outlet in the northeast corner, the lowest part of the reservoir. The breach describes an irregular S form into the embankment; the hard, lateritic soil of the embankment makes it however unlikely that the water had carved its bed naturally over time. Several laterite blocks were found in its vicinity, covered in concrete. An excavation was conducted by E. Llopis (ASPARA), who described two construction stages of the embankment, one with a core of laterite masonry and a second of soil and laterite blocks, and interpreted the modern outlet as a Khmer Rouge addition.[961] If there had been a preceding Angkorian outlet at the southern side, it would have needed some kind of sluice gate to manage the water level of the reservoir. There is however no evidence of canals to the north of the embankment that could have distributed the water.[962] By mapping large earthen and masonry embankments to the north of Koh Ker, Evans has shown that this region could have worked as a large catchment area for the natural stream, and that there was therefore no need for the *baray* to provide large quantities of water for rice growing.[963]

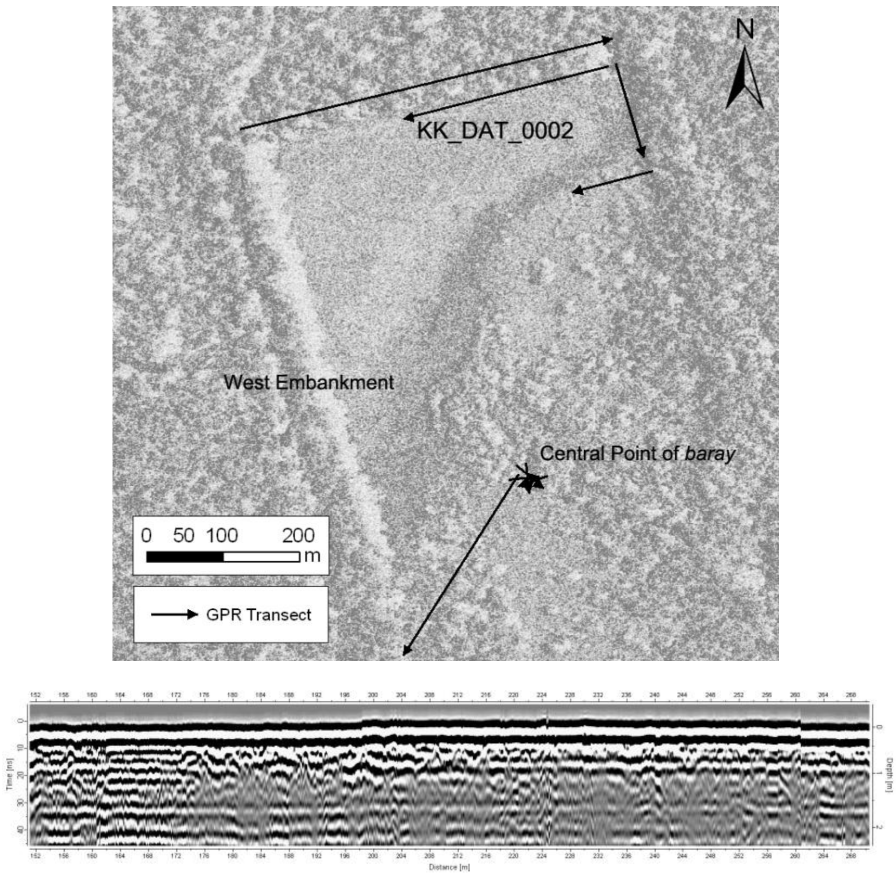


FIG. [116]: GROUND COMPOSITION MAY HAVE PREVENTED THE SEARCH FOR WATER MANAGEMENT FEATURES AT THE RAHAL, KOH KER (BACKGROUND: TERRASAR-X). BELOW: PROFILE KK_DAT_0002.

Banteay Chhmar

The reservoir of Banteay Chhmar[964] is located to the east of the main temple, oriented in the same angle which is just slightly off the east-west direction. It has a size of 1690m x 790m. A *mebon* is located in its centre that is surrounded by a double row of earthworks with a water filled moat separating them. A large causeway, starting from the central axis of the reservoir, connects it with the temple complex. The outer moat of Banteay Chhmar reaches the *baray* embankments but is not directly connected to it. The inside of the raised earthen embankments is completely covered by several steps of laterite stones, making it the only masonry framed large reservoir besides Sra Srang.[965] J. Goodman suggested the laterite comes from inside the *baray*,[966] GPR surveys inside the reservoir near southern embankment have however not detected a clearly identifiable lateritic subsurface.[967] The reservoir slopes from the southwest towards the northeast, where most of the collected water nowadays accumulates by precipitation.[968]

Inlets and outlets

A canal reaches the southern embankment in a straight line from the southeast but is blocked by the embankment, see Fig. [117]. The laterite staircase inside the embankment is not interrupted in this area; if the canal had at one point served as an inlet it lost its function with the masonry framing of the *baray*. It was suggested by Goodman that the canal is older than the reservoir and originally continued further on.[969]

FIG. [117]: TRANSECTS CONDUCTED AT SOUTH EMBANKMENT OF THE *BARAY* OF BANTEAY CHHMAR (BACKGROUND: GEOEYE, COURTESY EVANS).

There is no evidence of a continuation visible on GPR profiles conducted in the interior of the reservoir or outside the southern and northern embankment on the ground, or on aerial images that cover the reservoir. Potentially the main purpose of the channel was to bring construction material from the quarries south of Banteay Chhmar.[970] However, the reservoir has an impressive example of an entry or exit channel. A masonry about three meter wide canal leads through the embankment. The side walls consist of small laterite blocks and reach to the top of the embankment. Two direction changes of 90 degree could have had the intention to slow down the water flow into the *baray*. The masonry base of the channel is destroyed at the inside of the embankment, and laterite blocks are spread out into the baray. Lack of masonry or breaches in the other embankments could indicate[971] that the water may have entered and potentially exited the reservoir of Banteay Chhmar through the southern embankment.

Preah Khan of Kompong Svay

The whole complex of Preah Khan is orientated on a 35 degree angle to the north; this is also the case of the *baray*, the largest of the regional *baray* (2900m x 750m) which is located to the north-east of the main temple complex. The external enclosure wall extends $22km^2$ and meets the *baray* at a 90 degree angle; this relationship means that the *baray* is positioned partly inside and outside the city walls. Slightly north-east off the-centre is the *mebon* situated, from there; a straight canal runs towards the temple but ends at the south-western embankment of the reservoir and the temple of Prasat Staung. It appears as if part of the *baray* has a natural origin, in the dry season the remaining water stays only in a catchment of irregular shape in its centre while the rest of the *baray* runs dry.

Inlets and Outlets

The interior of the reservoir at Preah Khan of Kompong Svay (KS) was recently surveyed by researchers of the University of Sydney,[972] including topographic analysis, coring and GPR surveys. The GPR profiles identified the canal in the centre of the *baray,* which is displayed as a broad shallow anomaly, see Fig. [118]. The relatively flat topography of Preah Khan KS runs from northwest to southeast. Spean Totung Thngay, a masonry bridge that spans the north-western corner of the *baray* was therefore potentially the original inlet.[973] A modern culvert in the south-western embankment works today as an outlet. The search for a potential former outlet was started on the north-eastern embankment, because a small stream as potential water source passes the *baray* to the east. The GPR profile did not display definite evidence of an inlet, but a small but strong anomaly close to the northern corner could be evidence of masonry, see Fig. [118]. The survey however was complicated by the immense height of the embankments; made of lateritic soil they provide very little penetration depth, as well as the landmine threat of the paths. Today the *baray* is purely fed by precipitation.

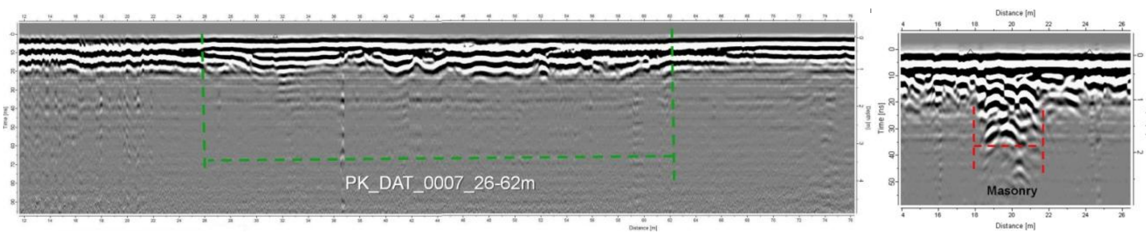


FIG. [118]: LEFT: CHANNEL FEATURE INSIDE THE BARAY OF PREAH KHAN OF KOMPONG SVAY. RIGHT: POTENTIAL MASONRY BURIED IN NORTHERN CORNER OF BARAY.

Ground survey also identified the remains of laterite remains of a masonry inlet for Boeng Kroam, a large trapeang (approx. 950m x 500m) to the northwest of the central enclosure. Several laterite blocks running perpendicular to the embankment were identified inside the north bank on its interior face.[974]

Beng Mealea

No GPR surveys were conducted at GPR. Trapeang Noem, the reservoir of Beng Mealea, an enclosure built in the style of Angkor Wat,[975] is aligned with the temple's outer moat to the west. Its dimension of 1580m x 780m is similar to the reservoir of Banteay Chhmar. The *baray* is connected to the temple complex by a large dyke that finishes at a masonry platform on its western embankment. In its centre is a small *mebon* called Batang.[976] The southern embankment was part of the Angkorian road network leading to Preah Khan KS.[977]

Inlets and outlets

In a drawing of this reservoir, Dumarçay (2003) indicates an inlet.[978] An extension of the temple moat reaches the *baray* at the southeast corner, where the water was directed into the reservoir. However, there is no outlet displayed. There is no published report about any modern surveys targeting additional inlets/outlets,[979] and the available aerial images do not provide enough information for further discussion on the water management.

(c) POSSIBLE FUNCTIONS OF THE RESERVOIRS

i. ATTRIBUTES OF THE RESERVOIRS

The collected information on *baray* and other large reservoirs indicates basic similarities but also marked differences. They vary in their embankment size and extent, orientation and their relation to an associated temple complex, see Tab. [6]. Most of the reservoirs are made of raised earthen embankments. Two large reservoirs, at Banteay Chhmar and Sra Srang, are fully enclosed by masonry. The latter was excavated, similarly to large *trapeang* near temples and palaces as it is the case in Angkor Thom, Pre Rup and Chau Srei Vibol. In the Yasodharatataka, the West Baray and the reservoir Preah Khan of Kompong Svay additional smaller earthen embankments and canals in their interior speak for the channelling of water within the reservoir. The majority of reservoirs were clearly included in a local water management network, displaying evidence of inlets and outlets, and were fed by an external water source, either an artificial channel or a natural creek; Sra Srang must have filled by precipitation or rising groundwater in the rainy season. An area inside the reservoir of Preah Khan of Kompong Svay still holds water all year due to its construction around a possibly natural lake.

Not all of the reservoirs were built upstream from the temple complex as was the case for the reservoirs at Angkor. In the regional centres the *baray* are geometrically included in the configuration of the enclosures. Most of those *baray* are located to the east of a temple complex, arranged in a configuration similar to local temples and their (smaller) reservoirs. A number of the reservoirs have a central *mebon*.

Assoc. Temple	Name	Assoc. Centre	Construction period	Reign	Remodelled	Oriented	Length* [m]	Width* [m]	Ratio	Area [ha]	Mebon	Jetty	Inlet	Outlet	Framed
Ak Yum	?	?	7th cent.	?	overbuilt	E-W	~3870	open?	?	?	?	?	?	?	no
Bakong	Indratataka	Hariharalaya	late 9th cent.	Indravarman I	possibly	E-W	3760	760	4.9	286	Lolei	no	yes	yes	no
Bakheng	Yasodharatataka	Yasodharapura	late 9th cent.	Yasovarman I	yes	E-W	7250	1844	3.9	1337	East M.	yes	yes	yes	no
Prasat Thom	Rahal	Koh Ker	*early-mid 10th cent.*	Jayavarman IV	?	SW-NE	1310	550	2.4	72	no	yes	?	?	no
Banteay Kdei?	Sra Srang	Yasodharapura	10th cent./ 13th cent.	Rajendravarman II	yes	E-W	790	410	1.9	32	yes	yes	?	?	yes
Baphuon?	West Baray	Yasodharapura	early-mid 11th cent.	Udayadityavarman II	?	E-W	7950	2080	3.8	1654	West M.	no	yes	yes	no
Beng Mealea	?	Beng Mealea	mid 12th cent.	Suryavarman II	?	E-W	1580	780	2.0	123	yes	yes	?	yes	no
Banteay Chhmar	?	Banteay Chhmar	late 12th-13th cent.	Jayavarman VII	?	E-W	1690	790	2.1	134	yes	yes	yes	yes	yes
Preah Khan KS	?	Preah Khan KS	?	?	?	NW-SE	1870	750	2.5	140	Pr. Tkol	?	yes	?	no
Preah Khan	Jayatataka	Yasodharapura	12-13th cent.	Jayavarman VII	possibly	E-W	3640	960	3.8	349	yes	yes	yes	yes	no

TAB. [6]: COMPARISON OF LARGE ANGKORIAN RESERVOIRS. EXTENT MEASURED IN GOOGLE EARTH TAKING TOP OF EMBANKMENT CORNER.

ii. FUNCTION OF THE RESERVOIRS

It is likely that the reservoirs had different and sometimes multiple functions. The water management system was expanded over centuries, and the model of new reservoirs must have been influenced by the functioning of existing ones. Several *baray* underwent reconstruction to serve a new purpose. There may have been multiple exit channels in the east embankments of the *baray* at Angkor beginning with the Indratataka, but there is only one known (potential) outlet for the Jayatataka which is the last great reservoir. Due to the specific topography, using the natural the *baray* could work as storage reservoirs. Structures and breaches in the northern embankments of the *baray* at Angkor imply that the water originally entered the reservoir at the most elevated of the reservoir, filling the reservoir up to *mebon* level. However, due to outlets in the east, they would not have functioned in the traditional western sense: to collect the water for distributing it to the fields in the dry season, as a water body always remained inside the reservoir. Large linear embankments north of the Angkorian reservoirs propose additional storage areas that provided water for a longer period in the dry season.

Representation of the "Sea of Milk"

One principal purpose of the exit channels in the *baray* embankments must have been to regulate the water table, so it would not threaten the *mebon* walls, and would provide all year round the view on the *taṭâka*, the representation of the ocean of milk around Mount Meru, which was represented by the *mebon*.[980] The water level regulation happened supposedly automatically, by constructing entry and exit level with the *mebon*, as it can be seen at the Indratataka. As it was the first of its kind, it might not have been as sophisticated as the succeeding reservoirs. Part of the system was possibly managed "by hand," by breaching embankments and directing the water elsewhere, so that the water table in the *baray* would fluctuate not more than a few metres. The small exit channel of a later construction stage of Krol Romeas supports this theory of an organized water management.

Retention & Distribution

Goodman and Sanday propose that *"the function of the baray could have well been special flood control structures designed to protect areas of habitation."*[981] This is similar to the argument of Van Liere, who proposed that "*bunds across the flat valley floor [were used] as flood retardation devices,*"[982] while dams, so at Bam Penh Reach, were large enough to modify major rivers. Fletcher has suggested that the reservoirs were only one part of a system that worked as a water retardation device that has to be seen as a whole; the water was already blocked by several embankments upstream in the wet season and was directed into the reservoir regularly when needed.[983]

Groslier had already proposed that the reservoirs, if not providing multiple harvests, could at least contribute the distribution of water.[984] Regarding the very thin layer of sedimentation,[985] and the rice field patterns inside many *baray*,[986] which cover the complete Indratataka and Yasodharatataka, part of the Jayatataka and most of the West Baray, could the *baray* have served additionally as rice fields in the dry season? When the water went below the height of the outlet the water would have receded continuously, if it was not filled up again by additional storage water further upslope. Groslier proposed that the water reserve in the lowest part of the *baray* could have been used to grow vegetable due to richer deposit of silts.[987] Extrapolated numbers from modern Cambodian rice growing[988] calculating one harvest per year, the Yasodharatataka with about 1200 hectares usable for rice production, could have provided 1200 households, or about 6000 people per year additionally with food. The *Service Hydraulique de l'Indochine* however measured that the water that was annually lost by evaporation did not exceed one meter (80-90cm in the *baray*), and the maximally two meters thick impenetrable clay deposit that covers the subsurface of the plain also made infiltration loss negligible.[989] Without an exit gate, as it exists today in the south embankment of the West Baray, the reservoir would not have lost enough water to be used as an annual rice field.

Retention that served for storage could have been an option however. The fluctuating excess water, totalling several millions of cubic meters of water in each of the reservoirs (calculated by *width* x *area of the baray* x *1m fluctuation* x h*ow often baray was being filled up per year*), could have been used for distribution or simply serving to prevent the water in the wet season to flood the urban area. Ishizawa gives an idea about how this process functioned:

> *"During the dry season, the embankments of the reservoirs would have been cut, then the water would flow slowly downhill. If dikes further down the slope were cut, then the water would flow to the next area, etc. The large areas surrounding the dikes would form large paddy fields, in which rice would then be planted. After the plants had taken root, then the next dike would be cut and the water would be allowed to flow into the next paddy field with only a minimal amount of water left in the uphill field. It could be said that this whole operation was a giant irrigation field."*[990]

To keep the *baray* flooded, this process would explain the need for massive northern embankments of the reservoir, which, due to their location uphill would have been barely reached by water from the interior. They could have then served a function as additional water catchment north of the *baray*.[991]

If the system of the *baray* had not worked, it is unlikely that the Khmer would have continued to build larger and larger reservoirs at Angkor and the moderate-sized examples found at regional centres. The question that requires further study is, how long did this system work? Dumarçay proposed that the system based on the *baray* failed already under Jayavarman VII,[992] which was the reason that from then on no more reservoirs were constructed. The water system was unified and a combination of dam-bridges worked as water catchment.[993] This however is questionable since Jayavarman VII was still responsible for the construction of the Jayatataka in the north, and after this king large constructions of monuments generally ceased. Further evidence to support a well-functioning system after this king is provided by Zhou Daguan who describes two 'lakes' filled with water; these bodies of water most likely refer to the West Baray and the Jayatataka[994]

It is apparent that the *baray* served multiple purposes: as barriers for floodwater, as enclosures enabling and regulating the sacred seas(s) of milk, and potentially as reservoirs for the redistribution of water for agricultural purposes. There is now sufficient evidence to argue that Van Liere's initial quote, *"all this is fiction and not a drop of water of these temple ponds [meaning the baray] was used for agriculture"*[995] has to be revised.

CONCLUSION

The Baray and the Network

The GPR analysis of masonry infrastructure, including dam-bridges, *baray* inlets and potential outlets shows clearly the function of the *baray* as part of the hydraulic network. The research provides new insight into the positioning and function of important parts of Khmer water management systems. The remaining components of the water network of Angkor are predominantly earthen clay embankments of the reservoirs and canals, including the elevated roads, which all might have served a multipurpose as water barriers to withstand the annual monsoon flooding as well as transport routes in the rainy season and even as living areas.[996] The engineers made use of the minor slope of the Angkor floodplain so that east-west running earthworks blocked the direct flow of water and might have worked as retention devices across the Angkor plain,[997] while the purpose of the north to south running canals from the centres towards the south was to quickly discard water towards Tonle Sap. In some circumstances laterite was used to enforce the earthen infrastructure, integrated in some of the *baray* embankments to work as channelling and overflow devices.[998] Evidence found by the GPR surveys for outlets and additional inlets in the embankments of the four large reservoirs of Angkor, implies that the *baray* were integrated in the canal system and cannot be seen as singular devices. Outlets at Angkor were detected in the eastern embankment. This questions the western understanding of irrigation, to use the *baray* as storage to distribute it in the dry season for higher yields. Regardless, the *baray* demonstrate the ability of the Khmer to direct and manage large quantities of water across the landscape.

CHAPTER (8) LANDSCAPE AND NETWORK

'I declare, it's marked out just like a large chessboard!' Alice said at last. (LG, II)

This chapter again widens the view, by looking at a number of monuments and their potential relationship to the surrounding landscape. The water flow system and its components are broadly examined. Redirected rivers, canals, embankments and roads are investigated on their impact on the 'natural' landscape. Long GPR profiles were conducted to investigate the elements of the network. The surveys were planned and the results interpreted in combination with remote sensing data. The entire network of Hariharalaya, which was later integrated into the Greater Angkor water management system, was covered by GPR profiles. Already mapped features were crossed and measured at several locations, and newly discovered anomalies classified. The area also served as a sample site to apply an additional remote sensing method: high resolution SAR data, to analyse the area concerning water saturation. In the central area of Angkor, relations between temples and channels/earthworks were investigated and artificial and natural channels identified which had not been mapped due to dense vegetation. The information from remote sensing data served as the 'horizontal' analogue to the 'vertical' information given by the GPR profiles, to map the extent and depth of channels and complement the archaeological map.

(a) ELEMENTS OF THE WATER FLOW SYSTEM

'I only wanted to see what the garden was like, your Majesty-' 'That's right,' said the Queen, patting her on the head, which Alice didn't like at all, 'though, when you say "garden," - I've seen gardens, compared with which this would be a wilderness.' (LG, II)

i. RIVER BEDS

The floodplain of Angkor is not dominated by one, but fed by several rivers; their tributaries run into the Tonle Sap. Strong seasonal changes in precipitation that bring drought in the dry season and extensive monsoon flooding in the wet season have influenced the run of the rivers. Due to the gentle slope from northeast to southwest, the water would have repeatedly spilled over the banks and formed new river beds. Coring has shown thick sedimentation down to 80m of alluvial sands in the plain that was possibly deposited since the late Holocene,[999] providing an upper deltaic morphology.

Few attempts have been made to model the landscape as it may have been before Angkor. In Groslier's interpretation of early settlement in the region, the landscape was divided into a forest free area at the seasonally-alternating shore line - where occupation would have occurred long before Angkor - and a densely forested and uninhabited area in the elevated regions to the north.[1000] He also indicated the possible outline of the original floodplain and early settlements, where the lake shore and banks of rivers provided the foundation for development.[1001] In the Angkor period the courses of the rivers that crossed the alluvial plain were modified. The streams were blocked and directed south, now those new courses form the artificial beds of the rivers Puok, Siem Reap and Roluos. Following the decline of Angkor, the water broke the Angkorian dykes at some places and found new routes.

Many original channels are still detectable with remote sensing and were partially mapped by Groslier, then in more detail by Pottier; both indicated water filled depressions as potential former beds of natural rivers.[1002] Further analysis of remote sensing data by Traviglia shows various areas the remains of several river beds crossing the floodplain.[1003] Clearly visible on recent satellite imagery[1004] are several former streams following the topography in the northern floodplain of Angkor from the northeast to the southwest.

Those low lying areas are often covered by rice fields. Forest-free and regularly flooded, they appear similar to former meandering rivers in remote sensing images and could be misinterpreted as landscape features preceding the Angkorian earthworks. It is therefore necessary to distinguish the ancient and former river beds from areas with high groundwater level that are annually flooded. The GPR signal disperses quickly and penetration depth is shallow in the clayey sand of the rice fields, simply because the dense soil is saturated by water. Vertical string-like reflections appear in the return signal, possibly from water pockets in the topsoil, but no large disturbances.

In contrast, the anomalies identified as former river beds leave a broad and chaotic signal response that is occasionally deeper than the set travel time window set on the GPR. Surveys conducted where the modern rivers have left their artificial bed show disturbance deep into the surface, where the water was channelled down the steepest slope, providing faster flow and stronger erosion of the loose sediments. The sediments appear similar to that visible in the canals, deposited layer-upon-layer and show different forms of bedding. The image of the soil display parallel layers, cross bedding and truncation of bedding planes.[1005] Single sedimentary layers are identifiable, though typically for alluvial river sediments they are not horizontal, but have deposited along the sides of the river bed. Stevens and Robinson have explained this phenomenon, visible in the GPR survey:

> *"Distributary channels form dense networks of channels that fed active delta lobes. The surrounding facies of highly channelized areas are braided, indicating sporadic and chaotic deposition possibly from overbank sheeting. The highly channelized nature of these deltas, combined with constantly shifting directions of deposition, suggests that high sediment loads dominated facies formation."*[1006]

Survey sites were therefore chosen based upon their visibility on SAR and visual satellite data - in Google Earth as well as other available remote sensing data - and general accessibility. Some disturbances identified by GPR were discovered by coincidence and were later checked with remote sensing data to analyse the anomaly's relation to the surrounding landscape.

ii. CANALS AND EMBANKMENTS

Canals are an extremely visible characteristic in the cultural landscape of Angkor because of their ubiquitous, elevated linear earthen embankments. Pottier,[1007] as well as Kummu,[1008] have shown that some of the canals were constructed almost parallel to the slope and had only one embankment to catch and retain water on one side. Other major canals were built perpendicular to the slope and double embanked. Most canals had been excavated to enhance the water flow and their embankments were raised with the excavated material.

The dense clayey sand found across most of Angkor was used to create near impermeable dykes. In very few occasions masonry was used to secure the sides or the bed of a canal, to withstand the channelling of large amounts of water through a narrow path, such as overspills as seen in Bam Penh Reach,[1009] as well as in Koh Ker[1010] or some entry/exit channels of the *baray*. Similar to other water infrastructure in Angkor, canals could have served several different purposes, such as transport, flood control, water distribution to rice fields, and attract settlement along the embankments. There are indications that some canals were also used to transport goods, e. g. construction material to build the temples.[1011] A series of disconnected linear embankments indicate a canal that led from close to the sandstone quarries of the Kulen to Banteay Samré east of Yasodharataka. The narrow width of the associated channel, only mapped by remote sensing,[1012] could possibly indicate a predominant use for carrying construction material on boats and rafts. The main Angkorian road to Beng Mealea runs further south passing Chau Srei Vibol.[1013] The presumably main canals for transporting goods to the Angkorian centres could have been the canalized beds of the Roluos River from the Tonle Sap to the Indratataka, and the Siem Reap River crossing central Angkor, as they still carry water all year long.

The discovery of additional canals improves and extends the archaeological map. The GPR-surveys mapped a large number of v-shaped soil-filled depressions that could be associated with the water management system. Remote sensing provides information about their orientation, direction and start or end point, while GPR can also further attributes such as width and depth. The anomalies identified as canals differ strongly in depth and are narrower then the features mapped by remote sensing. GPR transects conducted over some larger canals reveal deep excavations in its centre,[1014] which could indicate that part of those canals had water all year long and were deep enough to navigate or pull small boats to transport material or people.

Water Distribution

Groslier's theory of the hydraulic city[1015] included the use of canals to distribute water to the fields. The idea, that small temporary breaches were dug through the embankments of canals to irrigate the associated rice fields, was raised by Pottier regarding the outline of rice field patterns south of the West Baray.[1016] He pointed to the modern use of buried bamboo pipes in the embankments in water transfer from canal to rice field.[1017] One of the associated canals (CP504, in the site register called "Trapeang Pong to Wat Knat canal") started from the checkerboard grid south of the West Baray and continued straight southeast towards Siem Reap River, originally passing through this area as well as the area of the Damdek, a massive double embankment to the east of Hariharalaya from where it continued to run along the lake shore. To test Pottier's hypothesis on small breaches, a 3km long GPR survey was conducted over the embankment of the straight canal south of the West Baray, now used as a rice field; see Fig. [119]. A small earthen footpath runs along the heavily eroded southern canal embankment. The embankment is only slightly elevated compared to the former canal; its original height was not measurable. To facilitate the orientation within the radargrams and to locate the anomalies, the survey distance was divided into four profiles.

The depth of potential breaches in this canal was expected at around 50-100cm, the height of the ground surface below the embankment. The results are rather ambiguous, displaying several large breaches, up to 30m wide.

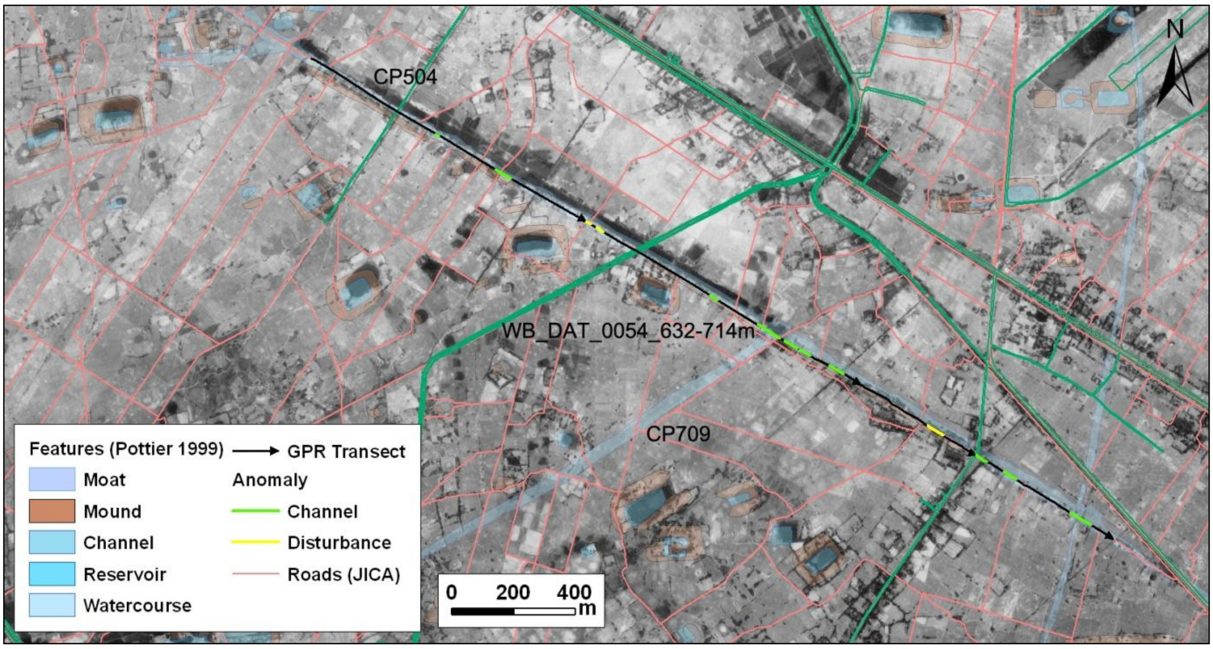


FIG. [119]: CANAL RUNNING TO THE SOUTHEAST FROM THE WEST BARAY (BACKGROUND: FINNMAP).

These breaches may refer to collapsed parts of the embankment or additional channels, visible in the example of the intersection with canal CP709 that creates the anomaly WB_DAT_0054_632-514; see Fig. [120]. Modern irrigation canals were recorded, but no traces of a similar bamboo pipe system in the embankment. Reasons could be an irregularly disturbed subsurface and the intensive use of the embankment as transport route and living space today. An example of modern breaches without the use of concrete shows they do not exceed 50cm width, indicating that there could be a problem of resolution; see Fig [120].

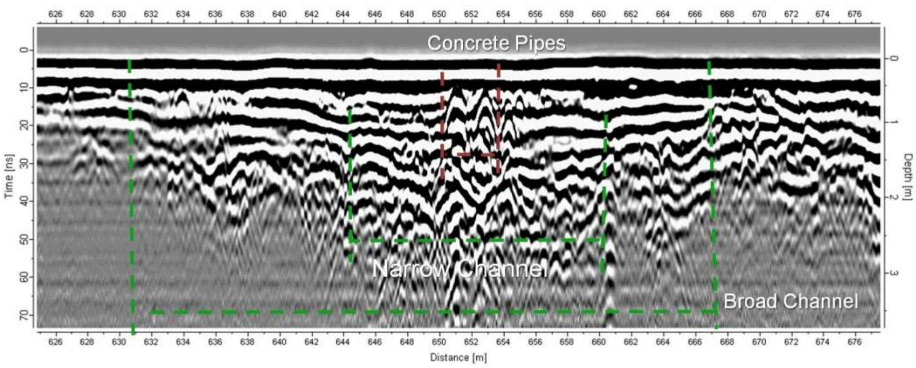


FIG. [120]: LEFT: INTERSECTION OF CHANNELS AT THE SOUTHEAST CANAL, INCLUDING MODERN PIPES. RIGHT: MODERN BREACH AT BANTEAY SRA.

Roads

The straight elevated Angkorian roads greatly impressed the 19th century explorers, such as A. Bastian, who first noted them in his report to the Royal Geographical Society.[1018] The radially-expanding major road network of *"over 1000 km length of raised earthen roads, fitted with support infrastructure (masonry bridges, 'rest houses', water tanks),"*[1019] and has been traced to Wat Phu in the northeast, Sambor Prei Kuk in the southeast, Preah Khan of Kompong Svay in the east, Phimai in the northeast and Sdok Kok Thom in the west.[1020] Roads were constructed from material found on site, the excavation of material left small trenches that filled with water and would serve as canals. This is also the case for the main routes within Greater Angkor, which were the focus of the GPR survey. Hendrickson has reminded lately that a major part of the Angkorian road network consisted of unpaved earthen embankments.[1021] Two archaeological trenches cutting through roads in the region showed no compacted surfaces.[1022]

A GPR survey analysed the potential to identify the interior structural features of an Angkorian road at Prasat Sampou, however as with surveys along *baray* embankments the hardened clayey sand decreases the penetration; see Fig. [121]. Therefore roads could often only be recorded in relation with either small channels on their side, or a down sloping horizon, indicating the start of the different and more compact material. The anomalies of embankments/roads in the topographically uncorrected radargrams were distinguished and classified.[1023] Further surveys were concentrated on the identification of embankments and the potential continuation of roads and temple axes that had not been mapped by remote sensing. Several areas served as sample sites: inside and east of Angkor Thom as well as the raised road embankment which connected Hariharalaya and Yasodharapura. Because the elevated elements of the network had several functions concerning the water management as well as the transport system, anomalies resulting from linear earthworks were summoned as 'embankments.'

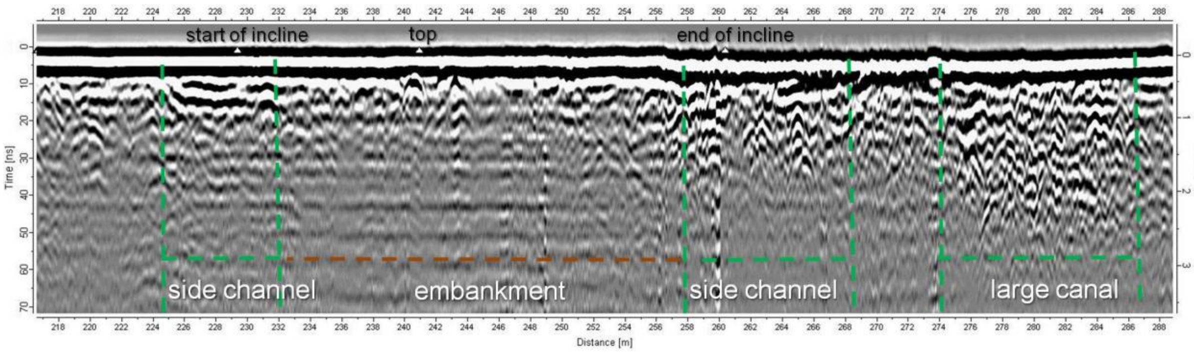


FIG. [121]: GPR RESULT OF ANGKORIAN ROAD AT PRASAT SAMPOU.

(b) ASPECTS OF THE HARIHARALAYA NETWORK

Alice had been trying to wind up, and had been rolling it up and down till it had all come undone again; and there it was, spread over the hearthrug, all knots and tangles. (LG, I)

Hariharalaya, the first capital in the floodplain of Angkor, is situated near the modern village of Roluos. The region was occupied for centuries when construction associated to the Bakong occurred in the 8th century.[1024] Jayavarman III (AD835-877) has been mentioned to have reigned at Hariharalaya.[1025] The main construction period occurred under Indravarman I (AD877-889/886),[1026] and the region developed its characteristics over a short period of time before the court was moved to the Phnom Bakheng in the early 10th century, and left the region mainly undisturbed by further development.[1027]

South of the Indratataka are the main enclosures of Preah Ko, Bakong, and Prei Monti. A system of channels complements a fully functional water management network. The network of Ak

Yum may have had the first water system in the Angkor region,[1028] but was later incorporated by the West Baray. Hariharalaya, however, may have kept its original arrangement as it remained on the periphery of the succeeding and larger network of Greater Angkor. From his understanding of its functioning Groslier constructed the main principles of Angkorian water management,[1029] which again inspired him to call it Angkor's first Hydraulic City.[1030] The complete network with a diameter of approximately 6km, centring on Bakong temple, was mapped in detail by Pottier in the 1990s.[1031]

To study this complete set of water management features as an integrated network, a detailed GPR investigation was initiated. The area had also been chosen as a sample site for TerraSAR-X satellite data; therefore the study combined newly-acquired data sets of surface and remote sensing radar technologies - a useful approach also for assessing the massive network of Greater Angkor. The information from the JICA GIS data served as route planning, the archaeological map as basis for interpreting the detected anomalies. Classification of water management features in this area included natural river beds, canals, moats, as well as structures such as bridges or masonry stone platforms; the overall intent to differentiate them from modern canals and concrete bridges that reuse the old network.

i. THE COMBINED RADAR SURVEY

> *All this time the Guard was looking at her, first through a telescope, then through a microscope, and then through an opera glass. A last he said, 'You're travelling the wrong way,' and shut up the window and went away.' (LG, III)*

Roluos River

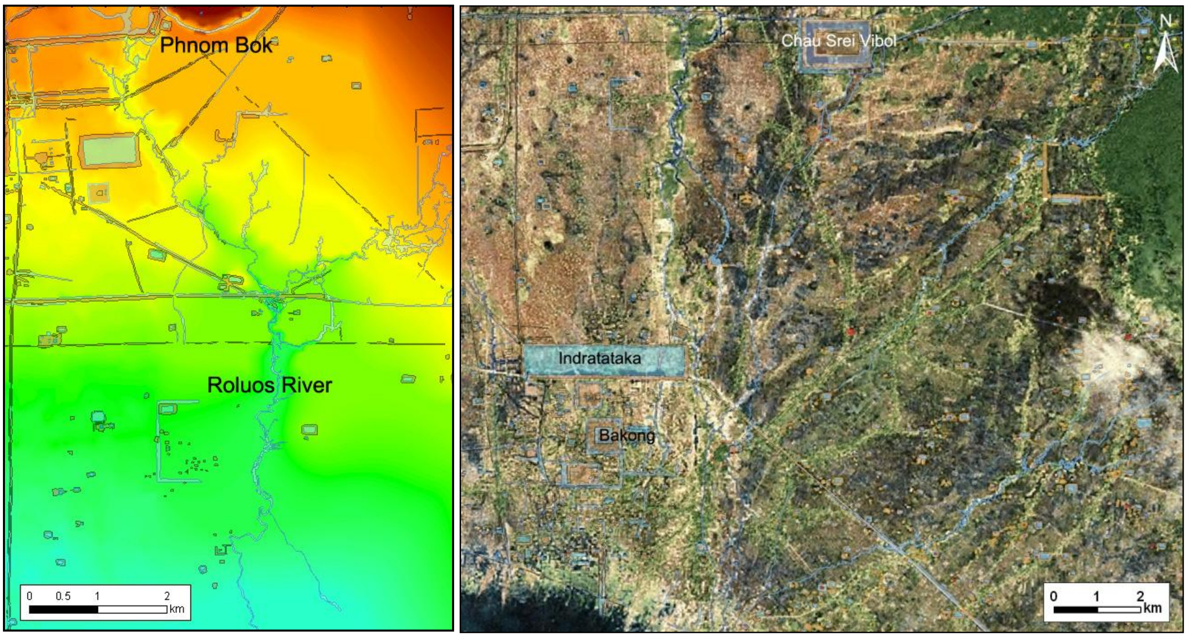


FIG. [122]: LEFT: ROLUOS RIVER BED SOUTH OF PHNOM BOK SHOWN ON DTM CREATED FROM JICA-DATA. RIGHT: RIVER BEDS TO THE NORTHEAST OF ROLUOS (BACKGROUND: POTTIER/ EVANS & LANDSAT7/NASA).

The network was originally fed by a river coming from Phnom Bok in the north - today named Roluos River. Remains of linear embankments alongside the river to the north of the *baray,* and the section running straight south toward the Tonle Sap, show that the river had been canalized. There is a large delta-like channel visible on the DTM created from JICA topography to the east of Banteay Samré. The immense width of several hundred metres of the channel indicates that at least part of the river had been running in this bed from the south of Phnom Bok for a long time. Very few remaining earthworks were mapped by Pottier that would indicate a redirection of the river in this region (see Fig. [122]), artificial channelling of the river is mainly visible close to the north-eastern corner of the Indratataka.

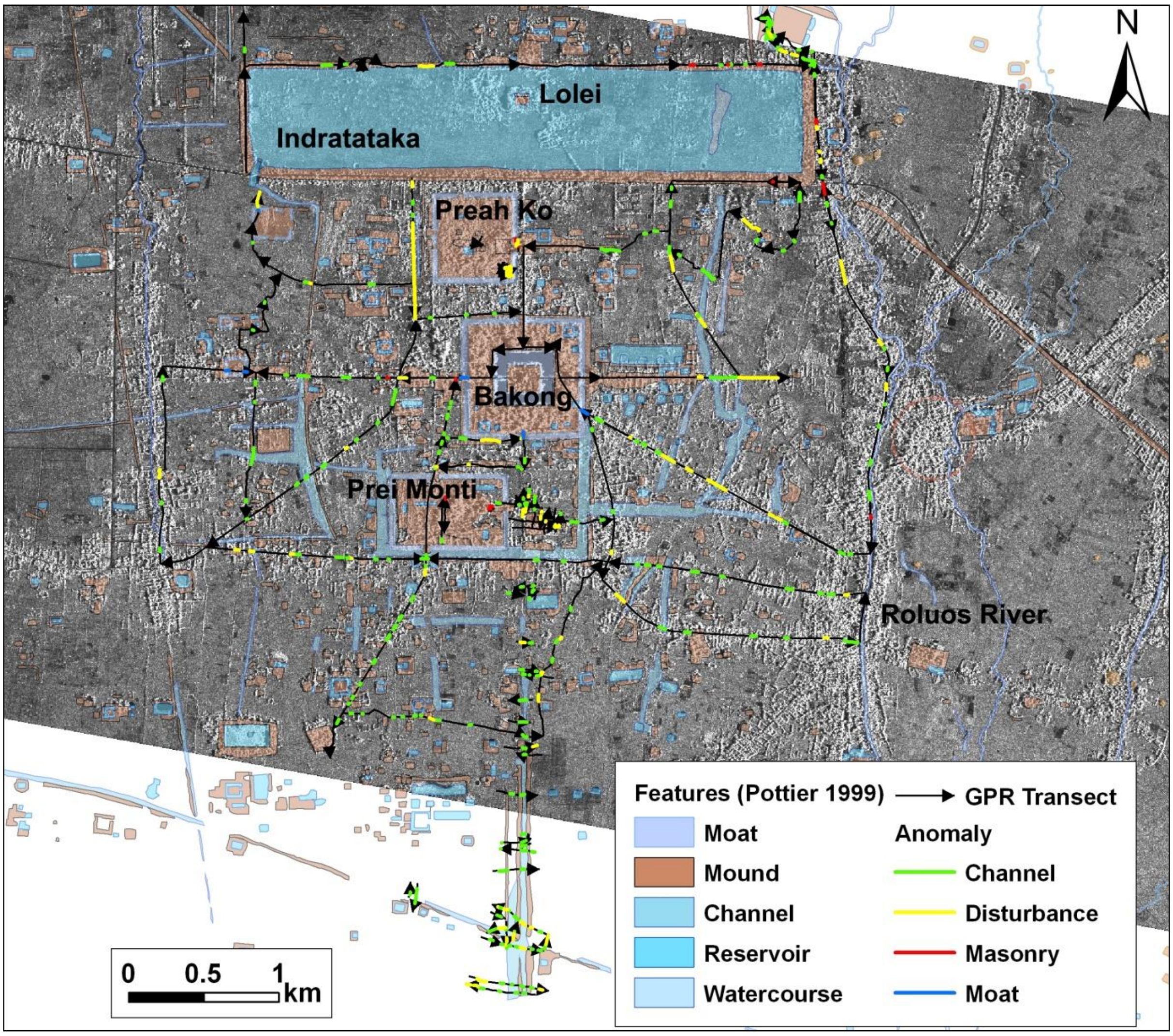


FIG. [123]: THE NETWORK OF HARIHARALAYA OVER TERRASAR-X IMAGE; INCLUDING GPR TRANSECTS AND MAPPED ANOMALIES.

The water today runs past the Indratataka to the east and from the south-eastern corner southwards outside the originally planned, straight course, clearly visible in TerraSAR-X, where the traces of the channel disappear in the broad shore of the Tonle Sap, as it can be seen in Fig. [122]. Inside Hariharalaya, Pottier has also mapped sections of natural river courses in the floodplain, some of which are visible on TerraSAR-X data. Those broad beds may be remains of channels that once ran through the eastern side of Hariharalaya in north-east to south-west direction. Satellite images show several broad water saturated areas in the region northeast of Roluos; see Fig. [122].

Those tributaries from the northeast were intercepted by the Roluos River; left inside the network cut off from their source, the remnants of those channels may have lost their purpose and silted up, and were later used as rice fields. Broad chaotic disturbances have been mapped regularly, often in association with the mapped channels, see Fig. [123]. Where they were not mapped by remote sensing, the possible original course of the water has been mapped anew, showing that the centre may have been built next to an existing natural water source. The Roluos River however was fully integrated into the network.

In the rice fields around the large earthen mound to the east of Prei Monti, which was described in Chapter (3), a series of soil filled depressions were detected, see Fig. [124] When however mapped into GIS, their locations did not coincide with other anomalies or features on the archaeological map to provide enough evidence of remains of a river bed, moat or canal. Because of their irregular appearance, they do not seem to be associated with other features and could therefore have been ponds originally - similar to the ponds visible on filtered remote sensing images north and south of the Yasodharatataka[1032] which were described in Chapter (1).

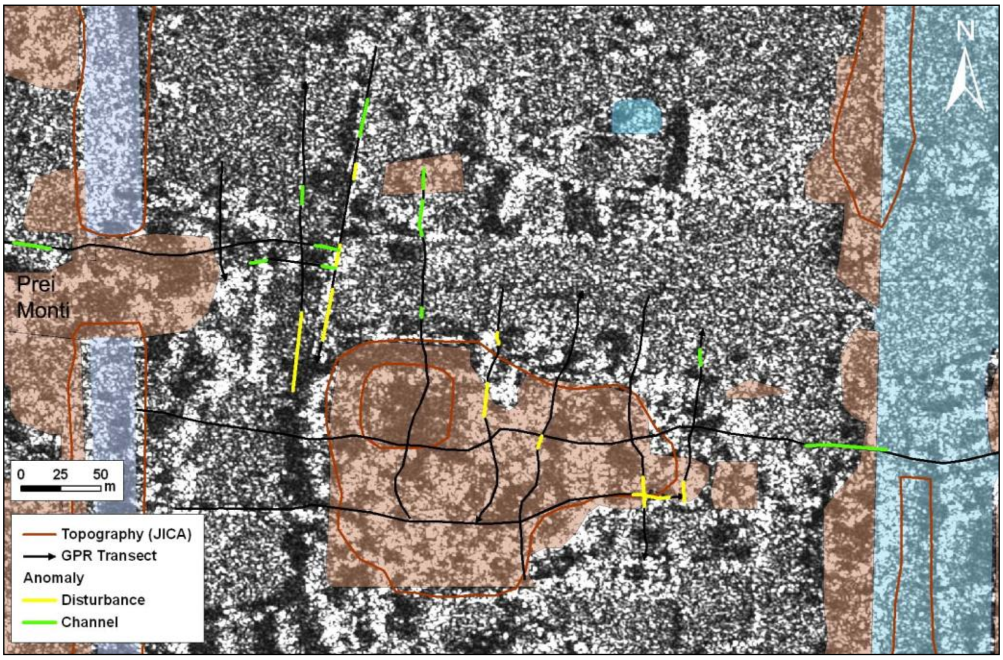


FIG. [124]: SURVEYS OVER AND AROUND THE MOUND IN THE AREA EAST OF PREI MONTI (BACKGROUND POTTIER/ TERRASAR-X).

The Canals

Several major canals of Hariharalaya were mapped by Pottier. The remaining embankments are generally low, possibly eroded by the annual monsoons and collapsed into the channel bed. Several missing links of disconnected parts of canals and their potential connection to the network were plotted on the Greater Angkor base map.

The anomalies associated with canals at Hariharalaya vary considerably. The GPR results indicate several successive excavations of canals, corresponding to the modifications of the Indratataka and its set of inlets and exit channels. Generally the anomalies referring to canals are narrower than the features mapped by remote sensing. The outer moat of the Bakong was recognized by GPR in its total width; however the GPR results show no evidence for the 85m wide moat/canal connection between the Bakong enclosure and Prei Monti. One canal was mapped by Pottier leading eastwards from this feature towards the Roluos River - which it apparently did not reach. The nearly 80m wide mapped feature was measured by GPR as only a 20m wide v-shaped anomaly (BK_DAT_0001_3_640-660m), with a 6m wide deeper central part. Groslier called the wide canals with gradually sloping sides *"vallées artificielles,"*[1033] that in the wet season were to channel large amounts of water, while, when the water receded from the sides, they were used as rice fields. This idea was supported by the GPR-surveys. Additional anomalies were recorded in a straight line over the potential continuation towards Roluos River. There, a strong anomaly was mapped (BK_DAT_0002_1_910-918m), possibly a masonry feature, which could be seen in connection to the river. This potential channel is however intercepted by the original channel of the Roluos River, making a simultaneous use of the two unlikely.

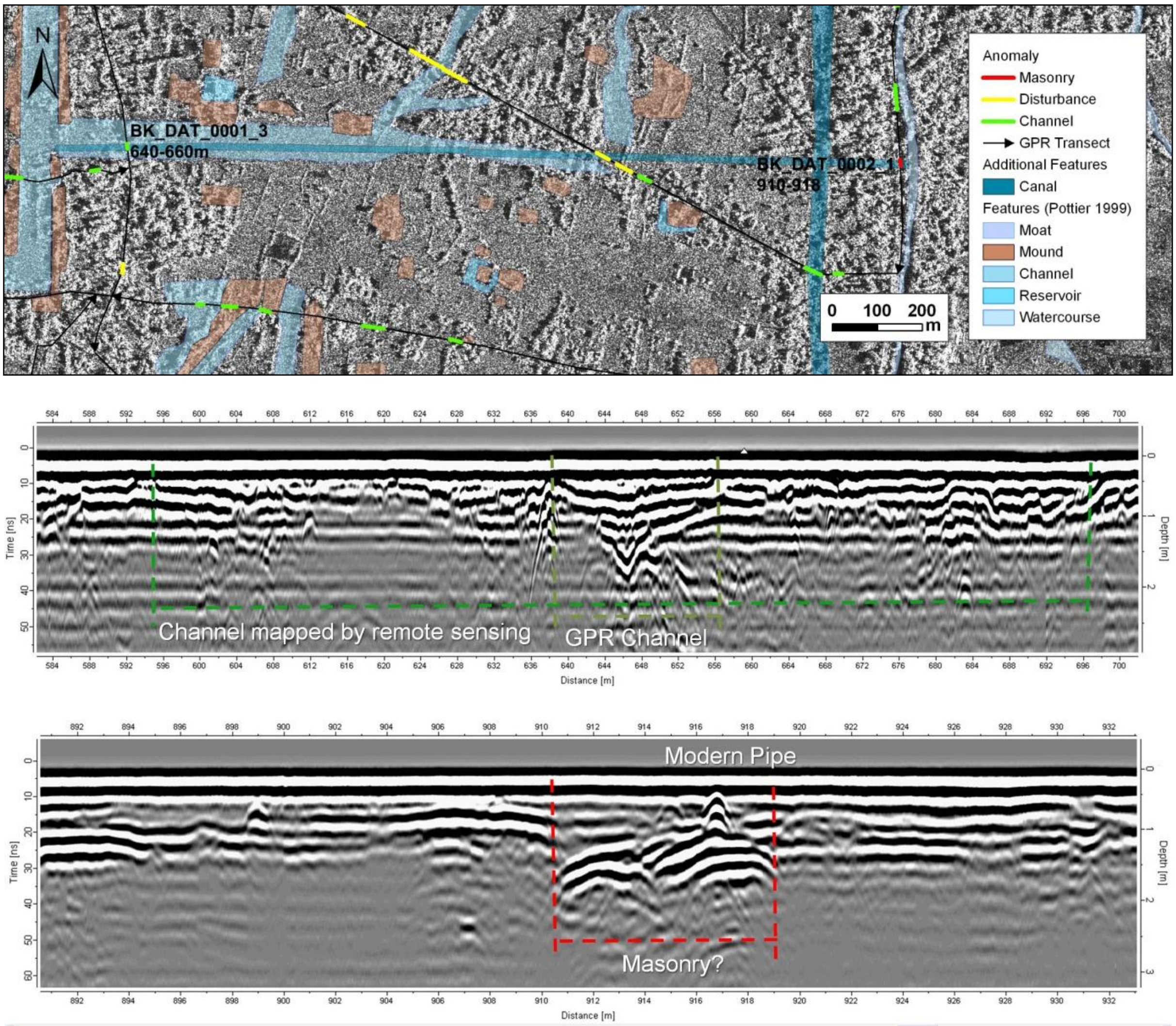


FIG. [125]: SMALL GULLY WITHIN BROADER MAPPED CANAL BED (BK_DAT_0001_3_640-660M AND POTENTIAL MASONRY AT BK_DAT_0001_3_910-980M.

Several other channels displayed small gully like depressions in the centre of canals, see Fig [125], which had been mapped as broad and wide by aerial survey. The measured width could possibly indicate that the narrow central part carried water most of the time, and the rest of the space between the gently sloped banks, sometimes unrecognized by the GPR, was seasonally flooded and used for rice farming, similar to their purpose nowadays.

A second major canal was mapped by Pottier bypassing all enclosures in a curved line to the west. The modern water filled canal in this area is now spanned by small bridges, and was crossed at three locations by GPR, which recognized an earlier canal bed below the modern bridge. Associated with the possibly modern outlet in the southeast corner of the Indratataka, and with an unusual form, it is uncertain if this canal has an Angkorian origin. Other recorded anomalies are potentially associated with a narrow canal running in a straight line southward to the west of the Preah Ko enclosure, passing the Bakong and reaching Prei Monti. This could have been the original western distributor.

From Hariharalaya straight southwards run three parallel earthworks run towards the Tonle Sap. A double embankment is traceable as far north as Prei Monti, a third one further to the west begins to the east of Trapeang Phong. The remains of the embankments are traceable as far as 14km southwards, running far into the seasonally flooded shore of the lake. The earlier described canal, that starts at the West Baray and runs towards south-east, intercepts the major canal to the south of the centre of Hariharalaya, and then continues in eastern direction towards Damdek. The aerial photo shows the earthworks are partly covered with shrubs and the areas in between is now to a large part used for rice farming. A series of east-west transects were conducted over the area, making the south canal the most detailed investigated water management feature of this survey. The width and depth of the feature were measured in irregular intervals of 50-250m over a distance of nearly 2.8km, see Fig. [126].

The survey shows that the south canal originally consisted of two channels, a larger one about 200cm deep in the centre and a smaller one on its western side. The size and depth of the two channels vary, as does their location within the embankments, indicating that the canal bed had been meandering within the embankments. The immense width of the original canal structure makes it unlikely to have been used by boats, especially when considering that the year-long water carrying Roluos River lead up to the temples, parallel to the south canal. The rather narrow channel width mapped by GPR between the embankments and its meandering appearance leads to the assumption, that water has found a path after the construction of embankments. The main purpose of the major canals, running perpendicular to the contour lines in direction Tonle Sap, would presumably have been flood control, to manage the vast masses of water that inundated the landscape with arrival of the monsoon and to shunt water quickly out of the relatively fertile area. The Roluos River for example, still functions as a flood reduction device.

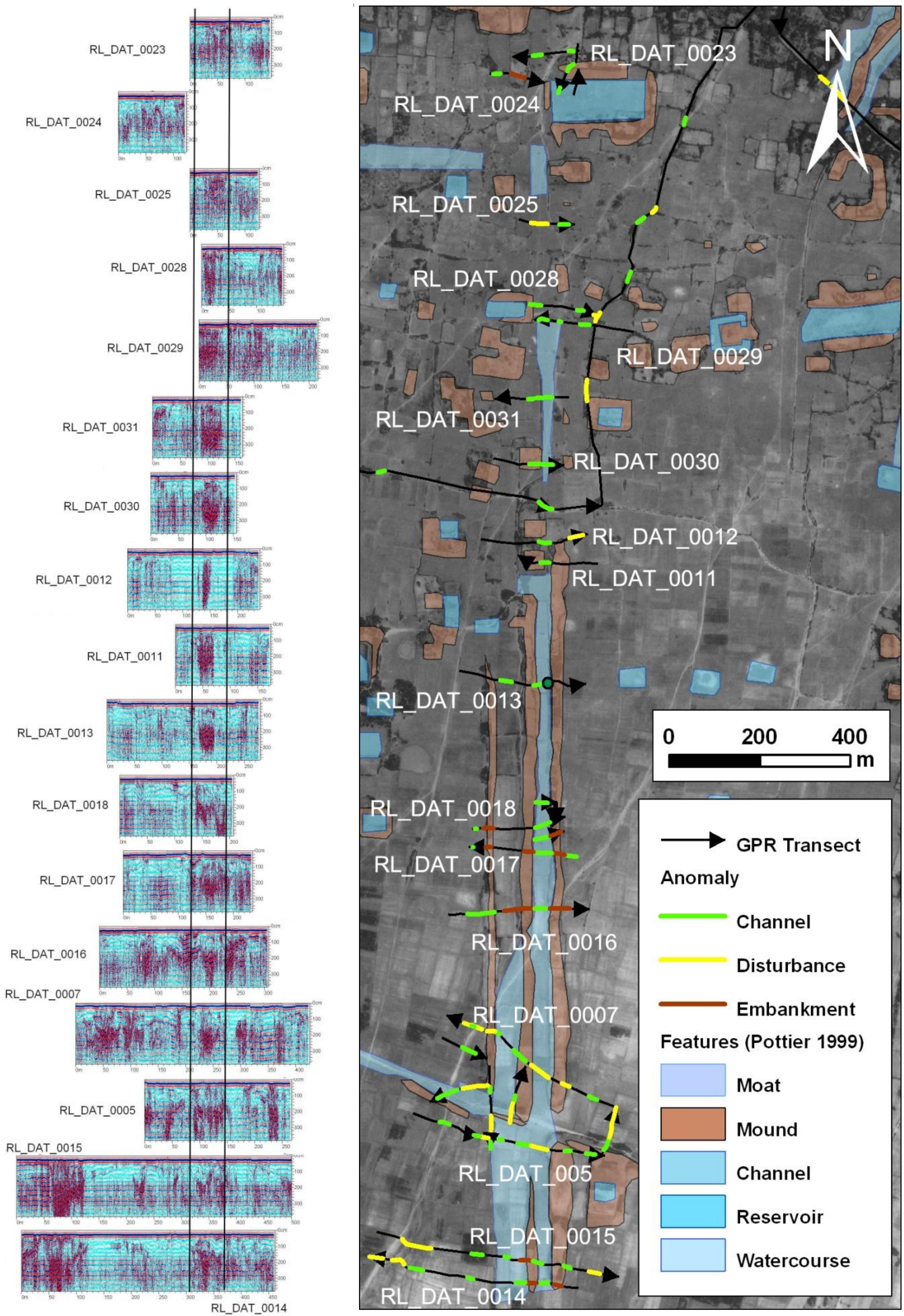


FIG. [126]: GPR TRANSECTS OVER THE SOUTH CANAL AT BAKONG (BACKGROUND: FINNMAP)

ii. The Functioning of an Early Network

The GPR results, partly and to some extent in combination with TerraSAR-X, demonstrate the complexity of the water management network - including those from the Indratataka displayed in Chapter (7). The extent of the known channels mapped by GPR, and the additional channels recorded, mainly support the aerial and remote sensing results and give some additional clues to interpret the function of the network, see Fig. [127].

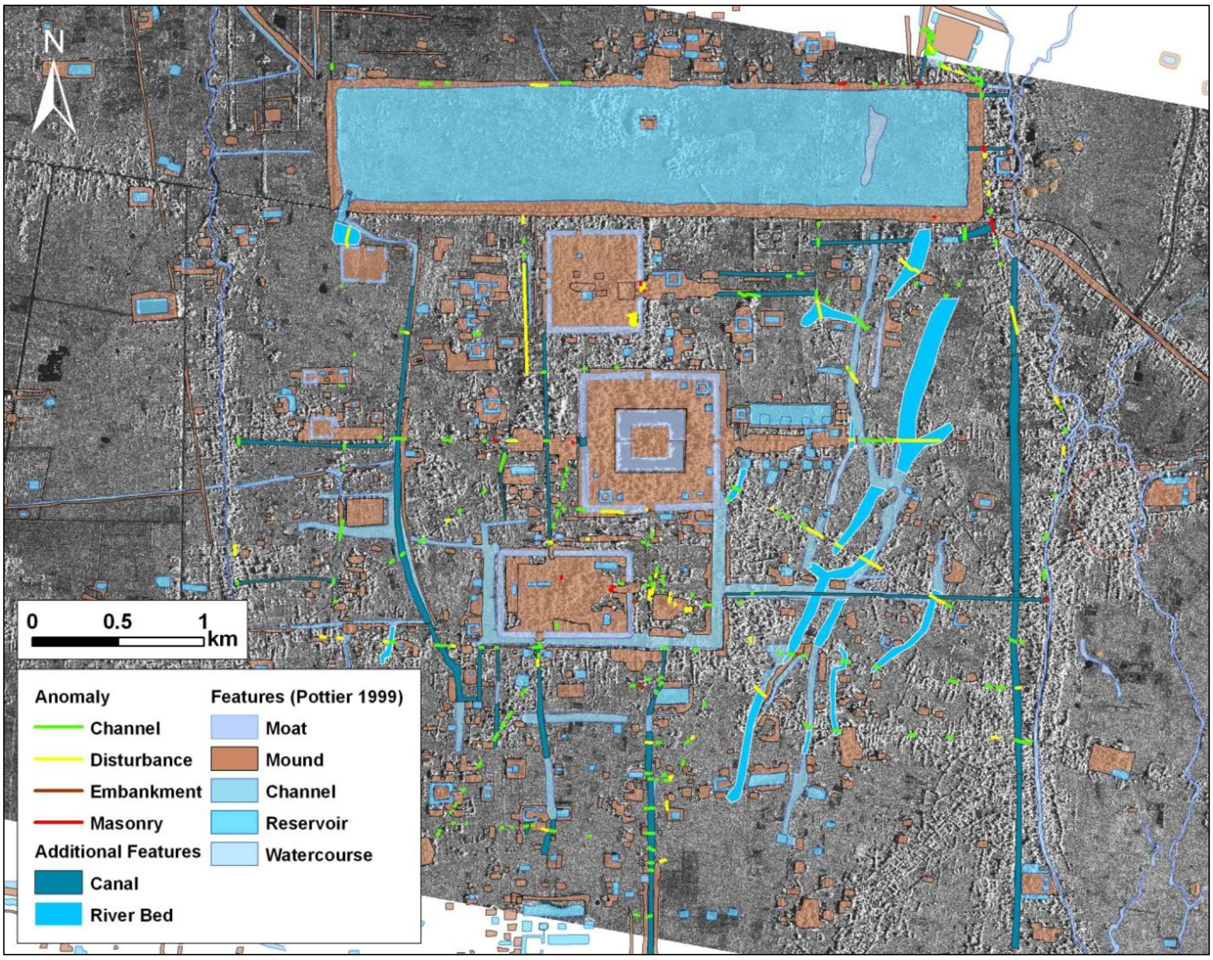


Fig. [127]: Interpretation of the original functioning of the network at Hariharalaya (Background: TerraSAR-X).

Water flowed south from Phnom Bok. The southern part of the Roluos River was artificially channelled until reaching a maze of earthworks in the northeast corner of the Indratataka and was then directed through a masonry inlet in the northern embankment into the *baray*. When the reservoir was filled up, the water was taken through an outlet in the eastern embankment and was directed south, either straight into the Tonle Sap through the Roluos River channel, or distributed into the network of Hariharalaya. The graphical connection of some anomalies indicates that a channel linked the moats of Preah Ko and Prei Monti. The water covering the broad edges of the canals might have been used to some extent for rice growing, since presumably the narrow central channel carried water over a longer period of the year. What is unclear is whether the lower areas formed by the streams coming from the north-east, after being cut off by the new Roluos River, had another purpose within the network in addition to or instead of being used for rice farming. The excess water was sent through broad channels to the south into the Tonle Sap.

(c) ASPECTS OF GREATER ANGKOR

'I see nobody on the road,' said Alice. 'I only wish I had such eyes,' the King remarked in a fretful tone. 'To be able to see Nobody! And at that distance too!' (LG, VII)

In the reign of Yasovarman I (AD889-915) the centre of the capital was relocated from Hariharalaya to the northwest, midway between the Bakong and Ak Yum. The centre of Yasodharapura was constructed in the area between Phnom Bakheng and Phnom Bok. The relocation was accomplished "*soon after 900*"[1034] with the consecration of the new state temple on Phnom Bakheng. Over the following centuries Yasodharapura was remodelled several times; the instalments of new monuments influenced earlier temple configurations. There is evidence for earthworks and canals that connected monuments and centres, which were obscured by later constructions.

i. THE "ANGKOR THOM RIVER"

Inside Angkor Thom

According to Jacques, several smaller settlements had existed already in the region north of the Phnom Bakheng.[1035] Groslier discovered remnants of Pre-Angkorian occupation from the Phnom Bakheng to the Royal Palace.[1036] Excavations led by Jacques Gaucher at the site of the royal palace unearthed evidence of earlier occupation, "*near the Phimeanakas postholes in nearly every ancient layer as well as a significant number of generally well preserved wooden pieces in situ.*" [1037] There is no description of wether those remains were contemporary with the temple on Phnom Bakheng. Groslier argued that a primitive laterite and brick shrine had been built at the Royal Palace already by Yasovarman I.[1038] Claude Jacques & Michael Freeman, following up on this idea, believed the site must have been already occupied when Yasodharapura became capital: *"Phimeanakas temple, erected by Suryavarman I at the exact intersection of the northern axis of Phnom Bakheng temple and the western axis of the East Baray (in no way could this have been by chance), was probably built on the site of a former shrine, attributed to a minister of Yashovarman I."*[1039] The archaeological map of Angkor Thom by Gaucher displays a deeply buried river bed that crosses under the present location of the enclosure.[1040] His team took thousands of cores some of which returned alluvial sand deposits at about 5m depth.[1041] This river bed is sketched as a thin meandering, multi channelled natural river that followed the central NS axis of the enclosure.[1042]

Six transects were taken over the central plaza of Angkor Thom, crossing the area where the channel was displayed in the archaeological map; see Fig. [128]. The expected depth of the river bed, and the environmental circumstances of a hardened clay surface, made it unlikely, however, that it would be detected by GPR. Five metres signal depth has been reached only in very few occasions, and not in areas of frequent use or occupation.[1043] At the site the deepest penetration was measured at about 48ns (250cm), measureable only from the silted up moat around the North Khleang. This might be the reason that there was no evidence for a natural channel on any of the GPR profiles. Regarding the JICA topography, the central plaza is apparently not elevated compared to the landscape surrounding Angkor Thom.[1044] Considering the assumed depth of this channel buried under a 5m thick layer of clay, suggests that this channel had already ceased to run before Angkor was inhabited and may not have had influenced the decision to build a pre-Angkorian settlement at this place.[1045]

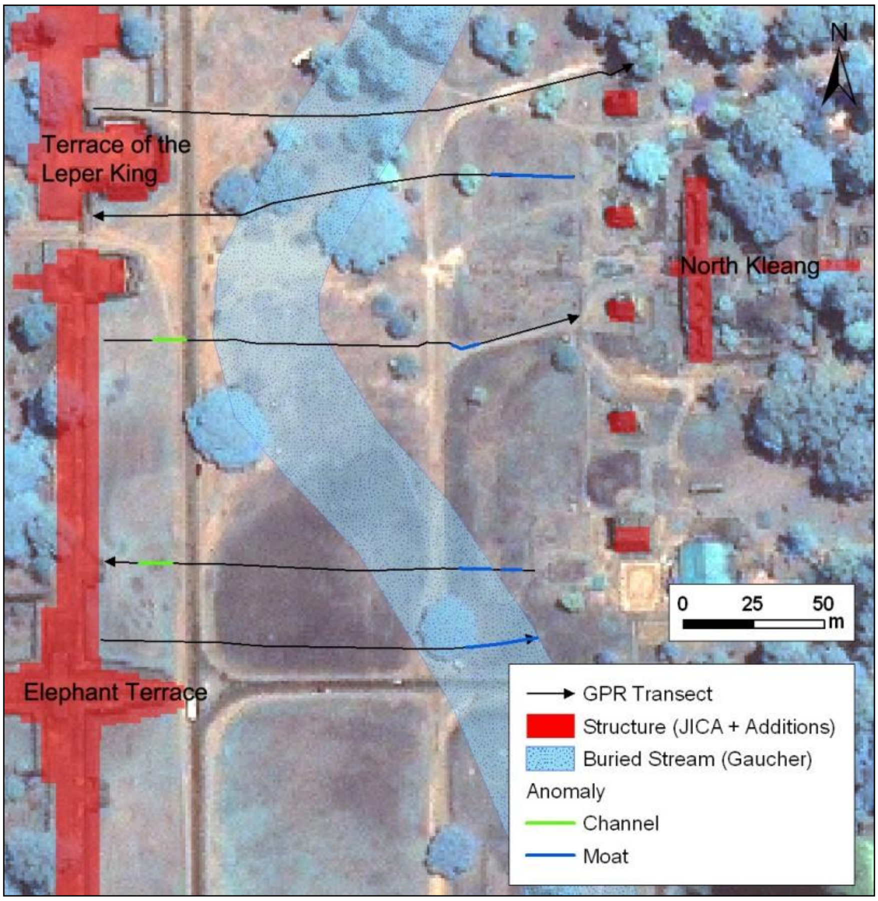


FIG. [128]: THE CENTRAL PLAZA OF ANGKOR, RIVER BED (GAUCHER), AND GPR SURVEYS (BACKGROUND: IKONOS)

The Northern Floodplain

The origin of this river could have been a large floodplain to the northeast of Angkor's centre. Satellite remote sensing images[1046] display a waterless, broad and meandering landscape feature that was identified as a potential former river bed,[1047] see Fig. [129]. The area appears lower compared to its surrounding and is predominantly covered by rice fields or is unused land. This region is not covered by the JICA high-resolution topographic data, so accurate height data is not available. The basin is mostly unpopulated. The modern settlements are positioned on the possibly higher grounds on the sides, which is recognizable due to thick bushland. Only a few Angkorian canals have been mapped in this area.[1048] Since in this survey area the sole target were large natural features, the two-way travel time window was extended to 82ns (about 400cm) and signal recording distance interval was extended to 8cm. To cover the distance in a shorter time, profiles were recorded by pulling the antenna behind a motorbike driven mainly on raised dirt roads or paths. The survey method proved to be faster without losing resolution.[1049] The possibilities for using a fast recording method to analyse road composition with Malå GPR equipment has been shown before, e. g. by Pereira *et al.*[1050]

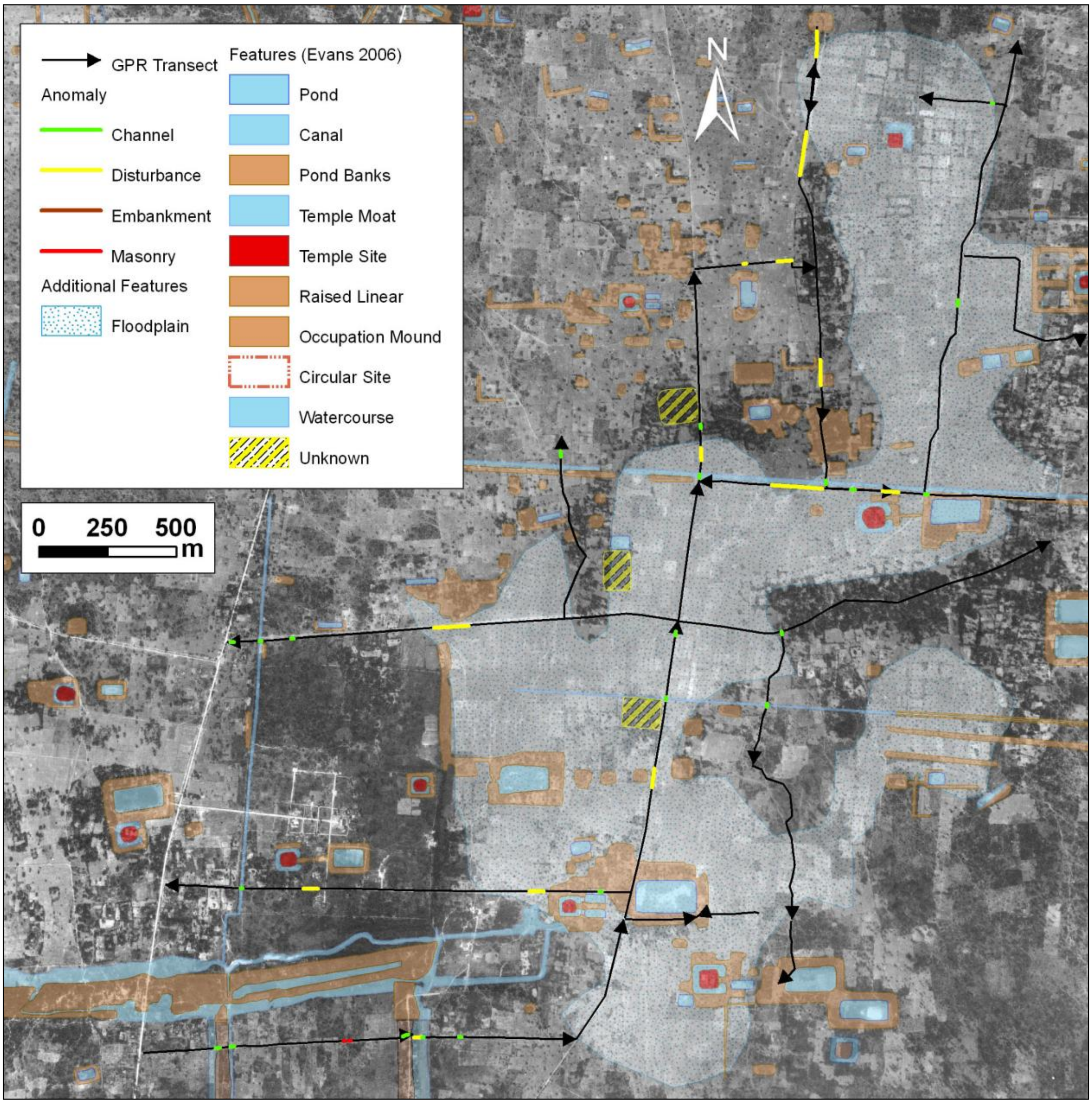


FIG. [129]: GPR RESULTS FROM THE SURVEY OF THE NORTHERN FLOODPLAIN (BACKGROUND: FINNMAP).

The ground in the northern part is sandy and dry. The paths that run on base height consist of very lose sandy soil, similar to areas south of Roluos, indicating at Angkor good penetration depth. Very few additional artificial canals or ponds were detected that had not been mapped. The results display very few anomalies that could be potential former river beds, displayed as a broad chaotic signal, but narrow in comparison to the extent of the floodplain. The signal is not as clear or deep as in areas detected in the vicinity of the modern river beds. The broad plain could be deeper than the surrounding and therefore seasonally been covered by water and part time of the year more saturated than other areas, therefore appearing in remote sensing images as a meandering broad river bed. Another reason for shallow deposition could be that the wide floodplain provided space for the original river beds to expand horizontally.

ii. The Bakheng and Associated Earthworks

It was not difficult to answer, as there was only one road through the wood, and the two finger-posts both pointed along it. (LG, III)

The Axial Roads of the Bakheng

To map the extent of early Yasodharapura, Victor Goloubew searched for evidence of axial canals/ causeway extensions in all four directions in the 1930s.[1051] He associated several remains of small temples and ponds with the axes, and discovered the former road connecting the temple mountain to the north with the Baphuon[1052] and continuing from there further to the north; see Fig. [6] in Chapter (1). This causeway is displayed in Gaucher's map and runs at a slight angle to the other north-south roads of Angkor Thom.[1053]

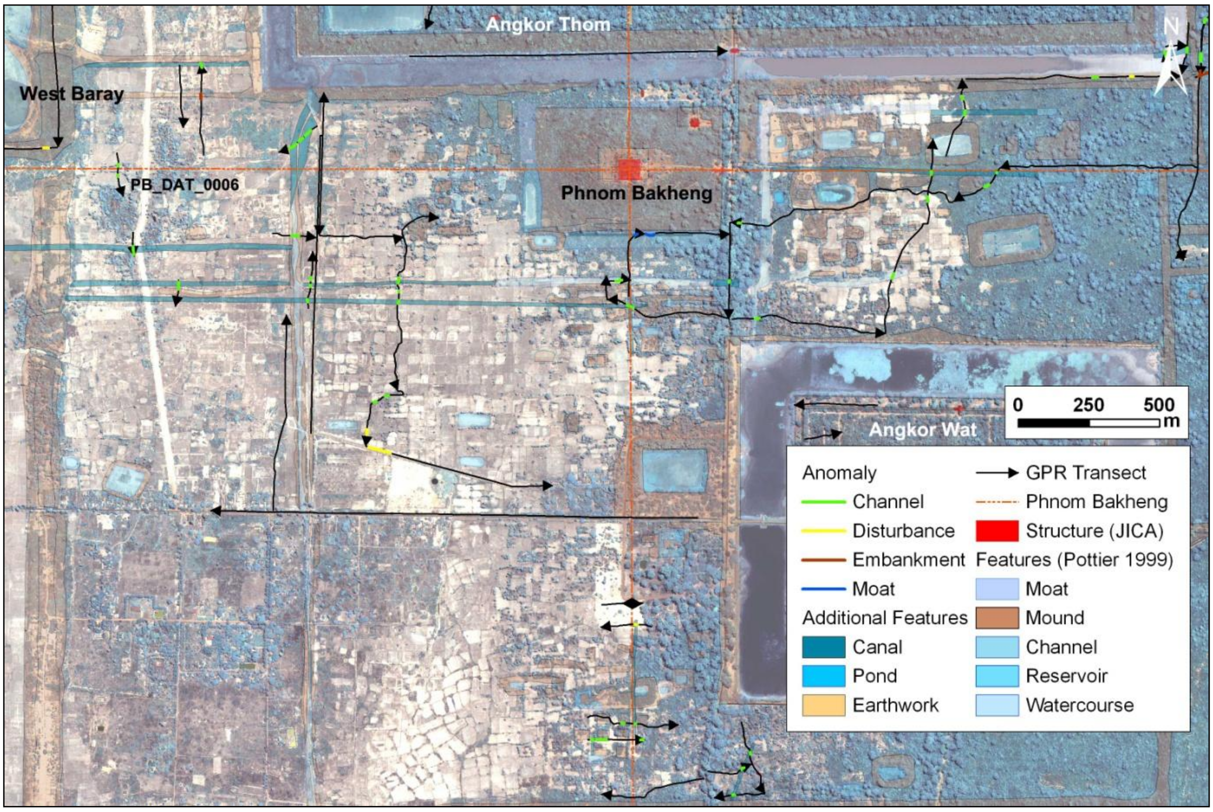


Fig. [130]: Phnom Bakheng and associated GPR results (Background: IKONOS)

The GPR survey identified the mapped canals in the area, traced the extent of discontinuous ones and recorded anomalies that indicate several previously unmapped canals. The rectangular moat of the Phnom Bakheng, which encloses the temple close to the foot of the hill, was traced to about 1m depth. With a width of about 10m measured by GPR, it is only a fraction of the moat identified by Goloubew and Pottier in aerial surveys; see Fig. [130]. Visible on aerial images are checkerboard-like rice field patterns that were associated with the central area of Phnom Bakheng.[1054] Two parallel east west running canals have been traced passing the chessboard pattern to the west of Phnom Bakheng, one possibly continuing to the west of the airport. Close to the southeast corner of the West Baray, Profile PB_DAT_0006 crosses the east-west axis to the west of the hill. Here, two anomalies were traced that may correspond to small canals on the side of a causeway running to the west in direction Ak Yum. Profiles crossing the north-south axis to the south of the Phnom Bakheng, to search for an earthwork/canal running straight south from the temple, show traces of a channel in three out of five profiles.

The Hariharalaya-Yasodharapura Causeway

Based on the earlier mentioned work of Trouvé and Goloubew, Pottier mapped the raised causeway from the Phnom Bakheng running towards the east. GPR profiles crossing the east-west axis to the east of the temple hill show evidence for a channel on this alignment. There is a gap on the east side of the Siem Reap River, and no evidence from the aerial surveys suggests a continuation of the causeway. Earthworks possibly associated with the east-west aligned causeway of the Bakheng axis have been traced to the east of the Siem Reap River.[1055]

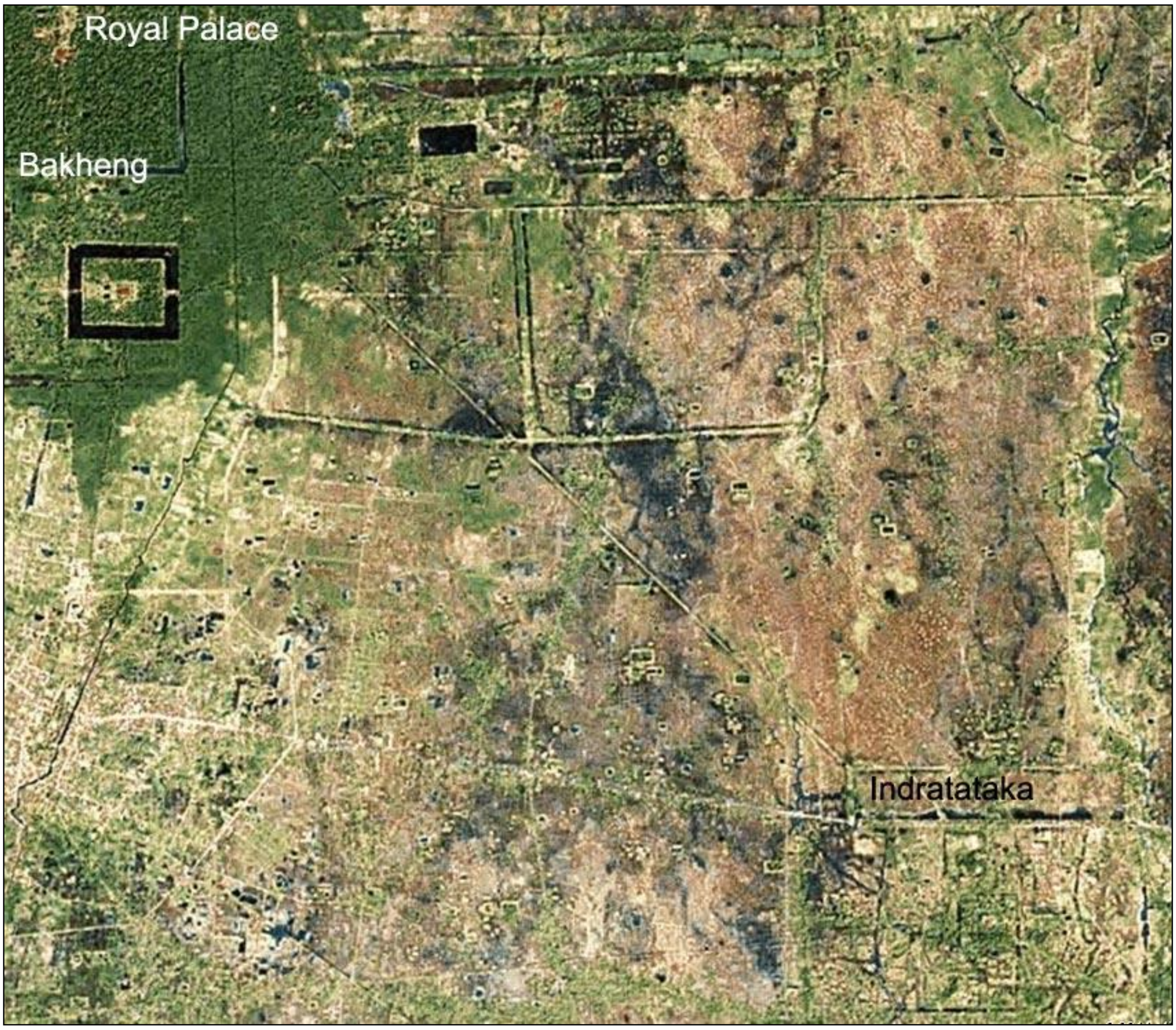


FIG. [131]: SATELLITE IMAGE OF THE HARIHARALAYA-YASODHARAPURA CAUSEWAY (LANDSAT7/NASA).

Remains of a linear earthen embankment, clearly visible as straight line on remote sensing images, start at the north-west corner of the Indratataka and run straight towards the northwest; see Fig. [131]. Those earthworks have been seen as evidence that Hariharalaya and Yasodharapura were connected by a causeway. The orientation of this embankment, which also disappears under the dense canopy somewhere close to the Siem Reap River, was marked by

Trouvé. He, however, expected it to turn to the north in direction Takeo.[1056] Jacques & Freeman have pointed out that:

> *"In fact, the causeway, which began at the north-west corner of the Indratataka reservoir ended on the left bank of the Siem Reap River at a point, which nowadays is in the alignment of the south wall of Angkor Thom, and not in that of the eastern avenue of Phnom Bakheng. The presumption is that in Yashovarman's time this causeway had been built to lead to a triumphal way ending at the royal palace, but which was subsequently completely buried under the walls of Angkor Thom."*[1057]

The archaeological map shows - over the last kilometres of the raised embankment coming from Hariharalaya - a slight angling westwards, which has so far been interpreted as a turn into the direction of Phnom Bakheng.[1058] When extending the straight embankment or the angled last part of it virtually to the northwest, both would however arrive at the plaza of the royal palace in Angkor Thom. Strong forestation has hindered additional mapping by remote sensing to find out, if the original path of the causeway changed direction to reach the Bakheng and/or if it continued towards the area of the royal palace. Field walking has not improved the understanding of this heavily forested area; the mapped causeway is barely recognizable and further northwest the topography does not appear linear or obviously associated with a causeway. The proximity to the succeeding temples of Angkor Wat and Angkor Thom, the distinct topographic features, the remains of mounds and ponds, suggest that the area was originally populated.

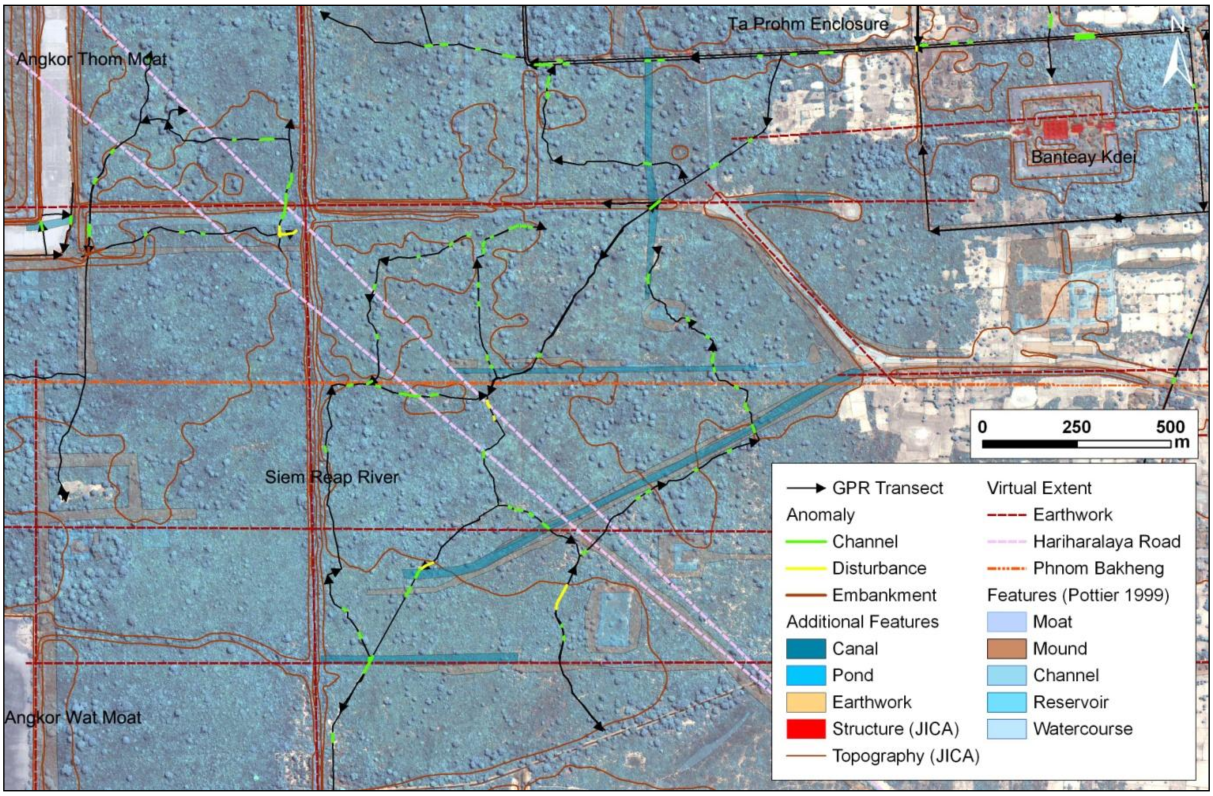


FIG. [132]: SURVEY AREA EAST OF ANGKOR WAT AND GPR TRANSECTS (BACKGROUND: IKONOS).

GPR surveys were conducted to search for anomalies associated with potential causeways/canals in the region east of Angkor Wat, east and west of the Siem Reap River., see Fig. [132]. According to Jacques, traces of the continuation inside the 12th century Angkor Thom precinct would have been destroyed with the construction of the walls. In expectation that a potential causeway could either have reached the Royal Palace area directly, or would have intersected an east-west causeway somewhere further to the east, two possible linear extensions of the road starting from the part which was mapped furthest to the northwest, were included in the GIS map - to outline the area the GPR profiles had to cross. The paths displayed in the JICA road data were used to plan the survey. Profiles were taken on both sides of the river in alignment with the embankment, as a well as over the axis of the Bakheng.

The vast number of anomalies measured by GPR and classified as canals, underline the impression from the JICA topography: that the region was heavily transformed and intensely used in Angkorian times. This, however, shows that in this densely forested area the archaeological map is incomplete. Some large anomalies mapped by GPR indicate artificial channels that do not match with any features on the map or the visible topography. GPR profiles that cross the fan-like outline of the possible road alignment display several anomalies that could be interpreted as canals. Some were mapped within the two indicated alignments of a potential road. The results, however, do not match with one single linear trace which would support a canal associated to a road that led towards the Royal Palace. Excavations that were conducted by GAP in the area to the east of Siem Reap River in January 2011 supported the suggestion that there was extensive use of this area in the 12th century.[1059] Ground surveys searching for the continuation of the road were suspended temporarily.

Regarding "Goloupura"

As discussed in Chapter (1) Goloubew not only traced the axial roads of the Bakheng, but included them into his idea of a rectangular walled outline of Yasodharapura (Fig. [6], Ch. 1). The GPR surveys conducted for the search of the road connection between the two centres crossed the area that Victor Goloubew had defined as a potential eastern border of the first centre of Yasodharapura, to the east of Angkor Wat near Siem Reap River. Pottier has given a number of reasons to discard the theory that the early centre of Yasodharapura situated around the Phnom Bakheng with the Bakheng as its state temple was surrounded by a 4km x 4km squared enclosure. A raised northern side of this imagined enclosure can be ruled out due to Gaucher's Angkor Thom map, which displays no evidence of an enclosure wall, moat or embankment.[1060] The GPR profiles covering this region did not present any anomaly associated with a linear north-south wall, embankment or canal and provided no evidence of any enclosure walls.

The Angkor Wat Canal

One of Pottier's arguments against the idea of "Goloupura" is the L-shaped double embankments (CP807) that connected the West Baray with an area south of Angkor Wat, which were interpreted by Goloubew as the south-west city walls. The remains of the Angkor Wat Canal (CP505) leave CP807 in a linear double embankment in direction south-southwest and continue in a straight line to the western landing stage of Wat Athvéar. Pottier detected in a field survey between CP807 and the moat of Angkor Wat a topographic depression in this area. He took it as evidence that CP505 continued to the Angkor Wat moat, connecting two monuments attributed to Suryavarman II,[1061] and erased by the construction of CP807.

Three GPR profiles that crossed the virtual continuation of CP505 towards the north, show additional evidence of anomalies associated with the direction of the canal, which supports the hypothesis that it once continued to the north of CP807 and that the canal preceded the construction of the double embankment CP505; see Fig. [133]. No clear evidence for a continuation of the canal was found inside the Angkor Wat enclosure or north of the northern enclosure wall of Angkor Wat on either side of the moat, to find out if it also preceded the construction of this temple.

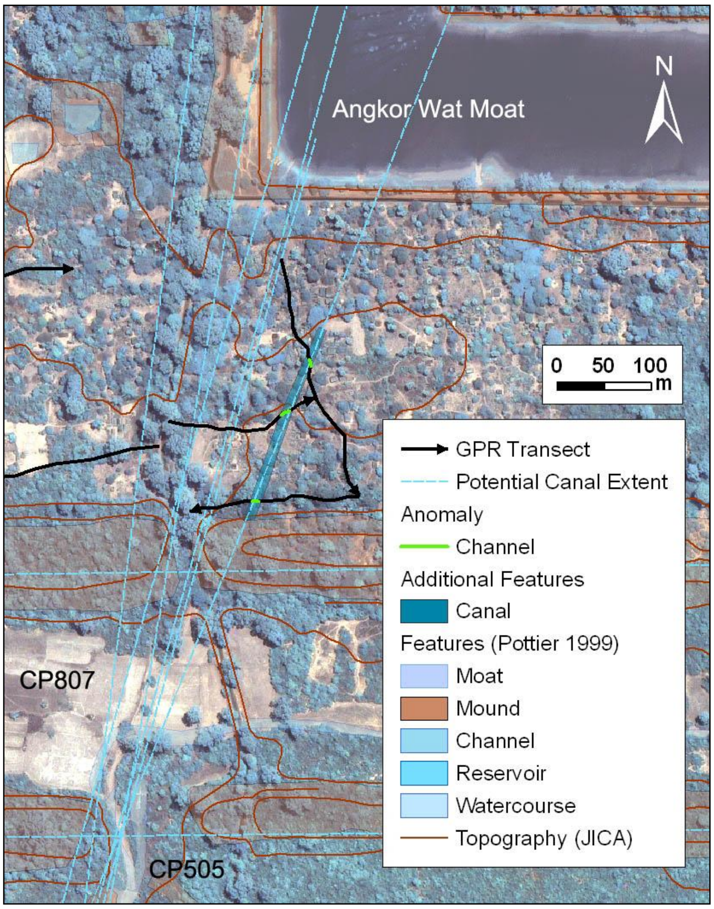


FIG. [133]: THE ANGKOR WAT CANAL AND ITS POTENTIAL EXTENT (BACKGROUND: IKONOS).

iii. CANALS AND CAUSEWAYS IN THE ANGKOR THOM AREA

Roads through the Enclosure

The interior of Angkor Thom is crossed by a chessboard-like network of roads and/or canals in alignment with the central axes. Additionally many small scale masonry structures exist within the walls of Angkor Thom.[1062] To identify the roads and ponds on Gaucher's archaeological map several GPR transects were conducted through Angkor Thom, using the trails displayed on the map that had been created within the mapping campaign.[1063]

The enclosure is, however, heavily forested. The GPS reception was inaccurate, and orientation was arranged using Gaucher's map, a compass and the distance measured by the GPR survey wheel. In contrast to the displayed map, most trails are not straight but follow the topography;

possibly altered in its later use by the locals. Some of the trails have become overgrown since they were blazed and are now blocked by new vegetation. Roots make a rough surface and large trees along the paths influenced the GPR signal, as roots interfered with the subsurface response. Contrasting the visible topography, the GPR profiles conducted over the trails in the south-west and the north-east quadrant show little evidence of either roads or canals. Only two larger anomalies were mapped on the long north-south profile; presumably buried depressions that could refer to canals preceding Angkor Thom. The larger one of them is located below a depression within the east-west alignment of the West Mebon and the exit channel in the centre of the east embankment of the West Baray, which was discussed as part of the search for inlets and outlets in Chapter (7); see Fig. [134].

Additional surveys to study the feature further to the east were abandoned after the unsuccessful search for trails running north-south. The limited number of anomalies is, however, explicable. The archaeological map of Angkor Thom was primarily based on topographic measurements; a depression was therefore regarded as a pond while a linear embankment feature was marked as a road or canal. To detect a canal by GPR, however, it needs to have been filled with new material. Because the walls of Angkor Thom prevented major flooding, overgrown, the Angkorian topography may still be existent, covered only by a relatively even layer of soil from vegetation. As the path of the GPR followed the existing topography, the results here only added little information to the known archaeology .

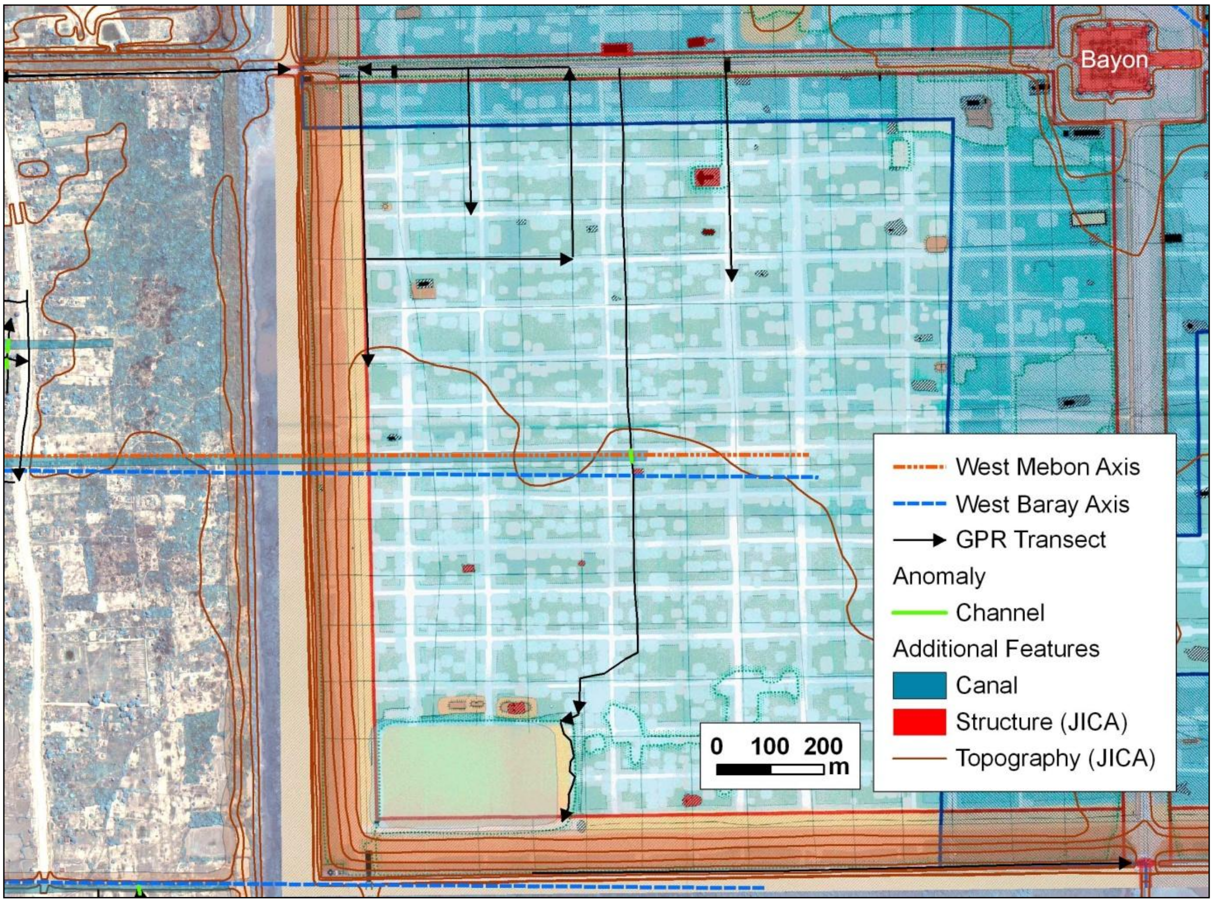


FIG. [134]: GPR PROFILES WITHIN ANGKOR THOM SHOW ONLY FEW ANOMALIES REFERRING TO ROADS/ CANALS OVER ARCHAEOLOGICAL MAP BY GAUCHER (BACKGROUND: IKONOS).

Ta Keo and the South Khleang

Jacques and Freeman have placed Ta Keo (late 10th to early 11th century, Jayavarman V) and the South Khleang (late 10th to early 11th century, Suryavarman I) into the construction period of the *khleang*.[1064] The JICA building data set was used to draw a virtual extension line between the east-west axis of Takeo and the South Khleang. The line shows that Takeo and the South Khleang were built on the same axis, which could indicate a connection between them whose visible remains might have been erased by the succeeding construction of Angkor Thom.

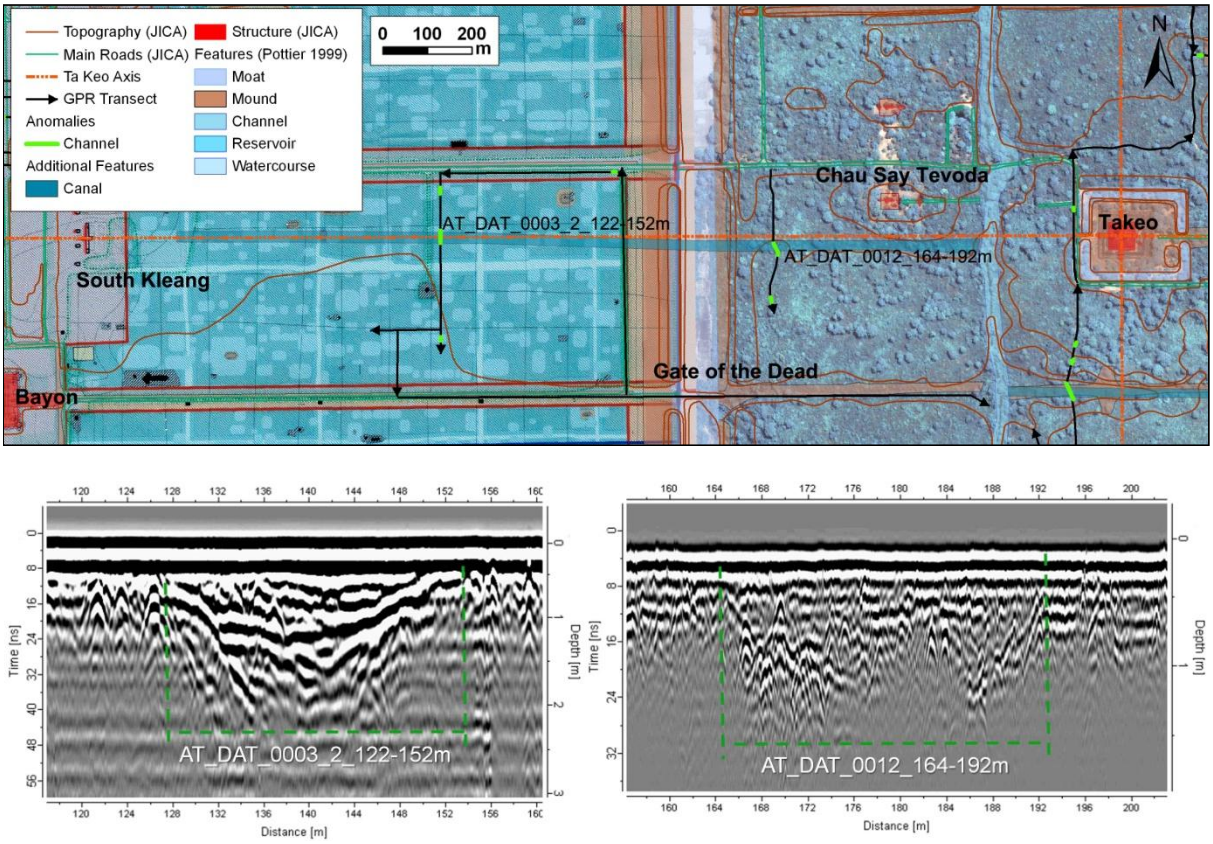


FIG. [135]: ORIENTATION OF TA KEO AND THE SOUTH KHLEANG (BACKGROUND: POTTIER/IKONOS) AND ASSOCIATED GPR PROFILES.

To investigate a potential relation between the two monuments, e. g. buried canals, causeways or roads, three north-south GPR profiles were taken in between the two intersections of the imaginary line with the extended axis. A large depression in alignment with the extended axis was detected in the most western profile conducted from the road over the path to the small temple Mangalartha (AT_DAT_0003_2_122-152m); see Fig. [135]. A second profile, running alongside the east wall of Angkor Thom, did not display any anomalies due to a strong layer of debris covering the road. The third profile east of the moat of Angkor Thom was conducted in the following field season to further investigate the feature, however, with a 500MHz antenna of less penetration depth. The survey path crossed a large earthen embankment that had not been mapped before. It displays another large anomaly (AW_DAT_0012_164-192m), which is not fully in alignment with the extended axis of Takeo. When connecting the two channel anomalies with a canal, it shows there may have been a connection, which has to be further investigated, as the GPR anomalies are not sufficient information to propose a connection between the two monuments.

iv. Siem Reap River and the Yasodharatataka

Research studies have identified the flow history of the Siem Reap River. To the north of Angkor, the river was redirected at Bam Penh Reach in the 9th/10th century, to shunt water southwards.[1065] It served initially as an additional water source for the Yasodharatataka, directing water to the north eastern inlet of the *baray*.[1066] Massive embankments between the Jayatataka and the Yasodharatataka indicate a period where water was directed towards the moat of Angkor Thom. Spean Thmar, the bridge near the Takeo, was built with reused blocks of a Bayon style temple,[1067] indicating that the water was directed southwards between the Yasodharatataka and Angkor Thom after the 12-13th century. Today the bed is cut considerably deeper into the ground.

The survey in the central part of Yasodharatataka and surrounding was conducted to analyse the depth and extent of a large 50m wide channel visible in Google Earth. It meanders from north to south through the Yasodharatataka, flows around the East Mebon, and follows no obvious artificial channel. The channel has cut through the small central E-W embankment inside the *baray* and extends towards the area on the northern side of the south embankment, which remains today one of the wettest areas inside the *baray* walls. The water leaves through one of the breaches of the southern embankment.[1068]

The profiles next to the Siem Reap River to the north of the *baray* display strong disturbances (JB_DAT_0018_116-196m, JB_DAT_0018_236-344m and JB_DAT_0019_0-72m), and might possibly refer to the originally indented course of the river or a period in which the river had left its bed. The northern embankment of the Yasodharatataka is considerably lower at the point where the river turns to the west. The survey did not detect an anomaly that could indicate a breach at this position, but to the west of the lowest point a channel feature was recorded (EB_DAT_0037_24-72m), that possibly included masonry in its centre; see Fig. [136].

Inside the *baray* a northeast to southwest running linear embankment originates from the turn of the Siem Reap River. A 20m wide linear depression is visible next to the mapped embankment that is now used as rice fields. It was interpreted by C. Pottier as the side of a channel.[1069] The GPR profiles cutting across this feature however show no evidence for a channel anomaly, making it unlikely. The linear embankment could however have been intended to channel a stream, which evidently ran free, as further to the east of the linear embankment large, strong anomalies were recorded (EB_DAT_0039_20-84m) that coincide with the meandering water flow feature visible in remote sensing. Additional transects that crossed the flow feature south (EB_DAT_0042_140-220m) of inside the Yasodharatataka, at the central embankment (PR_DAT_0019_988-1012m and PR_DAT_0019_1034-1059m), and south of the embankment (PR_DAT_0012_324-480m, and PR_DAT_0007_412-432m, PR_DAT_0005_792-820m) show evidence for a continuation, that the water was channelled through the bank southwards.

If this is a channel preceding the *baray*, the question is where the water originally came from, as there is no evidence on aerial photos to the north of the *baray*, and no potential source for this channel was detected inside the *baray*. More likely, at some point in time - after the Siem Reap

River course was changed at Bam Penh Reach and before the bed of the river had carved to the depth it has reached today - the low point of the embankment served as another inlet for the Yasodharatataka. Potentially this was the intended function for the linear embankment. From there, the water meandered relatively free down to the southern embankment of the *baray*, where it was directed through one of the breaches. Especially the small but distinct anomalies recorded inside and further south of the *baray* speak for an artificially directed water flow and make a natural origin before the construction of the *baray* unlikely, see Fig. [137]. Filtered satellite images give more information, as Landsat7 data of this region clearly displays the continuation of this stream to the south of the GPR survey.[1070]

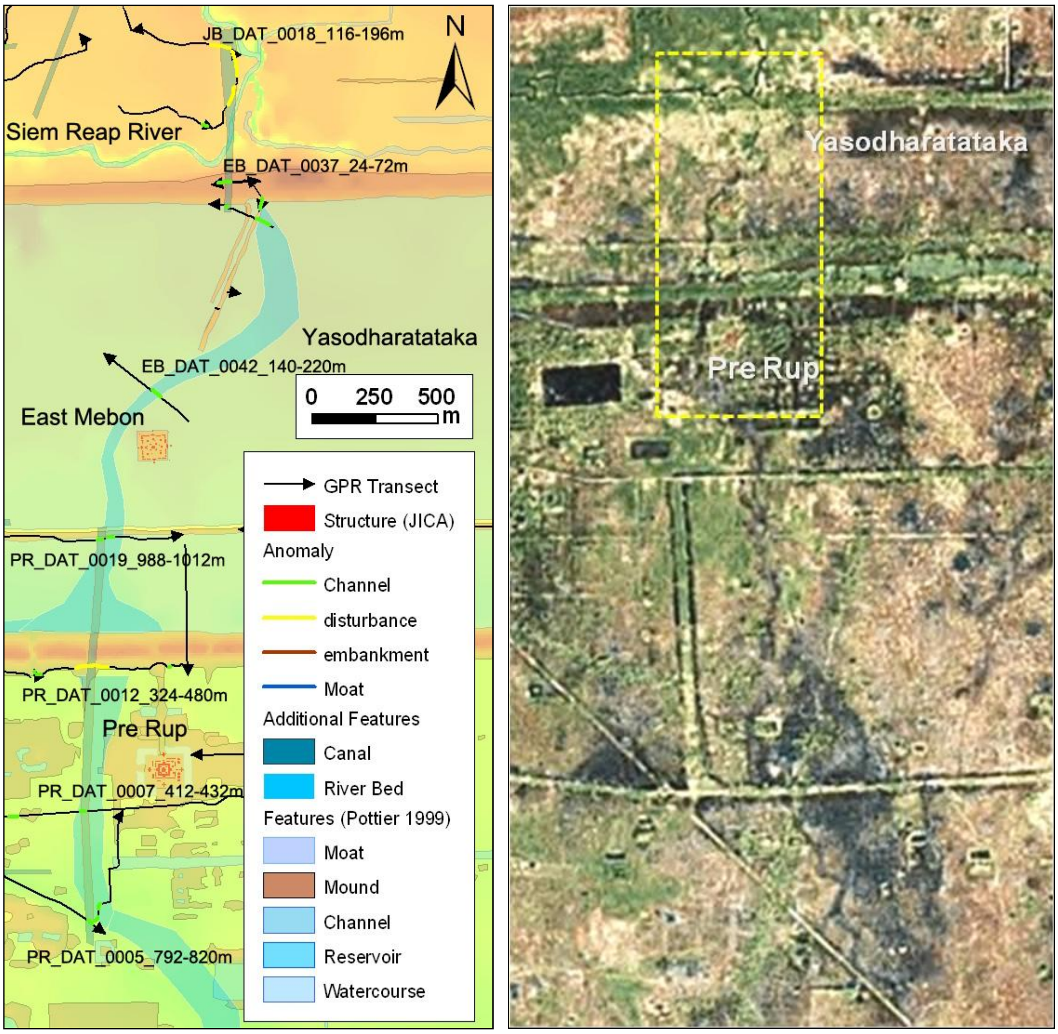
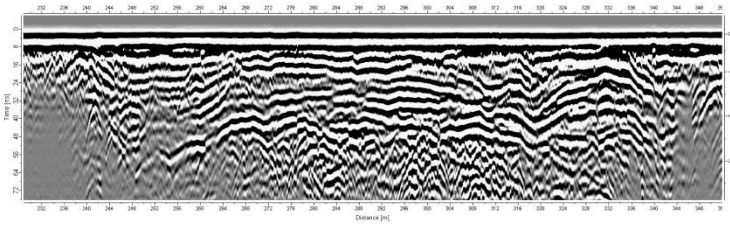
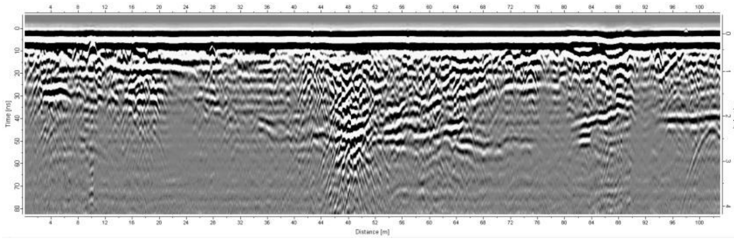


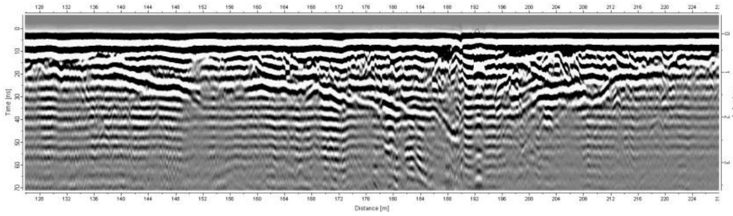
FIG. [136]: YASODHARATATAKA SURVEY AND EXTENT OF CHANNEL BED. BACKGROUND LEFT: DTM FROM JICA DATA, RIGHT: LANDSAT7 (NASA).



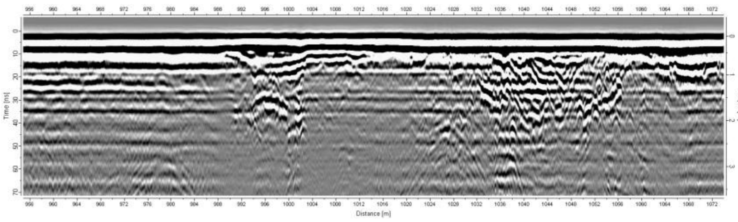
JB_DAT_0018 - Siem Reap River bed



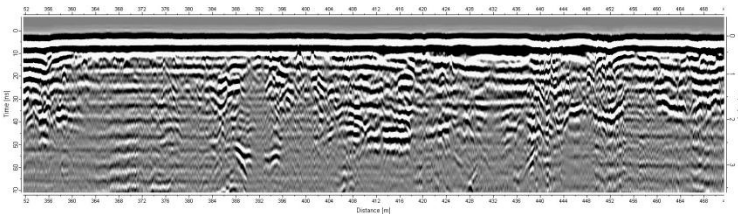
EB_DAT_037 - *baray* breach



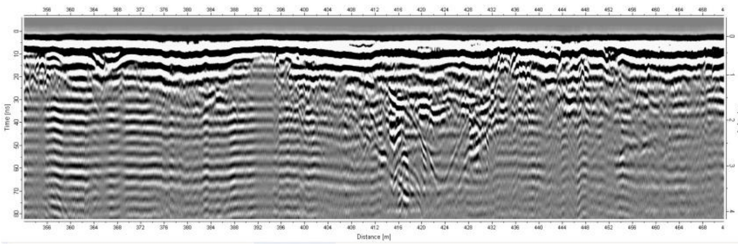
EB_DAT_0042 - inside the *baray*



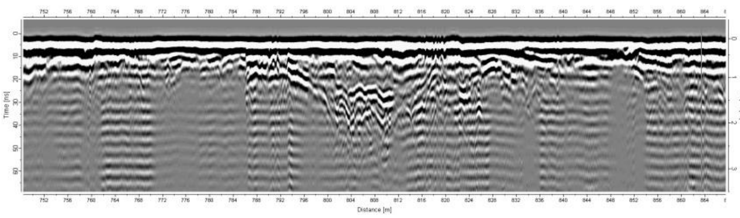
PR_DAT_0019 - middle embankment



PR_DAT_0012 - south of embankment



PR_DAT_0007- near Pre Rup



PR_DAT_0005- Sra Srang axis

FIG. [137]: MEASURED YASODHARATATAKA CHANNELS IN COMPARISON.

CONCLUSION

Natural streams were documented in various areas of the floodplain, sometimes corresponding to remote sensing data, such as in the north of the Jayatataka, the inside of the Yasodharatataka or close to the current river channels at the Siem Reap and Roluos River, where the rivers had at one time occupied other beds that later filled up with deposit.

The combined remote and close range sensing data from Hariharalaya helped to complement the map regarding canals and construct a model of possible water flows. In an analysis of features mapped by remote sensing and GPR, the results often show differences in the extent of the features from what was mapped by remote sensing. While some embankments are extensive, there is occasionally only a narrow channel in the centre that possibly carried water all year round. The canals sometimes show sedimentation and successive excavations. Sedimentation layers were also detected in moats and *trapeang*. The survey helped to display the function of a network from the canalization of the natural river to directing water towards the *baray*. The water entered through an inlet close to the northwest corner, which coincided with the highest point of the reservoir. The discovered outlet is evidence that at least at some point in time water was sent through an outlet in the east embankment, from which the water was either directed into the canals and moats of the centre's network or straight southward into Lake Tonle Sap. TerraSAR-X data served to distinguish water-saturated from non-saturated sites, and in some occasions provided information in addition to aerial photos and visual remote sensing.

In the Greater Angkor region, only parts of the extensive network were investigated. The GPR surveys were concentrated on some key issues regarding the connections within the centre. GPR surveys provided additional data on channels where remote sensing did not provide sufficient information, so in the west of Phnom Bakheng, to add a canal or its extension to the archaeological map. In other areas, where forest cover prevented remote sensing from mapping the network, the GPR displayed a number of anomalies possibly referring to canals.

IMPLICATIONS AND POTENTIAL

'Consider your verdict,' the King said to the jury. 'Not yet, not yet!' the Rabbit hastily interrupted. 'There's a great deal to come before that.' (AW, XI)

Fascination and Choices

Since explorers brought back tales about the medieval Khmer capital, Angkor has been a place of continued fascination – not least for archaeologists - its monuments, its secrets, its vastness … Yet, over the years scientific work has continuously changed the perspective and scope of knowledge on this enormous archaeological site. To be part of this, walking in the footsteps of those researchers, has been a personal fascination. For my thesis on *Angkor Underground* the focus was on the subsurface, a still little-studied field in Angkor, yet with great potential in a cultural landscape left behind and buried by centuries of construction, remodelling and decay.

Fortunately, for my wish to contribute to the understanding of the *low density urban complex* of Greater Angkor, GPR-surveying was available: a non-invasive close-range geophysical approach that is characterised by versatility in application and 3-dimensional mapping, allowing research to target a variety of archaeological issues. To carry out the work, a framework of questions was set up and choices had to be taken, to identify potential research objects and define the associated survey areas, targeting occupation patterns, the interior of enclosures and the vicinity of monuments, and elements of the water management network. Several other Khmer centres in northwest Cambodia were also investigated to cross-reference results. Because of the immense area of Greater Angkor, a distinction was made between rather small-scale grids and large-scale profiles – so along with the detailed survey of areas of smaller size, it was possible to target large areas as well, by transecting long distances.

For the archaeological prospection, old and new research was reviewed to understand the regional geologic and environmental characteristics, as well as the history of Angkor from its inception to its decline, following the changing approaches of study and perception. Architectural and excavation plans were used and maps were consulted to comprehend and connect elements within the palimpsest landscape.

Getting GPR on the ground

As a first step in the application of ground-penetrating radar, the chosen technique was tested from December 2007 till January 2008 for its potential to identify archaeological remains on site. The regional environment and geology had to be considered. Soil properties and seasonal flooding and human made obstacles had a large impact on the outcome of results. During the research the actual results were compared with expectations, and the survey procedures were accordingly adjusted. After initially applying both, the 500MHz and the 250MHz antenna, the latter was chosen for most of the surveys as it provided greater signal depth without losing too much resolution. For the following field seasons from December 2008 till February 2009, from November 2009 till February 2010 and in June and July 2010 the initial cart was replaced by a handle to pull the equipment on a skid, to reduce transport weight and minimize the potential of equipment failure.

Initial analysis was done on site with integrated equipment programs, followed by more detailed processing using special GPR gridding software. It was important to have software that could deal with and simplify large amounts of data of a variety of archaeological sites, which was collected extensively on site in 3 years over a total of 11 months. A total of 200km of GPR profiles were conducted across the floodplain of Angkor, and about 900 anomalies were identified and classified for this study. More than 12ha of the Angkor area was covered by GPR grids, which corresponds to more than 240km of walking.

In addition GPR results were complemented with other techniques. Available and new *remote sensing* images provided necessary information to plan the surveys, to interpret the results and for further analysis of landscape features. GIS was used to merge the different information into a spatial data base for further analysis. In a number of cases the results were additionally studied by excavation, either by the author or members of GAP and were integrated in the thesis.

There is a large amount of information buried in the subsurface of Angkor that GPR can detect, identify its location and form, and so help to precede further studies seeking a better understanding of the history of Angkor. The potential and limits of GPR were assessed on various features in the Angkor region and some regional centres - as a stand-alone technique and in combination with remote sensing and archaeological excavations. As a result the surveys helped to discover so far unknown structures, most prominently in the case of the proposed quincunx tower configuration whose demolished remains lie east of Gopura 4 West, and the buried inlets and outlets of several of the major water management features.

Loose Soil and Compact Surfaces: Environment

The principal GPR survey areas were all situated within the floodplain of Angkor where the near-surface geology consists predominantly of clayey sand. Soil composition was a dominant factor in radar signal penetration depth, and had a strong influence on the results. The main soil attributes concerning the survey were basically wet and loose ground in seasonally flooded areas compared to dry and compact soil on elevated parts of the plain.

Greatest signal depth of over 5m was measured in former river beds, where the original clayey sand was washed away and replaced by relatively recent deposits of loose sand. The raised earthworks of canal and reservoir embankments as well as temple and habitation mounds provided lesser signal penetration depth. Generally this depth was sufficient for the mapping of anthropogenic evidence close to the surface. Natural rock layers were only measured in the vicinity of the volcanic hills of Phnom Bakheng and Chau Srei Vibol and did not play a major role in the analysis. Modern roads and paved areas prevented interpretation of the subsurface as the multiple layers of compacted rubble and concrete dispersed the radar signal immediately. The signal penetration depth differed markedly in other places outside Angkor. Lateritic soil close to the surface, as seen in Koh Ker and Preah Khan of Kompong Svay, provided little penetration depth. In those locations anomalies were measured only in the uppermost layers of soil.

Detectable or Untraceable: Living Patterns

Small differences in the soil were of great importance in area surveys without masonry remains, as was shown for the analysis of 'living patterns': habitation sites, cemeteries and production sites. The surveyed mounds consisted predominantly of hard clayey sand. The measured - for the most part chaotic - patterns of anomalies within the mounds may be due to layers of occupation, but were not further interpretable with the method applied. A simple distinction could only be made between potentially once occupied and unused space, where geometric features, so at Banteay Srei, could give a hint on the extent of the site. Concerning the pre-Angkorian cemetery site of Phum Sophi, only recently excavated areas were easily recognizable, which was the case for looted graves. Untouched grave sites were not detectable. Some areas had, over the centuries, also served as habitation mounds, so the surface is significantly compacted. In contrast, for production sites the central part of those mounds - such as the fire chamber of kilns at Bangkong or the slag contingent of furnaces at Preah Khan of Kompong Svay - was clearly distinguishable from its surrounding. Again soil density and composition affected the surveys. While the soil covering the kiln provided signal penetration depth to receive an image of and measure the fire chamber, the material used for the slag mount did not permit sufficient penetration.

Structures and Gaps: Monumental Configurations

A shallow penetration depth, in itself, may give significant subsurface information concerning masonry remains. The successive relocation of the political centre, and the remodelling of the central part of Angkor over the centuries, extended the area of development. Monuments were increasingly constructed near preceding ones and cut across the earlier landscapes of causeways and adjacent buildings. The end of large scale construction left the subsurface fairly undisturbed with archaeological evidence covered by a relatively small amount of deposit.

Medieval Khmer constructions were predominantly on naturally or artificially raised elevated grounds, which were not susceptible to flooding. This narrowed the target area for potential structural features to a small percentage of the total region. By considering the characteristics of Khmer architecture and their application of geometry, the search was focussed on the remains of potentially destroyed elements of monuments. Existing architectural plans and results from former excavations helped to confine the survey area more precisely. The grids inside Angkor Thom, at Prei Monti and inside Angkor Wat revealed buried structures in relation to still-standing masonry remains or elevated terrain.

The most significant discovery made was the configuration of the six towers and additional foundations in the vicinity of the main entrance of Angkor Wat. The image of the subsurface clearly shows a relation to the outline of Gopura 4 West and the main temple. The following excavation revealed evidence that the towers were in part contemporary with the construction of Angkor Wat, and were (at least partly) demolished with the construction of the *gopura*, whose central part was later remodelled with temporary structures. - In combination with historic data, the results help to enhance the knowledge on the construction history of the western entrance at Angkor Wat, underlining the gain of visualizing the subsurface of the surrounding area of a monument. The interpreted pattern can be investigated to identify the succession of construction and demolition in the stratigraphy of excavations.

The survey also targeted enclosures that so far have not been in the focus of research. The target was predominantly masonry foundations at locations selected, the rules of elevation and geometry narrowing the survey area to small but relevant parts of the interior. The masonry foundation discovered to the south of the stela pavilion of Prasat Komnap, and possibly the results from Prasat Oung Mong, mirror the ensemble of structures at the *asrama* of Prasat Prei.

Around the reservoir of Chau Srei Vibol, the anomalies possibly refer to modern structures standing in relation to the remaining masonry stairs, while little else is distinguishable as anthropogenic. The subsurface of the elevated parts of Banteay Sra, especially in the northeast corner display evidence for structural remains. More extensive coverage of the surveyed enclosures was otherwise prevented by forest (Angkor Wat), shrubs (Prasat Komnap), land mine threat (Chau Srei Vibol) or flooding (Banteay Sra), and was constrained by a concern about whether, at the time the complete coverage of interiors of enclosures would reveal sufficient additional information to justify the work effort.

Inlets and Outlets: Reservoirs Infrastructure

There is evidence that water entered into the *baray* through the northeastern corners. Additional potential masonry inlets were found by GPR in the northern embankment of the Indratataka, and possibly the masonry floor of an inlet in the northeast corner of the Yasodharatataka.

The GPR results also provided new evidence of potential outlets in the central area of the eastern embankments of all four *baray*. There is a variety in the design of these eastern outlets as they differ in size, style and regarding the material used: a masonry floor at the Indratataka, massive and well carved masonry structures at Krol Romeas, possibly a simple but broad earthen breach at the West Baray. A potential outlet barred by the Ta Som enclosure walls in the Jayatataka, has not yet been investigated by excavation. This would probably not have worked for long - as the Ta Som is considered to have been constructed in the same period as the *baray*.

Here the study contributes to the understanding of the development of the hydraulic infrastructure and system. The discovery of additional inlets and outlets adds to the debate and can clarify the function of the reservoirs, as assumptions on how water was distributed out of the *baray* are numerous. Earlier research has shown that the massive embankments are largely impermeable, and natural evaporation of the water is negligible. This leaves breaching of the embankments, possibly supported by reinforcement of the walls which, however, do not indicate any specific purpose, as sluice gates would. Several construction stages at Krol Romeas, and additional inlets and outlets in one *baray*, considering the masonry structure in the southern embankment of the Jayatataka, show that perhaps new practices were implemented during the development of the *baray*, which may have influenced their function. The inlet in the northeast corner regulated the water level of the reservoir, which was lower than the *mebon.* The outlet in the east provided a runoff for the excess water to distribute it to the rice fields or shunt it towards Tonle Sap. As no exact dates exist about the time of functioning of any of the *baray* and their infrastructure, a precise dating of the outlets would help to clarify the working order, which would contribute to understanding the development of the network.

Close Range and Remote Sensing: Landscape

As a result of the large scale GPR surveys a database was developed of anomalies that identified additional channels as part of the water management network. The surveys mapped the extent of embankments and the actual depth and width of canals, showing that the size of the water carrying canal beds differed significantly from what was mapped by remote sensing methods. Canals that were mapped by remote sensing but not detected by GPR must have either not functioned for long, or only modest sedimentation happened at the time the channel was used.

In the case of the ‘river bed’ running through the Yasodharatataka, it was shown that the channel becomes smaller downstream and therefore could not have been a river of the original floodplain.

Large parts of the plain were covered by seasonal flooding. In combination with remote sensing, GPR has shown potential to distinguish areas of former river beds and to establish a map of the “original” landscape. A clear distinction between the original streams and the artificial network, however, is complicated, as signal patterns are similar and can often only be categorized as disturbance, channel, moat and pond, and to a lesser extent breach and embankment, with additional remote sensing data. A large proportion of the anomalies interpreted as potential channels are not associated with any elements displayed in the archaeological map. Some of them may have been natural features, originally shallow ponds and natural streams, which once had covered large parts of the floodplain. They can be seen on satellite images in the area closer to the Kulen and to some extent south of it, which shows no strong evidence of urbanization and possibly indicates the original landscape.

When the rivers were redirected from their original path into canals in the Angkorian period and the landcape was urbanized, those older fluvial features must have been filled with soil and are now covered by rice fields. For some parts of the network it can be assumed that during remodelling, existing canals were filled with earth and embankments to prevent them influencing the new flow direction. Others will have eroded naturally. By covering the region with a net of single GPR transects, as in the case of Hariharalaya, the extensive surveys have shown that the technique is capable of comprehensive mapping, and the data appraises and complements the archaeological maps. It adds to the understanding of how the hydraulic infrastructure of the network developed, and how the landscape was integrated.

Potential of GPR

GPR at Angkor has in itself been useful for the discovery of assumed objects, it has successfully been applied for the identification of reported features, and it has been helpful for the appraisal of known features. Sensing its objects from close range, it has to be adapted to the conditions on ground, which, in comparison with remote sensing, can mean various forms of restriction.

The full potential of GPR is realized in cooperation with other disciplines, to connect different of researchers for a complementing study, by linking preparatory surveys and the work following it. The analysis of an archaeological site is dependent on the level of preceding knowledge. Regarding a target area that has been detected by remote sensing, the research can appraise existing maps. If the site is described in historic sources, the focus for GPR surveys is to identify the precise location, gather information about a potential underground structure, and measure its extent and form. Architectural plans provide the needed information in the search for missing elements of an assumed configuration. The GPR survey can then provide the data on potential, former or proposed geometries of the structures, to complement the information from visible remains or the outline of related structures. When only the distinct topography of a site indicates a potential archaeological feature and no additional information is available, the GPR serves as a tool for the search for and develop an initial interpretation of potential cultural remains, preceding excavations and other studies. The collective results show that great gain is made from cooperation with other disciplines.

Central Angkor, due to its construction history, was a palimpsest of construction, destruction and remodelling, with large parts still buried and having yet to be investigated. At the same time, the whole of Greater Angkor was a *low density urban complex*, overlaying a natural landscape, and whose engineered networks of canals and embankments were successively modified or replaced. GPR was suited for the small-scale investigations of the different and hidden components of the historic periods, as well as for the large-scale investigations of earthworks and water-management devices. The results show that knowledge about the subsurface, provided by this non-intrusive survey tool, can be critical for understanding development and change throughout Angkor.