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# Airborne laser scanning as a method for exploring long-term socio-ecological dynamics in Cambodia

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## ABSTRACT

Early Khmer societies developed extensive settlement complexes that were largely made of non-durable materials. These fragile urban areas perished many centuries ago, and thus a century and a half of scholarly research has focussed on the more durable components of Khmer culture, in particular the famous temples and the texts and works of art that are normally found within them. In recent years however there has been a considerable effort to broaden the perspective beyond conventional approaches to Khmer history and archaeology. Remarkable advances have been made in the domain of remote sensing and archaeological mapping, including the application of advanced geospatial techniques such as airborne laser scanning within studies of heritage landscapes at Angkor and beyond. This article describes the most recent applications of the technology in Cambodia, including the results of a newly-completed campaign of airborne laser scanning in 2015—the most extensive acquisition ever undertaken by an archaeological project—and underscores the importance of using these methods as part of a problem-oriented research program that speaks to broader issues within history and archaeology.

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## 1. Introduction

Archaeologists working in many parts of the world have already begun to address many of the “grand challenges” facing contemporary archaeology (Kintigh et al., 2014) by using landscape-scale investigations to elucidate complex relationships between climate, subsistence, and urban morphology over multiple scales of time and space. The work has offered new insights into the sustainability of the great low-density cities of the Maya, for example, with findings that clearly resonate into the contemporary world (Dunning et al., 2012; Fisher et al., 2009; Isendahl and Smith, 2013). At the present time, however, very little comparative research at such a spatio-temporal scale has been pursued in monsoon Asia, in spite of the fact that the region—home to several great ‘tropical forest civilisations’—offers some of the greatest archaeological potential in this domain of inquiry (Fletcher, 2012). The Cambodian Archaeological Lidar Initiative (CALI) aims to address this shortcoming by extending a previous landscape-scale airborne laser scanning (hereafter ‘ALS’) survey completed in 2012 (Evans et al., 2013) to produce a highly consistent, comparable suite of data for archaeological landscapes across Cambodia in order to facilitate

comparative, quantitative spatio-temporal analyses.

Since the 1990s, evidence has gradually emerged that vast, previously undocumented urban landscapes may lie beneath the forests that surround the well-known temple sites of Southeast Asia. Using the unique ability of new laser imaging technologies to ‘see through’ vegetation and uncover remnant traces of past societies, CALI completed a new ALS campaign in March–April 2015 that has dramatically expanded coverage beyond the test areas covered in the 2012 campaign (Evans et al., 2013). At the time of writing much of the data are still being analysed and ground verified, while in other areas excavations based on the results are nearing completion. It is already clear, however, that the programme has successfully uncovered and mapped previously concealed urban networks by comprehensively imaging the areas surrounding all of the major temple complexes in Cambodia, the heartland of the Khmer. The new data provide a foundation for conducting the first highly-detailed landscape studies of those urban areas, in order to arrive at a more sophisticated understanding of chronology, environment and residential life. The maps provide a framework for conducting extensive and systematic field investigations to document ceramics and other time-diagnostic material. The new data are being integrated with existing archives of archaeological and environmental data within a geographic information system (GIS). The net result of this work is a uniquely

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comprehensive spatio-temporal database of urban morphology spanning nearly two millennia, from prehistory to the transition to modernity in Southeast Asia. Spatial analytical techniques are being used to interrogate the database, in order to analyse the growth and decline of early urban centres and reveal long term patterns of human–environment interactions at the regional scale.

## 2. Background & rationale

One of the main issues in the archaeology of the pre-modern Khmer world is that masonry was used almost exclusively for the construction of religious monuments (with the exception of bridges and other features related to water management such as culverts and spillways). The urban and agricultural networks extending between and beyond those monuments—including structures as significant as the royal palaces of Angkorian kings—were almost entirely made of earth and of non-durable materials such as wood and thatch (Fletcher and Pottier, 2002). As a result, most scholarship on early Khmer societies has come from the fields of architecture, art history and epigraphy, and the urban context of the monumental remains is relatively poorly understood. The construction of these extended agro-urban environments, however, involved re-engineering the landscape on a scale perhaps unparalleled in the pre-industrial world: wooden neighbourhoods, for example, were built on top of mounds of earth designed to keep them above floodwaters in the wet season; many thousands of ponds and canals were excavated; and roads, field walls and dykes were made of earthen embankments. Cultural deposits are relatively shallow in Cambodia, and (compared to neighbouring countries) remain relatively undisturbed by modern development, which means that the traces of these agro-urban landscapes remain inscribed on the terrain with considerable clarity in the form of patterned undulations on the surface, or what we might term ‘archaeological topography’ (Opitz and Cowley, 2013).

In recent years, using an integrated suite of methodologies ranging from remote sensing to excavation, archaeological maps of Angkor have been produced which, for the first time, provide a holistic picture of the settlement, including residential areas, agricultural systems, infrastructural networks, ritual spaces, and a fivefold increase in the number of documented temples (Evans, 2007; Evans et al., 2013; Pottier, 1999).

The work at Angkor has had far-reaching implications for our understanding of interactions between humans and their environment in medieval Southeast Asian landscapes. As has been argued for many years (Diamond, 2009; Fletcher, 1995, 2012; Groslier, 1979), “resolving questions relating to the scale, structure, and population density of Angkor is critically important not only for evaluating the sustainability of settlement growth there, but also for explaining the collapse of classical Angkorian civilisation and for understanding the nature of early urbanism in tropical forest environments in general” (Evans et al., 2013). One of the conclusions to be drawn from Angkor is that its immense ‘engineered landscape’ may have imposed a kind of inertia that limited its adaptive capacity in the face of rapid socio-ecological change. Sophisticated technologies of water management may have provided a degree of resilience on an annual scale by ensuring food and water security for an ever-larger and increasingly urbanised population; paradoxically, however, those same systems would also have created a systemic vulnerability to longer-term climatic variation on the decadal scale or greater (Buckley et al., 2010; Day et al., 2012; Diamond, 2009; Evans et al., 2013; Fletcher et al., 2008; Lieberman and Buckley, 2012; Penny et al., 2007).

Recent research (Evans, 2010; Evans, 2010–2011 [2013]; Evans and Travaglia, 2012) has indicated that massive investments in water engineering were not unique to Angkor, but may have been a

common characteristic of many early Khmer cities from the pre-Angkorian period (~5th to 8th centuries AD) through the Angkor period (9th to 15th centuries AD) and possibly even into the post-Angkorian period (15th to 19th centuries AD).

Almost all of those places, however, remain poorly understood beyond their civic-ceremonial centres, much the same as Angkor itself until recently. Projects of archaeological mapping have been set in motion by various international teams in association with Cambodian colleagues, and have made significant progress in beginning to come to terms with archaeological landscapes at provincial centres of the Angkor period, and at the settlement complexes that came before and after Angkor (Evans, 2010; Evans and Travaglia, 2012; Heng, 2012; Phann et al., 2007; Shimoda, 2010). Until 2012, however, the key limitation of all this work—including at Angkor itself—was the inability of conventional sensors, and even more advanced active sensors such as high-resolution polarimetric/interferometric synthetic aperture radar, to penetrate the vegetation that obscures much of the archaeological topography. Even at Angkor, where projects of archaeological mapping had been underway for a century and a half, large blank spaces remained on the map (Evans, 2007).

The 2012 ALS campaign over Cambodia undertaken by the Khmer Archaeology LiDAR Consortium (KALC) showed clearly that laser-scanning technology provides an extremely effective solution to this problem (Evans et al., 2013). The application of ALS completely transformed our view of all of the covered areas, in some cases unexpectedly revealing entire urban landscapes beneath dense jungle canopy (Evans et al., 2015). The campaign has resulted in a range of significant research outcomes in archaeology as well as other domains such as forest ecology (Singh et al., 2015a, 2015b), and ALS-derived datasets now play a key role in the management of the World Heritage site. Analysis and interpretation of the 2012 data will continue for years to come. Because of the incredible richness of the archaeological topography, it has become clear that Cambodia has a heritage landscape that is perhaps without parallel in Southeast Asia, although it is under threat from modern development. The 2012 ALS campaign in Cambodia, even though limited in extent, for the first time allowed us to envisage that assemblage of engineered landscapes as a unique laboratory for exploring socio-cultural adaptations to environmental variability and change, within the theoretical framework of modelling vulnerability, risk, and adaptation in human systems. Such a program requires a comprehensive understanding of urban form over the widest possible scale of time and space, and this understanding can only be derived from extremely detailed archaeological maps followed by a program of ground-work to enhance the temporal dimensions of the data. This provided the overall rationale for launching a greatly-expanded ALS campaign in 2015, funded by the European Research Council (Fig. 1).

## 3. Methodology

The KALC program in 2012 acquired ~370 km<sup>2</sup> over northwest Cambodia in a campaign that was specifically designed to maximise the resolution and accuracy of the resulting terrain models and highlight archaeological topography (Evans et al., 2013). The methodology and parameters used for the 2015 campaign were much the same as for 2012. Acquisition was completed at the end of the dry season in March/April in order to take advantage of peak ‘leaf-off’ conditions in deciduous trees, and also towards the end of the annual burn-off of vegetation by the rural population, with a view to maximising ground returns. This period is also the cusp of the dry and wet seasons, so the first rains of the year had extinguished many of those fires, reduced the levels of smoke and haze, and compacted leaf litter and other debris on the forest floor. The

amount of cloud cover and rain during this period however is not yet enough to cause significant difficulties for flight operations.

A Leica ALS70 HP instrument was mounted in a pod attached to the right skid of a Eurocopter AS350 B2 helicopter along with a 60 megapixel Leica RCD30 camera. Data specifications were for >16 points per m<sup>2</sup> with a vertical accuracy of 15 cm RMSE. This accuracy and point density (or in most cases, much greater point density) was achieved by flying at altitudes of 800–1000 m above ground level at a speed of ~80 knots, with the ALS70 configured to Multi-pulse in Air (MPiA). The pulse rate was 500 kHz with a scan angle of 45° from nadir and a swath sidelap of 50% (i.e., almost all terrain was scanned twice from different angles). Aircraft attitude was measured by a Honeywell CUS6 IMU at a rate of 200 kHz and positional data was logged at 2 Hz using a survey-grade L1/L2 GNSS receiver mounted in the tail rotor assembly. Full waveform data was additionally acquired over heavily-forested regions of the Kulen block with scan lines perpendicular to the MPiA lines and the ALS70 instrument set to a pulse rate of 120 kHz (Fig. 1), but at the time of writing these data had not been analysed or processed into discrete points.

A network of fixed survey benchmarks was established on the ground prior to flight operations with a relative accuracy of  $\pm 3$  mm, and conforming to the Cambodian national WGS84 survey monuments to within  $\pm 20$  mm horizontal and  $\pm 50$  mm vertical. During flight operations, survey-grade L1/L2 GNSS receivers were placed on our network of benchmarks and logged positional data at 1 Hz for differential correction in post-processing; no ALS data were acquired at any distance greater than ~35 km from a ground station. Also prior to flight operations, a reference network of at least 100 ground control points was measured in or near each major acquisition block using survey-grade L1/L2 GNSS receivers in real-time kinematic (RTK) mode (horizontal accuracy of  $\pm 20$  mm horizontal and  $\pm 50$  mm) and overflown for each aircraft sortie. Data were processed into imagery products in Terrascan and ArcGIS software according to the methods established for the 2012 KALC acquisition (Evans et al., 2013; Evans et al., 2015).

#### 4. Results & discussion

The total coverage of the CALI program in 2015 was ~1910 km<sup>2</sup>, compared to the 2012 coverage from the KALC program of ~370 km<sup>2</sup>. Accounting for a ~50 km<sup>2</sup> overlap between the 2012 and 2015 acquisitions, the amount of ALS data acquired over Cambodia in 2012–5 specifically for archaeology now totals ~2230 km<sup>2</sup>.

At the time of writing, post-processing of the 2015 data was incomplete and only limited areas were available for analysis. Nonetheless, as with the 2012 ALS campaign completed by KALC, the available new data from CALI illustrate, confirm and expand upon a range of long-held and well-established assumptions about archaeological landscapes from conventional studies. On the other hand, the new data have once again produced a range of unexpected—and sometimes quite enigmatic—outcomes that call into question various long-standing theories about the development of Khmer society, agriculture and urbanism. Looking specifically at each of the major acquisition blocks (Fig. 1), and the major implications for Khmer history and archaeology:

##### 4.1. Beng Mealea, Phnom Kulen & Northern Angkor

Conventionally, the classical Angkorian period begins with the 8th–9th century city of Mahendraparvata, in the forested Phnom Kulen ranges to the north of Angkor. Until recently the structure of this city was very poorly defined; however, the 2012 ALS campaign suddenly brought the urban network into very sharp relief, as well as adding insights into the level of Angkor-era deforestation and

the sustainability of its water management infrastructure (Evans et al., 2013; Penny et al., 2014). It was suspected, however, that the 2012 campaign had captured only a subset of a much more extensive urban network on Phnom Kulen. The 2015 data confirm this suspicion and show that archaeological features continue well beyond the edges of the original 2012 coverage (Fig. 2). There is evidence that Angkor-period archaeological topography is to be found almost continuously over an area of at least 40–50 km<sup>2</sup>.

Much of this archaeological topography consists of linear or grid-like arrays of mounds (Fig. 3), of the kind that were first identified in archaeological maps of Angkor in aerial and radar imagery by Christophe Pottier and the author in the 1990s and early 2000s (Evans et al., 2007), and that have now also been identified at the pre-Angkorian site of Sambor Prei Kuk in the new ALS data (see below). Surface surveys and excavations of these mounds have revealed little of archaeological interest (Jean-Baptiste Cheavance and Martin Polkinghorne pers. comm.), and they remain among the most enigmatic features of Khmer landscape archaeology. In low-land areas such as near Banteay Srey (Fig. 2; Fig. 3e,f) these gridded mounds (sometimes referred to by archaeologists as ‘dome-fields’) seem to have an association with significant water management features. However, this association is difficult to establish in Phnom Kulen, where the gridded mound-fields are abundant and important elements of the ‘hydraulic city’ of Mahendraparvata are ubiquitous, making a spatial correlation almost inevitable.

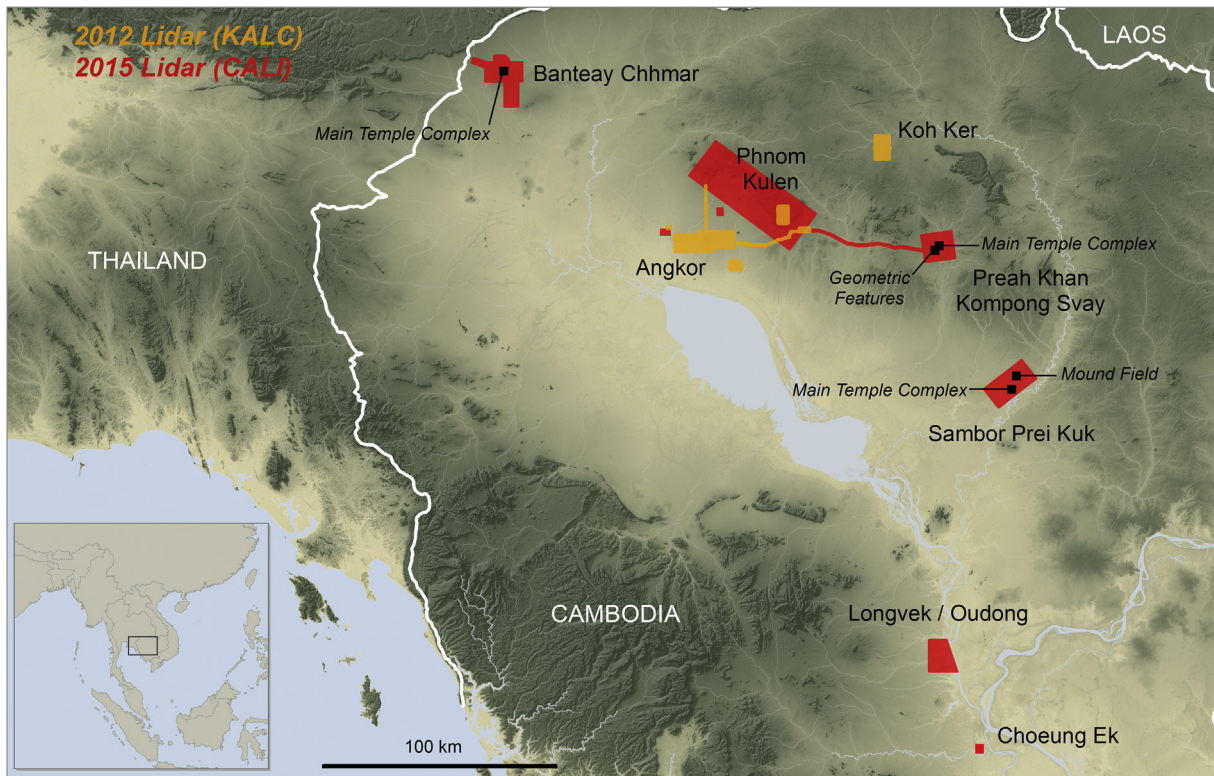
Equally enigmatic are the geometric rectilinear patterns (Fig. 4) made from earthen embankments—variously described as ‘coils’, ‘spirals’, ‘geoglyphs’ or ‘gardens’—first identified south of the moat of Angkor Wat in the 2012 data (Evans and Fletcher, 2015; Evans et al., 2013). These are now also clearly visible in the 2015 data at Beng Mealea, and can be seen in particular abundance at Preah Khan of Kompong Svay (see below). Excavations of these linear features at Angkor have also revealed little of archaeological interest, and their function remains unclear, although they too seem to be located in close proximity to (what would have been) large standing bodies of water.

The 2015 data also provide new insights into relatively well-known archaeological sites. The quarries between Beng Mealea and Phnom Kulen, for example, have been the subject of inquiry since the 19th century, and are generally recognised as the main source of sandstone for Angkor’s monuments. Canals have been traced linking the quarries to central Angkor (Boulbet, 1979; Evans et al., 2007) and one recent study (Uchida and Shimoda, 2013) reported the ‘discovery’ of ‘more than 50’ discrete quarries in the area, with distinct groupings of individual quarries with different sandstone characteristics. In reality, as the new data clearly show (Fig. 5), the area between Beng Mealea and Phnom Kulen is essentially one enormous quarry field of ~500 ha with localised heterogeneity in sandstone characteristics, which—although it is mostly infilled—has occasional surface expressions. The signature of infilled pit quarries was first recognised in the 2012 data and was used to identify and ground-verify the largest quarry so far identified at Koh Ker (Evans, 2013:15), and the same signature is clearly visible here. The 2015 data show evidence of opportunistic quarrying in other areas around the foothills of the Phnom Kulen ranges, as well as on top of the plateaux; however, these areas are very modest in size (~5 ha at most) and it remains clear that the main source of sandstone for the temples of Angkor was the giant quarry field between Beng Mealea and Phnom Kulen that is now mostly buried.

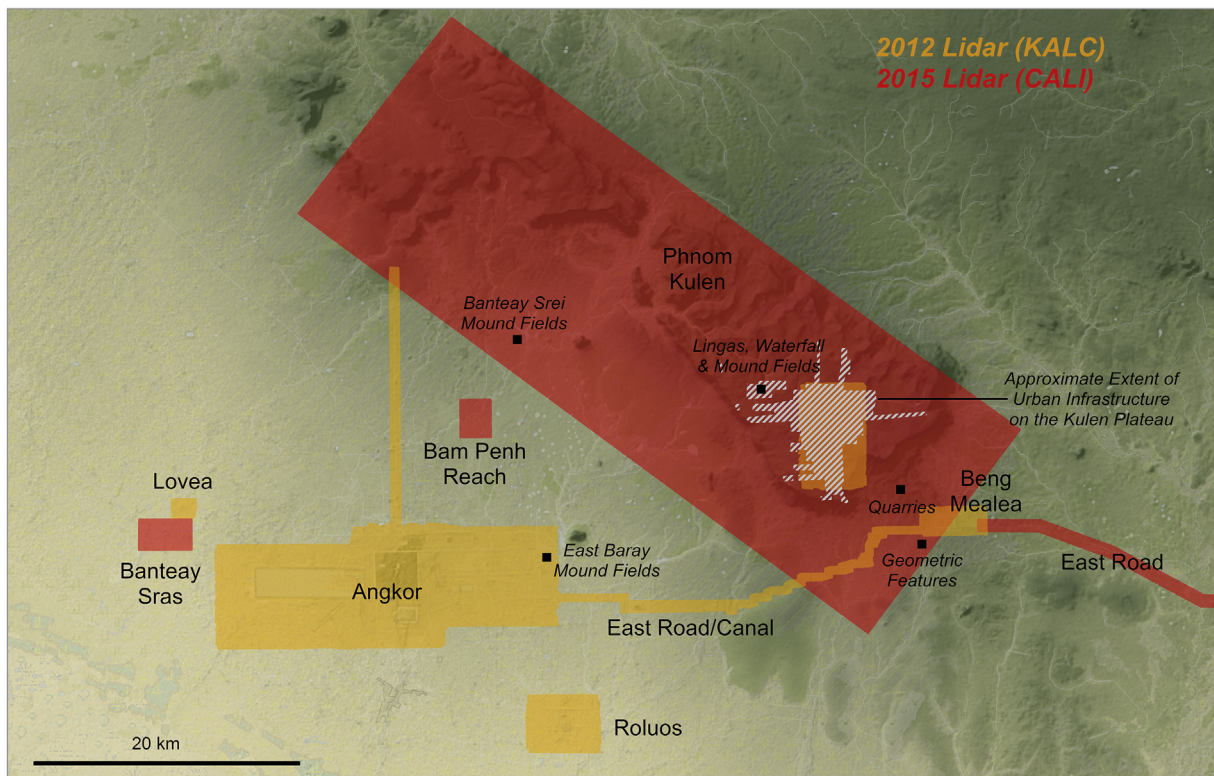
##### 4.2. Sambor Prei Kuk

The temple complex of Sambor Prei Kuk, a capital of the pre-Angkor period from the first few centuries AD until the start of



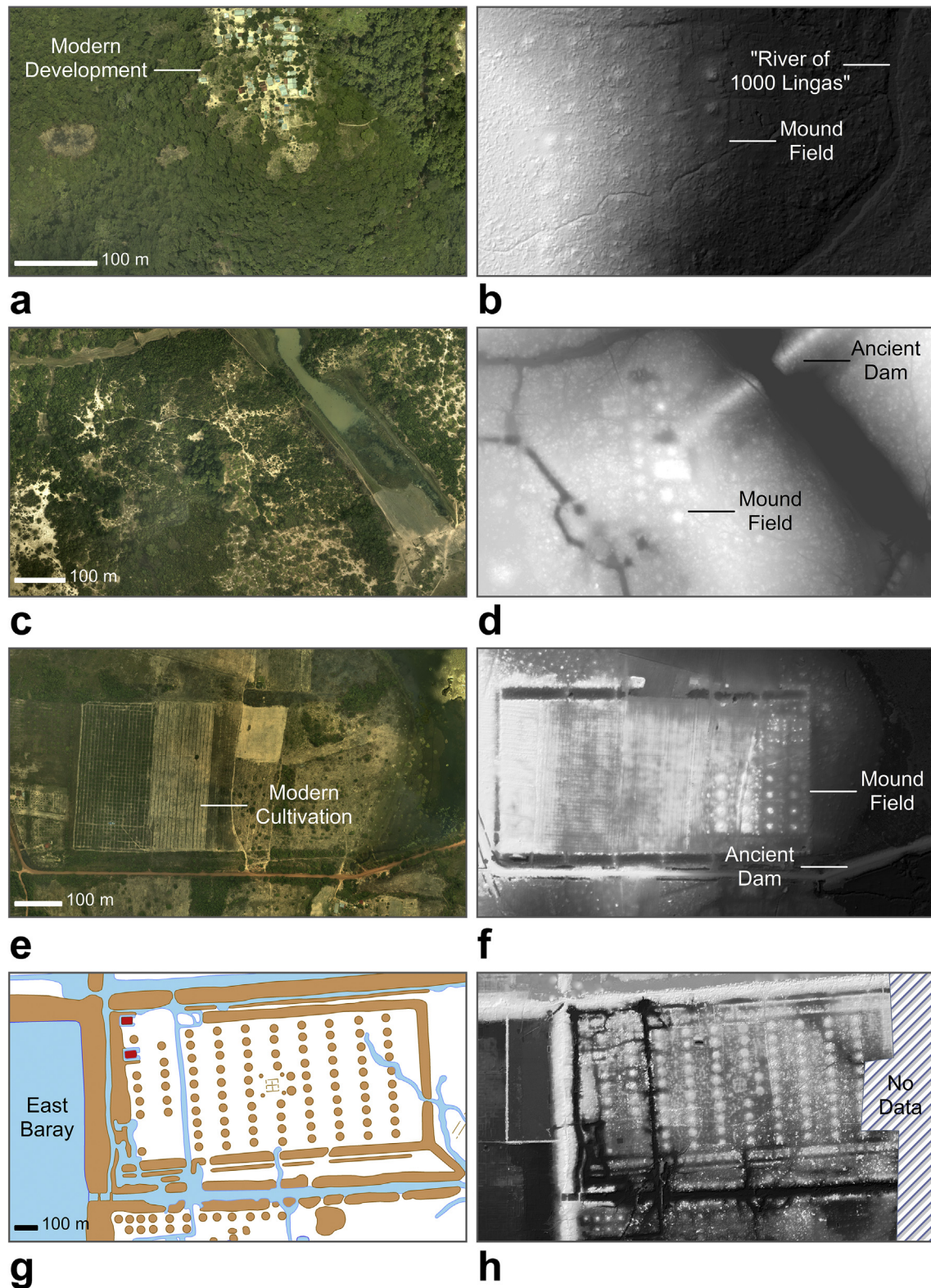


**Fig. 1.** Overview map of Cambodia showing the main coverage blocks for the 2012 and 2015 ALS acquisitions, and noting features mentioned in the text. Background elevation courtesy of NASA SRTM.



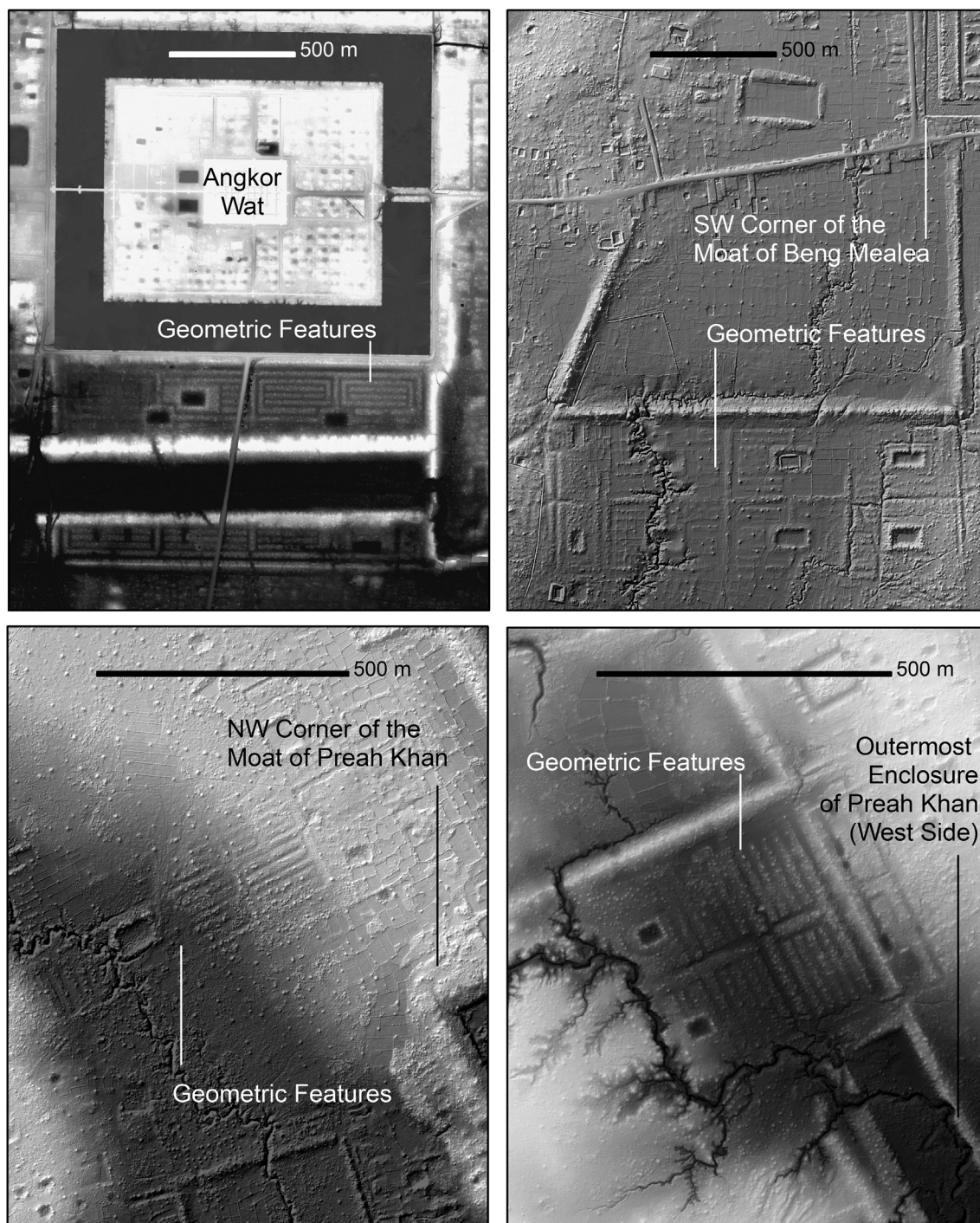
**Fig. 2.** Detail map of northwest Cambodia in the Angkor region, showing the main coverage blocks for the 2012 and 2015 ALS campaigns, and noting features mentioned in the text. Background elevation courtesy of NASA SRTM.





**Fig. 3.** 'Mound fields' across Cambodia. Panels **3a,b**: In the Phnom Kulen acquisition block (see Fig. 2) in an area covered by modern development and forest (**3a**) the laser scanning data reveal a mound field (**3b**). Panels **3c,d**: Immediately to the north of the main temple complex at Sambor Prei Kuk, vegetation (**3c**) obscures a mound field and an ancient dam (**3d**). Panels **3e,f**: Immediately to the west of Banteay Srei temple at Angkor, cultivated areas and vegetation (**3e**) obscure – and have partially erased – a mound field of ~8 'rows' and ~12 'columns' (**3f**). Panels **3g,h**: Near the exit of the East Baray reservoir at Angkor, new archaeological mapping (**3g**) based on the 2012 ALS data has added further detail to a ~10 × 10 grid of mounds (**3h**) and revealed a second mound field to the south of the exit. Panels **3a,c** and **e** are conventional aerial imagery acquired in the 2015 campaign. Panel **3g** is based on archaeological maps by Damian Evans, Christophe Pottier and Pelle Wijker. Panels **3b,d,f** and **h** are ALS-derived bare earth models with a histogram stretch, overlain by a semi-transparent hillshade model.



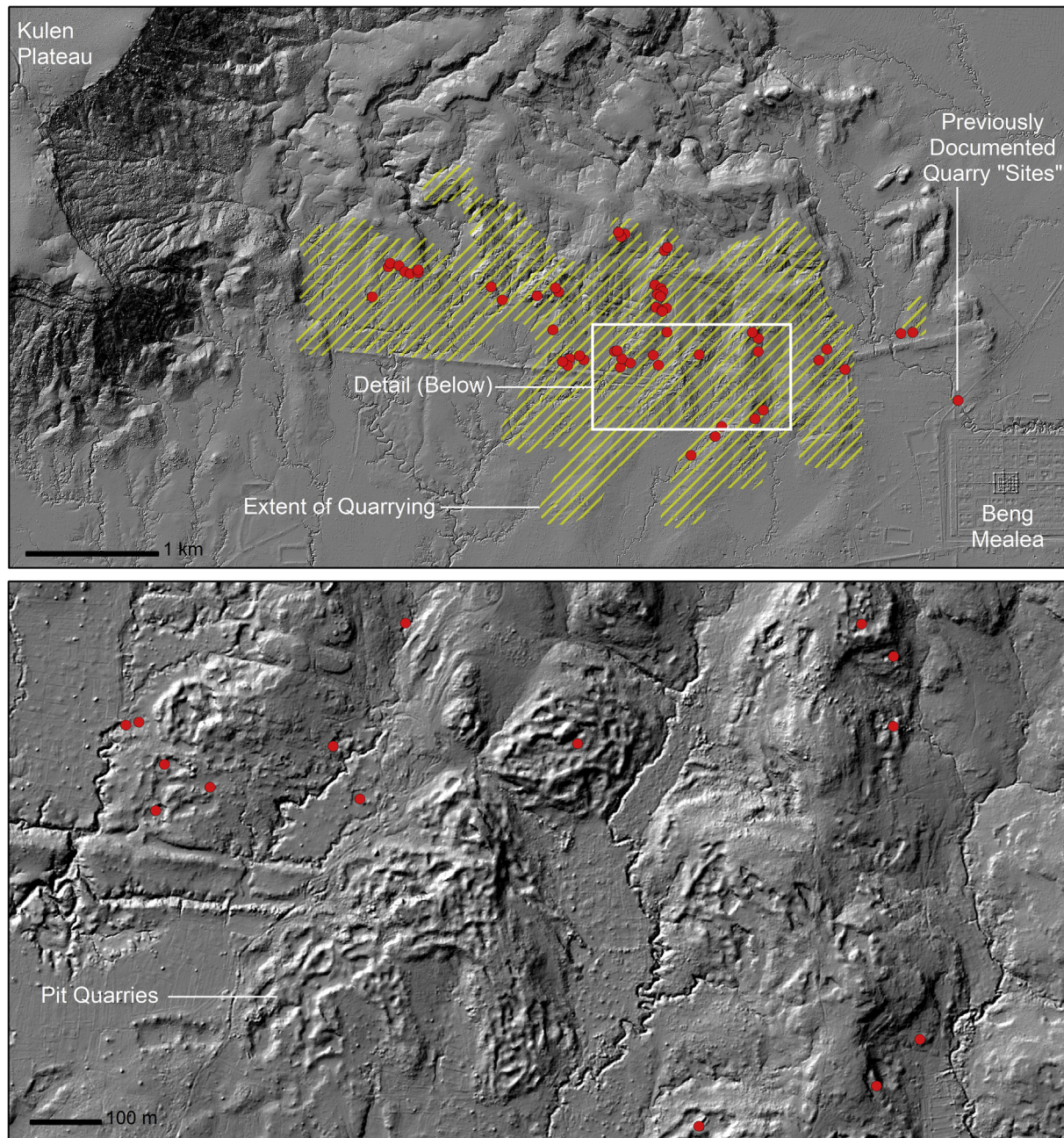


**Fig. 4.** Unexplained, geometric linear patterns associated with major temples across northwest Cambodia. Imagery consists of ALS-derived bare earth models with a histogram stretch, overlain by a semi-transparent hillshade model.

the Angkor period in the 8th–9th centuries, represents a major lacuna in our 2000-year archive of Khmer urbanism and has significant archaeological potential (Shimoda, 2010). The CALI program acquired ALS data over ~200 km<sup>2</sup> at this site. The new data do not represent a radical revision of previous mapping work completed by various teams, but rather clarifies, confirms and expands upon various elements that had previously been identified. Heng (2012) had identified a canal network within the pre-Angkorian site which the new ALS data shows to be far more complex than depicted on

previous maps. This, in turn, may call into question conventional models of the development of orthogonal, ‘gridded’ water management systems and the extent to which they are embedded within urban layouts; this is usually thought to be an Angkor-period innovation, but here we have an example of a very sophisticated urban water management system potentially dating from several hundred years earlier. The engineered landscape of Sambor Prei Kuk is also clearly more extensive, densely-inhabited and more complex than previously believed, and includes elements of urban





**Fig. 5.** Extent of the vast quarry field between Beng Mealea and Phnom Kulen as revealed by the 2015 ALS data, compared to the previous view of discrete quarries as identified by Uchida and Shimoda (2013). Imagery consists of ALS-derived bare earth models with a histogram stretch, overlain by a semi-transparent hillshade model.

form (for example a gridded array of mounds (Fig. 3c,d), and an ancient highway extending to the north) that have not been previously documented at the site. The highway extending to the north is of particular interest as it extends in the general direction of Preah Khan of Kompong Svay. Both Preah Khan and Sambor Prei Kuk each have well-known ancient highways linking them to Angkor, as part of a radial highway network in which it has conventionally been believed that ‘all roads lead directly to Angkor’ (Hendrickson, 2012). If the highway newly-documented here does indeed connect Preah Khan and Sambor Prei Kuk, it would represent the first-known provincial ‘loop’ in the highway system, and would suggest that overland links of transportation and communication between major centres of the era might be usefully reappraised.

#### 4.3. Banteay Chhmar & Preah Khan of Kompong Svay

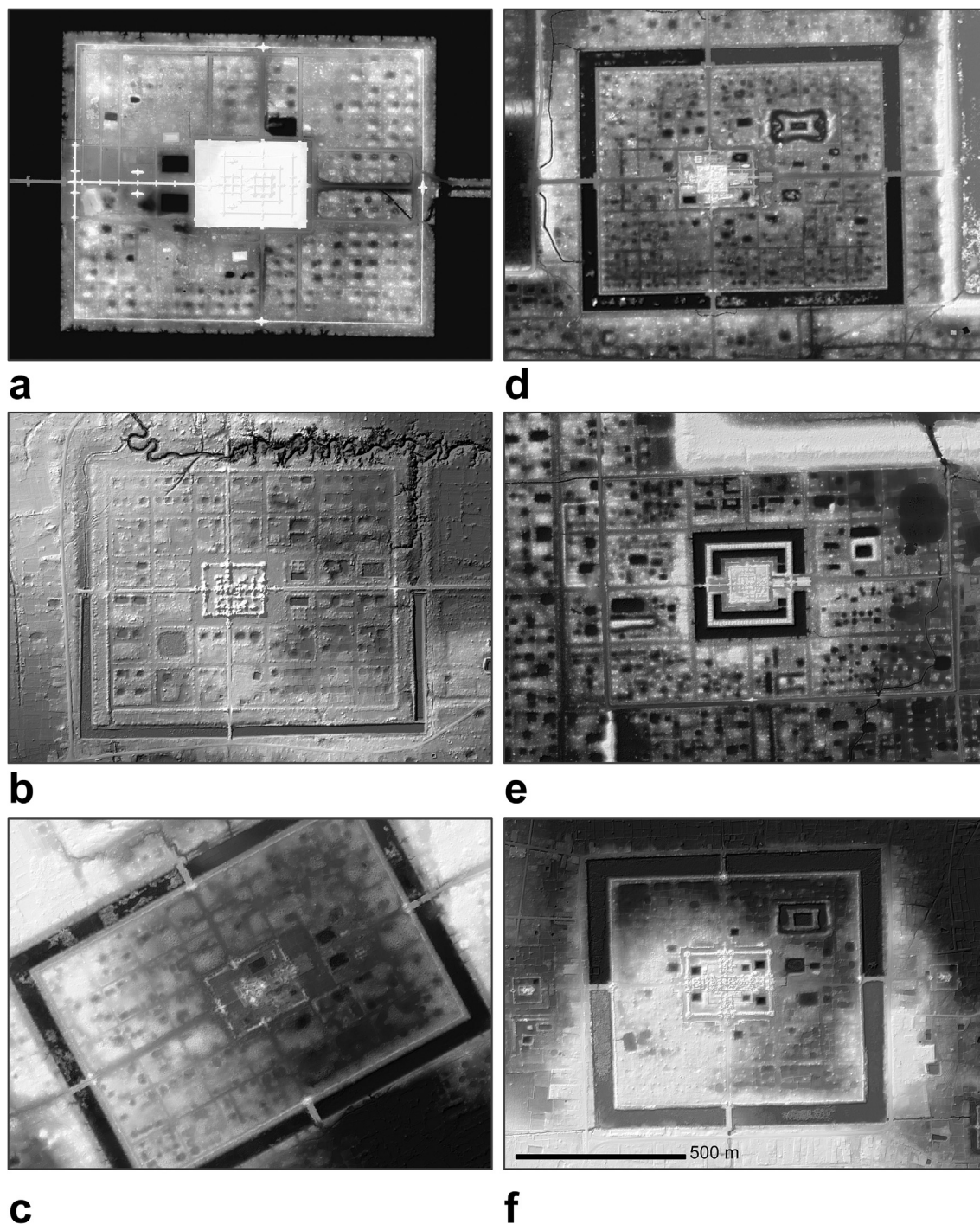
Moving forward in time, the CALI program also acquired ALS data for the two most important provincial centres of the Khmer Empire: ~220 km<sup>2</sup> over Banteay Chhmar, a military centre of the 12th to 13th centuries, located in an arid zone that shows evidence of an extensive water management system (Evans and Travaglia, 2012); and ~150 km<sup>2</sup> over the industrial complex of Preah Khan of Kompong Svay, both of which have recently been the focus of studies using conventional remote sensing and ground survey techniques. Preliminary results at the two locations are strikingly different.

At Banteay Chhmar, the new ALS data essentially confirm previous mapping work, and do not significantly change the overall



interpretation of the archaeological topography (Fig. 6f). Among all the 11th to 13th century CE temples of the Khmer, Banteay Chhmar is the only one so far mapped with ALS that shows almost no evidence of a formal urban grid extending throughout any of its successive enclosures, and represents a (so far) unique exception to the model of urban development proposed by Pottier (2012) and Evans et al. (2013), in which ‘open cities’ of the early Angkor period

gradually evolve into urban complexes with formally-planned urban cores by the 12th to 13th centuries CE. The reasons for this are unclear: was Banteay Chhmar a ‘city’, or was it a ‘garrison-temple’ (Sharrock, 2015) on the fringes of empire that was inhabited ephemerally or episodically? The results at Preah Khan of Kompong Svay, on the other hand (Fig. 6c), present a remarkable contrast: many years of study using conventional sensors and ground survey



**Fig. 6.** Comparison of major ‘temple cities’ at the height of the Khmer Empire in the 12th to 13th centuries CE, all at the same scale. Left column are developments associated with king Suryavarman II (first half of the 12th century), with areas within the moat divided neatly into  $\sim 100 \times 100$  m ‘city blocks’; right column are developments associated with king Jayavarman VII (late 12th century to early 13th century), showing much greater variability in spatial patterning. **6a:** Angkor Wat. **6b:** Beng Mealea. **6c:** Preah Khan of Kompong Svay. **6d:** Preah Khan of Angkor. **6e:** Ta Prohm. **6f:** Banteay Chhmar. All images are ALS-derived bare earth models with a histogram stretch, overlain by a semi-transparent hillshade model.



had led to the conclusion that the enclosures were sparsely inhabited (Hendrickson and Evans, 2015), and yet the new ALS data clearly show an urban layout within the central moat of the site that is analogous to the early-12th century grids of Angkor Wat (Fig. 6a) and Beng Mealea (Fig. 6b)—complete with the enigmatic ‘coiled’ embankments (Fig. 4)—surrounded by an extended, less-organised urban grid that resembles the late-Angkorian urban centres of Jayavarman VII (Evans and Fletcher, 2015; Evans et al., 2013). Excavations recently completed at Preah Khan in 2016 confirm the accuracy of interpretations of archaeological topography visible within the laser scanning data (Mitch Hendrickson pers. comm.).

The ALS data also underscore and confirm a point that was raised in relation to the water management system of Banteay Chhmar in a report from 2011 by Evans et al.: that all three of the major canals attached to the site are designed to lead water away from the temple complex, not towards it. Two of those three canals do not terminate in water storage areas, which suggests that evacuating water for flood mitigation was as important at the site as storing water for the dry season, in spite of the 19th century cliché (Richards, 2007) that Banteay Chhmar is anomalously located in an arid and desolate zone. Almost certainly, in fact, the extremes of the wet and dry seasons presented equal challenges to whatever populations existed in the region, and the likely existence of a spring within the moat of Banteay Chhmar (Evans et al., 2011) would have been a crucial factor in the sustainability of the site during the dry season.

The results at these two sites speak directly to evolving debates about the decline of the classical Angkorian Empire, in which it has been argued that increasing complexity and urbanisation in the 11th to 13th centuries generated large populations of non-rice-producing inhabitants who would have been heavily reliant on elaborate state-sponsored water management systems for the production consistent yields of rice (Evans et al., 2013).

#### 4.4. The post-Angkorian capitals of Longvek and Oudong

Among the most enduring and fascinating topics in studies of the Khmer past has been the ‘collapse’ of Angkor in the 15th century. In conventional accounts this is ascribed to a Thai invasion and sacking of Angkor in 1431–2 in which “the old capital was taken and entirely devastated by the Siamese”, as a result of which the kings of Angkor migrated elsewhere and “Buddhism of the lesser vehicle presided over a melancholy but serene peace” in the centuries to come (Groslier, 2006:3). In spite of the dubious nature of the evidence for the sacking of Angkor, and regardless of evidence for the continued vitality of Angkor and Cambodia in the post-Angkorian period (Groslier, 2006; Marston and Guthrie, 2004; Vickery, 1977) the period between the late 13th to early 15th centuries is now associated with the kind of dramatic demographic decline at Angkor implied by the word ‘collapse’. Recent work arguing for a mass migration or dispersal of the Angkorian populace (Lucero et al., 2015) exemplifies this point of view.

The laser scanning data from 2015 offer us the opportunity to assess one specific aspect of the theory of ‘collapse’. If the post-Angkorian period involved the sudden movement of hundreds of thousands of non-farming urbanites from the ‘downtown’ area of Angkor to post-Angkorian capitals, instead of a more gradual demographic decline due to the breakdown of the water management system and the absence of the food security it provided, then this great ‘diaspora’ should be reflected in the density and/or extent of the urban centres that immediately succeeded Angkor. However, interpretations of the laser scanning data do not support the idea that large, densely-inhabited capitals followed on from the ‘collapse’ of Angkor at post-Angkorian places like Longvek or Oudong, where—even if we can surely see evidence of a relocated

royal court—evidence of a substantial relocated population is essentially absent within the ALS data (Fig. 7). Furthermore, even without the need for cutting-edge technologies, even a cursory analysis of publicly-available satellite imagery casts doubt on historical accounts (Groslier, 2006:116) that post-Angkorian capitals like Srei Santhor had 50,000 inhabitants or more.

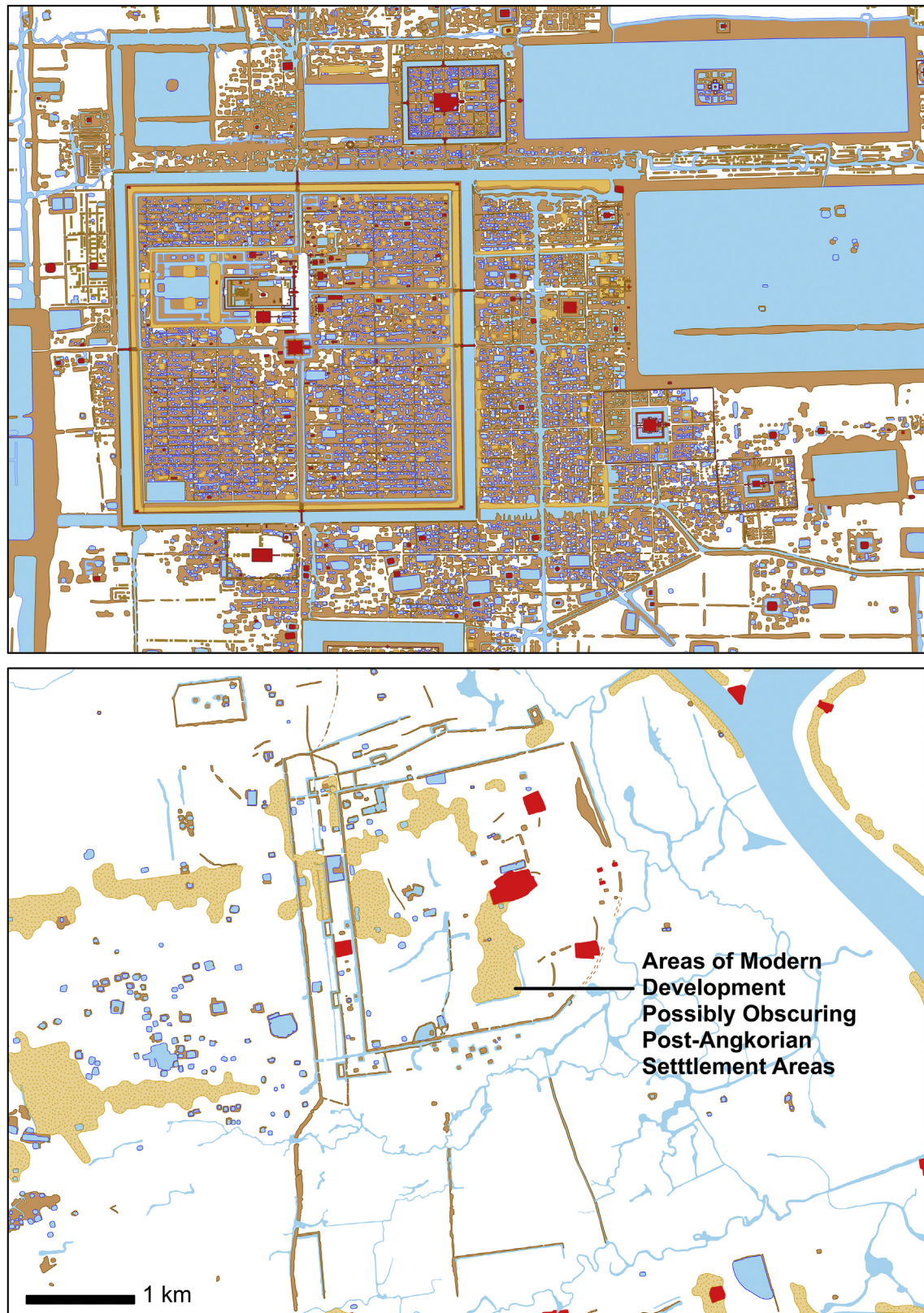
Rupture and mobility are consistent themes in Khmer history and archaeology, perhaps nowhere more so than in studies of the development of Khmer urbanism (Briggs 1999 [1951]; Ewington, 2008; Jacques and Freeman, 1997; Jacques and Lafond, 2007; Vann, 1999). It now seems plausible that an illusion of pre-modern mobility and urban disjuncture has been created by episodes of fusion and fission of authority among different royal houses located within an incredibly complex regional political landscape (Evans, 2010–2011 [2013]; Lieberman, 2003; Stark, 2006; Vickery, 1986, 1994, 2003), and may not, in fact, have involved the physical ‘movement’ of anything much at all, let alone radical demographic shifts, or entire cities being carved *ex nihilo* from the wilderness.

## 5. Conclusion

The acquisition of landscape-scale ALS data allows us to generate incredibly detailed and informative archaeological maps which, even in the preliminary stages of analysis and interpretation, can have important implications for the understanding of socio-ecological dynamics over large scales of time and space. At its height in the 12th to 13th centuries AD, the Khmer Empire stretched across much of mainland Southeast Asia, with a network of highways connecting far-flung settlements to the Angkorian heartland in (what is now) Cambodia (Jacques and Lafond, 2007). It becomes clear from the billions of topographic measurements in the new ALS data that early Khmer societies profoundly, and repeatedly, transformed the landscapes in which they lived and inherited from their predecessors, and that this was a process that took place over millennia at a regional scale (Hawken, 2013; Higham, 2014b; O’Reilly et al., 2015).

Beyond the borders of present-day Cambodia, the surface archaeological landscapes surrounding those temple complexes have, by and large, been systematically destroyed through agricultural and urban developments over the last hundred years, although the contours of most are known at least in general terms (Higham, 2014a), and these datasets will be included in future analyses. Fortunately, however, the majority of the significant Khmer urban centres lie within the borders of present-day Cambodia; here, decades of conflict and relative underdevelopment have conspired to preserve the archaeological topography. Nonetheless, for the sake of consistency and completeness, in the coming years, CALI in association with various other projects will seek to expand the coverage of ALS data to other sites of archaeological significance within the former Khmer Empire, e.g. to places like Wat Phu in present-day Laos and Phanom Rung and Phimai in present-day Thailand.

These data will be used to consider socio-ecological systems at regional scale, over at least the past two millennia. On the one hand, airborne laser scanning technology is able to provide centimetre-level detail on the signature spatial patterning of neighbourhoods and individual households (Evans and Fletcher, 2015; Stark et al., 2015), which offers us the possibility of ‘scaling up’ very fine-grained data from focussed excavations to create demographic models for vast urban areas. On the other hand, landscape-scale data can be used to assess the degree to which massive hydraulic infrastructure afforded a degree of resilience to smaller-scale disturbances (e.g. annual variations in rainfall and religious transformations) while at the same time creating systemic problems



**Fig. 7.** Comparison of settlement density within central Angkor (top) with the post-Angkorian walled capital of Longvek (bottom), at the same scale. Blue and brown areas mark water features and mounded features respectively; at Longvek, it is suspected that some modern development may obscure post-Angkorian remains. Red denotes temple or pagoda precincts. Maps created by Pelle Wijker and Em Sreang based on ALS data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



(e.g. cumulative environmental degradation, or a lack of adaptability) that made the societies vulnerable to transformations occurring at larger spatial and temporal scales (e.g. long-term climate variability). As the present study shows, ALS technology has the potential to make significant contributions to the field of resilience studies in archaeology (Fisher et al., 2009), whose theoretical approach is well-suited to large, multi-disciplinary studies focused on long-term landscape change. One of the key challenges in this domain is the lack of 'big data' with the kind of scale, consistency and detail required to move beyond abstract modelling (Redman et al., 2007), and ALS provides an obvious path forward to providing those kind of data in relation to archaeological landscapes.

Ultimately, these studies will allow us to move beyond proximal, culturally-specific explanations for the collapse of early societies in monsoon environments (typically, the invasion of a neighbouring civilisation), towards a more complex understanding of how large-scale socio-ecological processes may create systemic vulnerability to such events. In doing so, archaeologists will be much better prepared to address one of the core issues facing studies of societal resilience in the face of hydroclimatic instability (Butzer, 2012; Butzer and Endfield, 2012), which is the danger of reflexively assigning significance to mere correlation between episodes of drought/flooding and societal collapse. By considering humans and their environment as dynamic coupled systems, future programs based on regional-scale ALS acquisitions might analyse the precise articulation between those two systems, moving away from mono-causal explanations and environmental determinism towards more sophisticated models of socio-ecological systems that acknowledge their full complexity. In tropical forest environments worldwide, these kinds of studies would not be possible in the absence of fast-developing geospatial technologies such as high-resolution airborne laser scanning, which are increasingly showing that the extent of anthropogenic changes to 'natural' landscapes during the past few thousand years has so far been substantially underestimated.

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