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## Radiocarbon dating of Angkorian art and monuments - Direct dating of iron reinforcements

Emmanuelle Delqué-Kolic, Stéphanie Leroy, Jean-Pascal Dumoulin

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Emmanuelle Delqué-Kolic, Stéphanie Leroy, Jean-Pascal Dumoulin. Radiocarbon dating of Angkorian art and monuments - Direct dating of iron reinforcements. Joint ICTP-IAEA Advanced Workshop on Accelerator Mass Spectrometry Radiocarbon Dating for Heritage and Forensic Sciences, IAEA; ICTP, May 2023, Trieste, Italy. hal-04122130

**HAL Id: hal-04122130**

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Submitted on 8 Jun 2023

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# Radiocarbon dating of Angkorian art and monuments

Direct dating of iron reinforcements



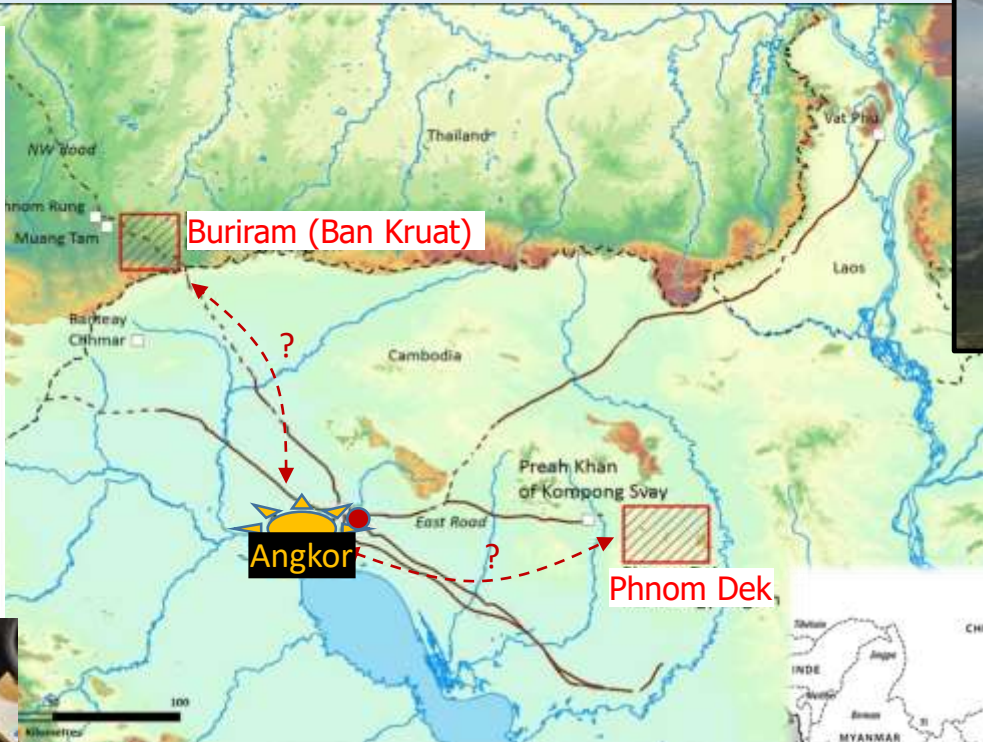
Emmanuelle Delqué-Količ, Stéphanie Leroy, Jean-Pascal Dumoulin and the LMC14 Team



# The Khmer Empire (IX<sup>th</sup> - XV<sup>th</sup> c. CE)



Statues



Military



Construction of irrigational system



A multidisciplinary approach to evaluate the role of iron (production, trade, consumption) in the expansion of the Khmer Empire (9th to 15th c. CE)  
Dir. Stéphanie Leroy



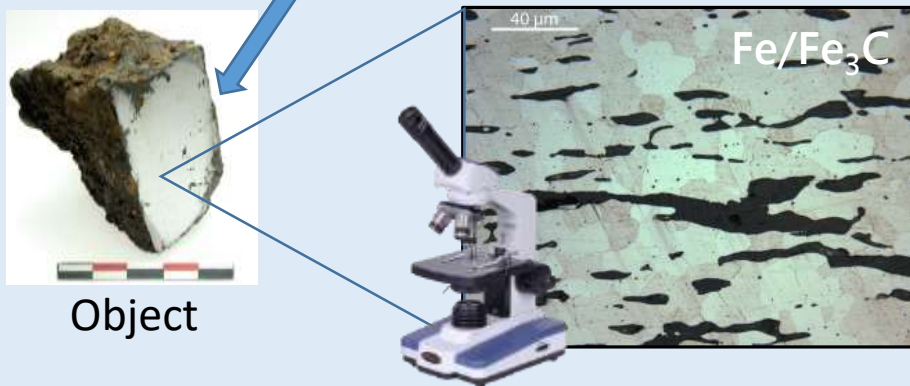
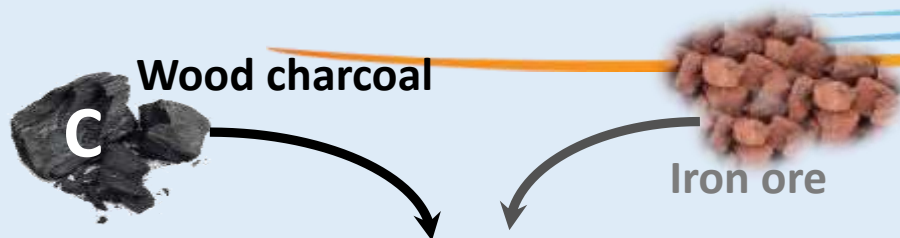
# Angkor, monumental city

## ANGKOR



HISTORICAL CHRONOLOGY :  
interpretation of epigraphic sources/  
stylistic evidences  
→ Sources of debate

# $^{14}\text{C}$ dating of iron



$^{14}\text{C}$  Dating

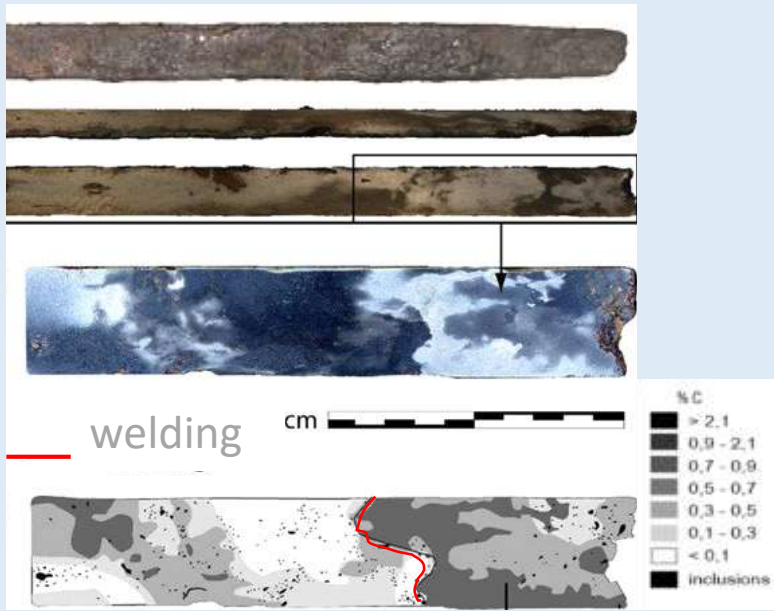


Manufacturing date  
of the metal

- ➔ Heterogeneous material with low carbon content
- ➔ Artefact history

# $^{14}\text{C}$ dating of iron

## Metallographic observation of a cross section (optical microscope)



Object



Cutting, polishing



$\text{HNO}_3$  (3%) etching

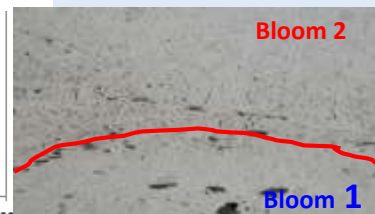
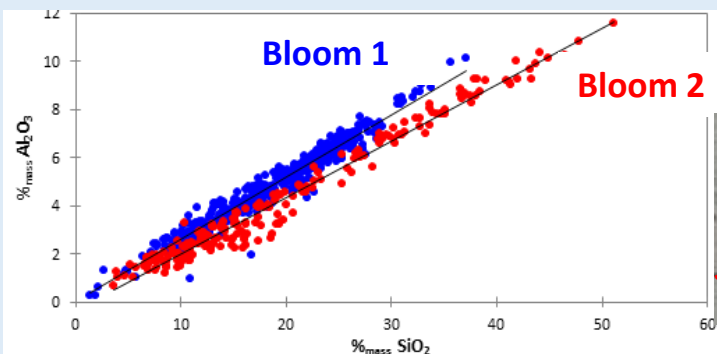


Distribution and content of carbon



Welding lines : Recycling metal ?

## Compositionnal analysis of the slag inclusions (SEM-EDS)



Use of flux ( $\text{CaCO}_3$ ) ?

Recycling (made with different blooms) ?



# $^{14}\text{C}$ dating of iron

## Sampling

- Drilling with TiN or CoB coated drills in the **most carburized areas**
- 50 to 1000 mg of iron



## Combustion, Graphitization

- Iron particles + CuO (CuO/Fe=5) + Ag wire, 850°C, 5 h



- $\text{CO}_2 + 2\text{H}_2 \rightarrow \text{C} + 2\text{H}_2\text{O}$ , with Fe at 600°C



## Measurement

- AMS Artemis, Pelletron NEC 3MV, graphite source



AMS Artemis, Saclay, France

## Calibration

- North/South hemisphere influence
  - ✓ Mix\_Curves("SE Asia", "NH", "SH", 50, 10)

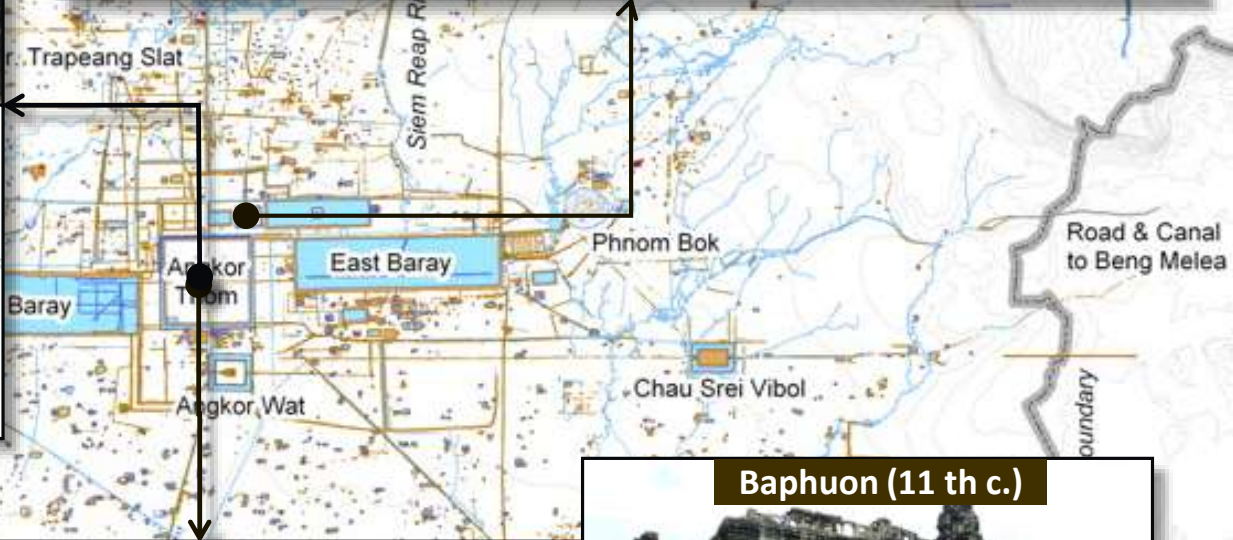
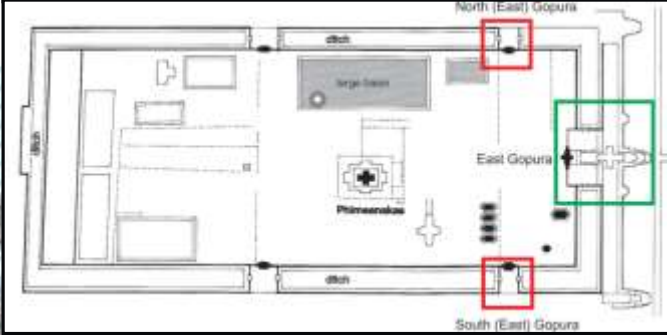
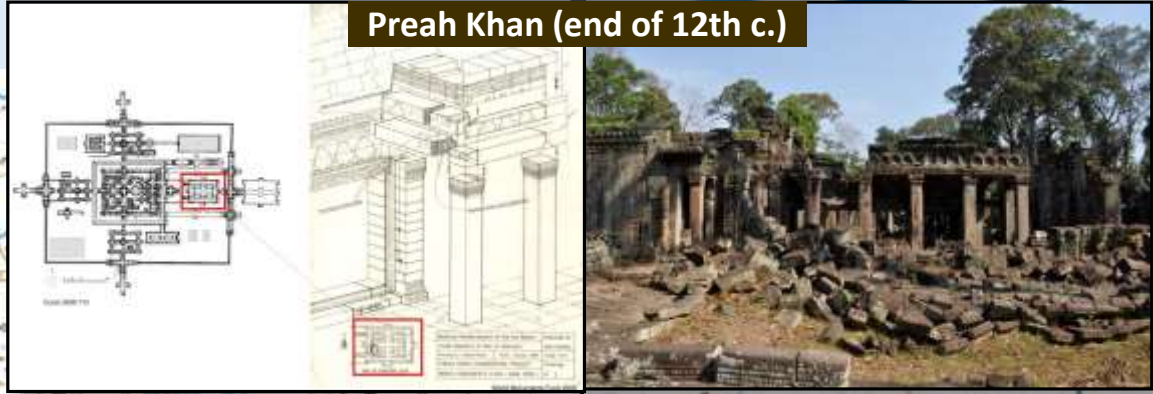


# Angkor monuments

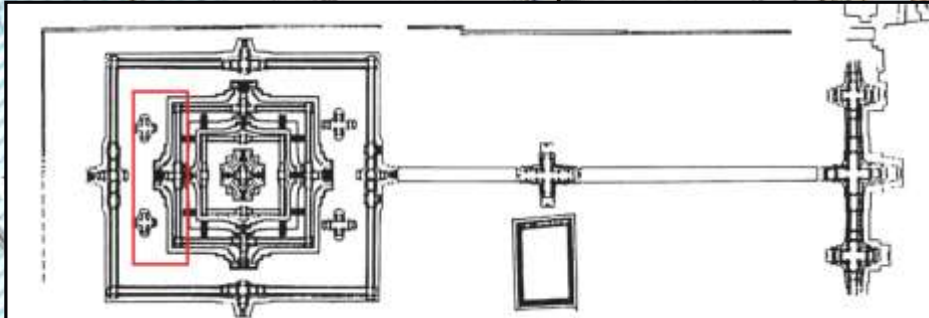
Royal Palace (11th c.)



Preah Khan (end of 12th c.)



Baphuon (11th c.)





# Angkor monuments

Royal Palace (11th c.)

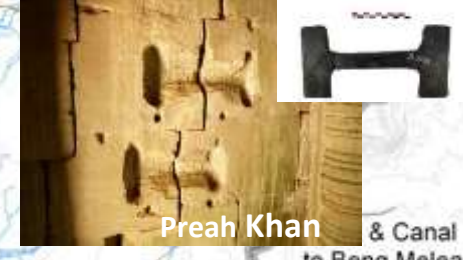


Preah Khan (end of 12th c.)



Typological classification

Metallographic observations

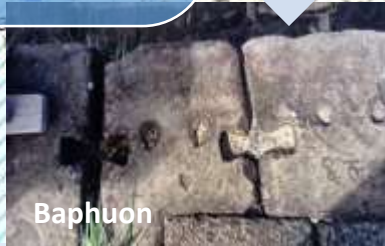


Preah Khan & Canal to Beng Melea

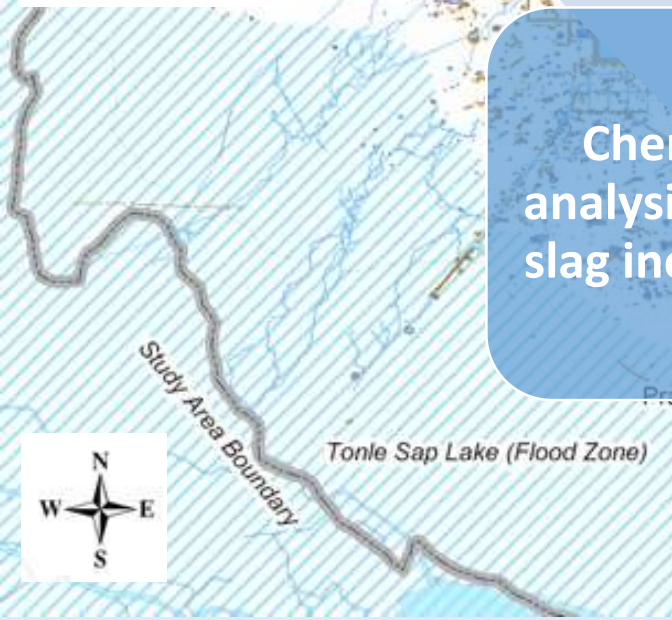
Chemical analysis of the slag inclusions

Radiocarbon dating

Baphuon (11th c.)



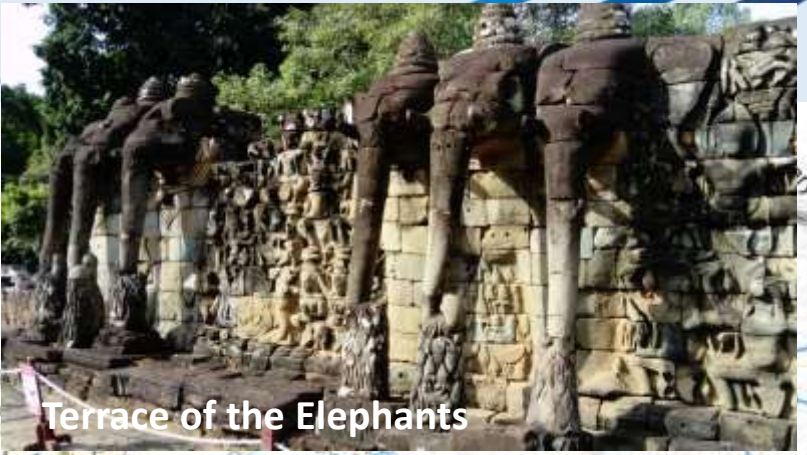
Baphuon



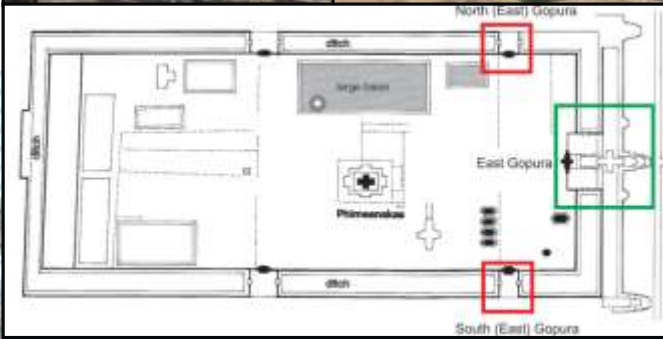


# The Royal Palace

Royal Palace (11th c.)



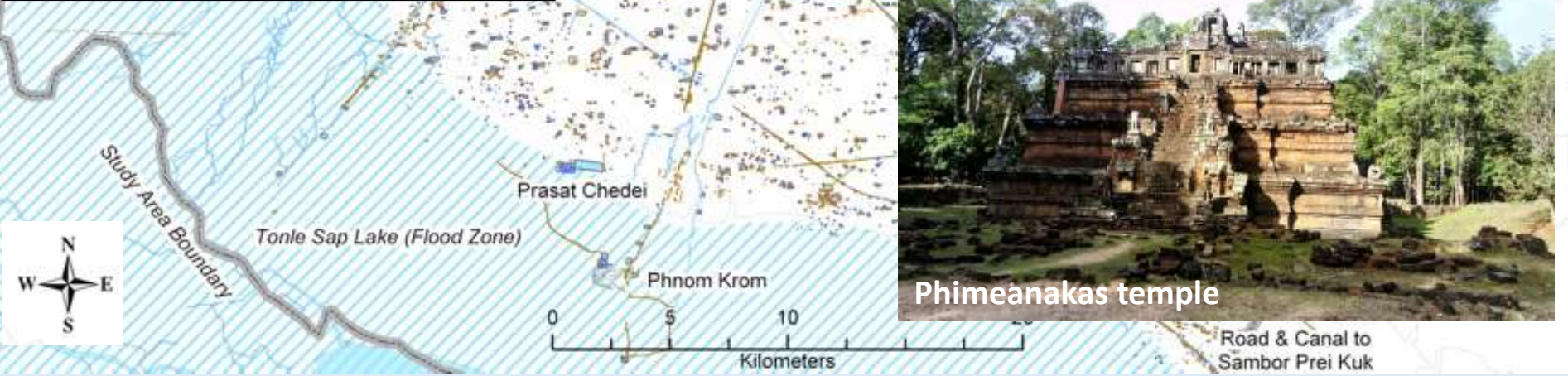
Terrace of the Elephants



Road & Canal to Beng Melea






Phimeanakas temple



Road & Canal to Sambor Prei Kuk

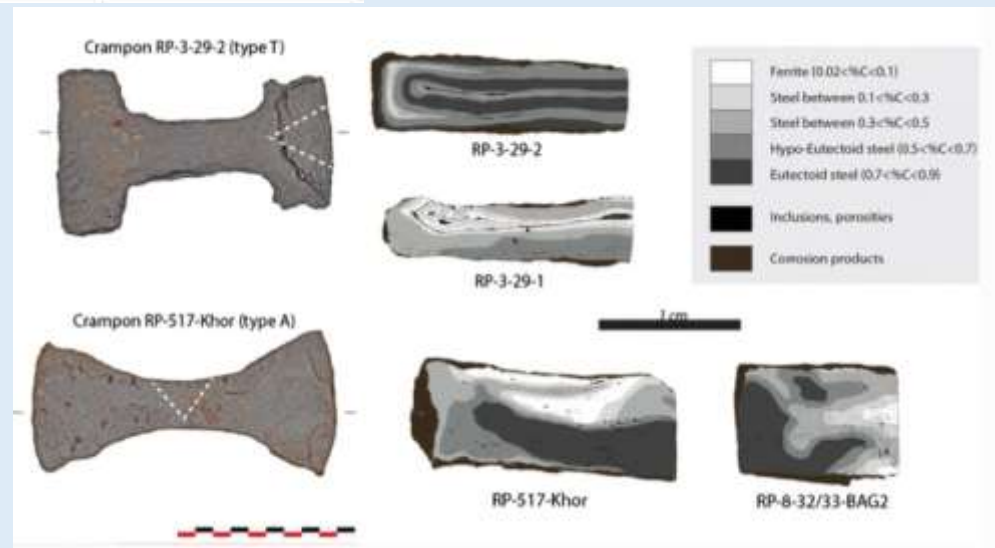
# The Royal Palace

LEVEL 1 General shape	LEVEL 2 Ends shape			LEVEL 3 Body dimensions		
Shape 1 is characterized by a <b>Straight angle T</b> (also called "en double T" in previous works)	<b>T</b>			<b>T1; T2; T3</b>		
	1 Short end ( $R < 3$ )	2 Medium end ( $3 < R < 4$ )	3 Long end ( $4 < R$ )	$R = \frac{(I1 + I2)/2}{L}$ L: $l > 200$ mm M: $180 \text{ mm} < l < 200$ mm S: $l < 180$ mm		
Shape 2 is characterized by an <b>Obtuse angle I</b> ( $\text{Angle} > 90^\circ\text{C}$ ) (called "en double T" in some works)	<b>I</b>				<b>I1; I2; I3; I4</b>	
	1 Tight end ( $r > 7$ )	2 Large end ( $r > 7$ )	3 Flared end	4 Roundish end	Ratio (R) = length (l) / width (w)  T: $R < 5$ M: $5 < R < 6$ F: $6 < R < 7$ VF: $R > 7$	
Shape 3 is characterized by no visible angle <b>Curve A</b> (also called "en double queue d'aronde" in previous works)	<b>A</b>			<b>A1; A2; A3</b>		
	1 Roundish end	2 Straight end	3 Asymmetrical end	Ratio (R) = length (l) / width (w)  T: $R < 5$ M: $5 < R < 6$ F: $6 < R < 7$ VF: $R > 7$		

Shape « T »

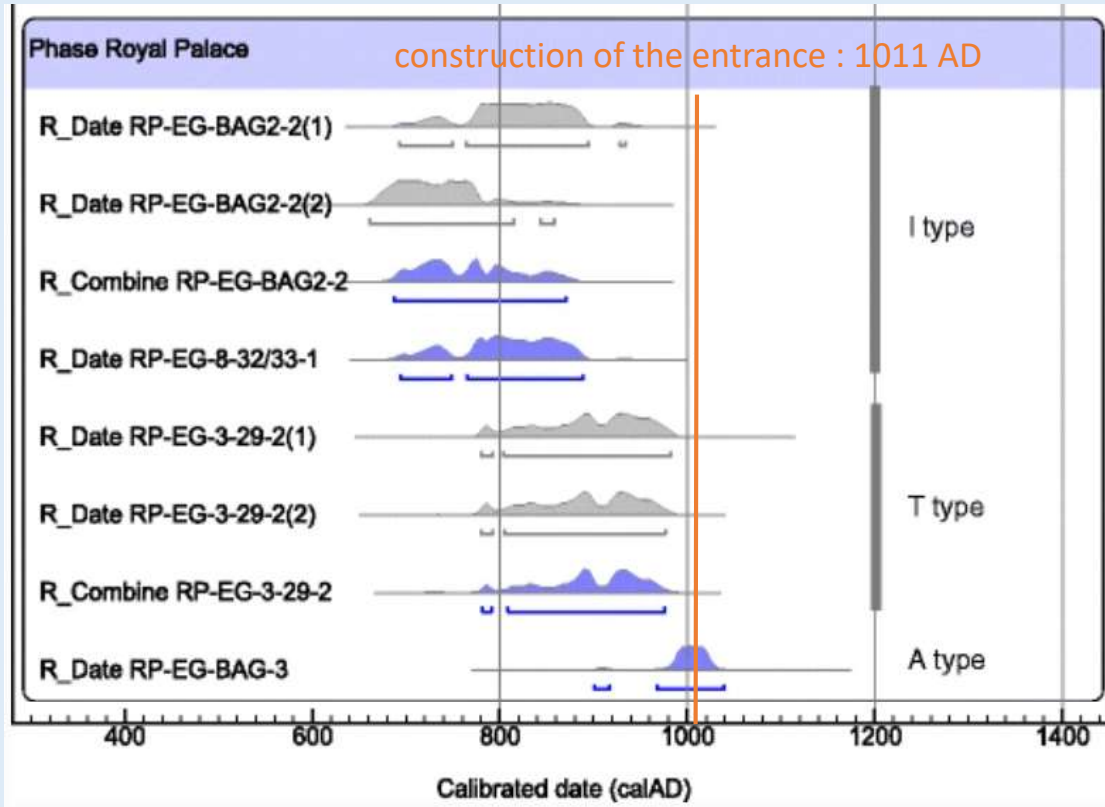
Shape « I »

Shape « A »





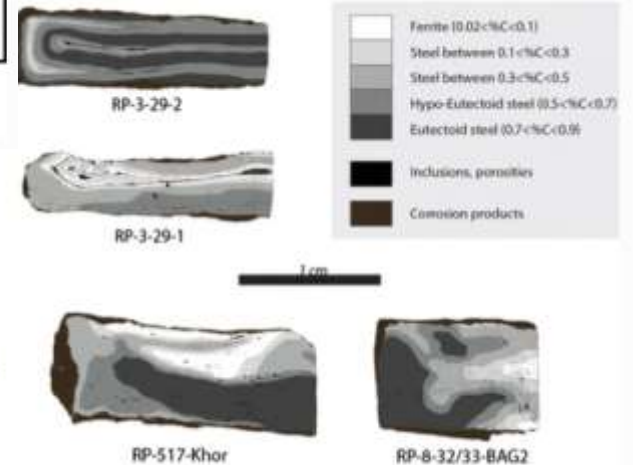
# The Royal Palace



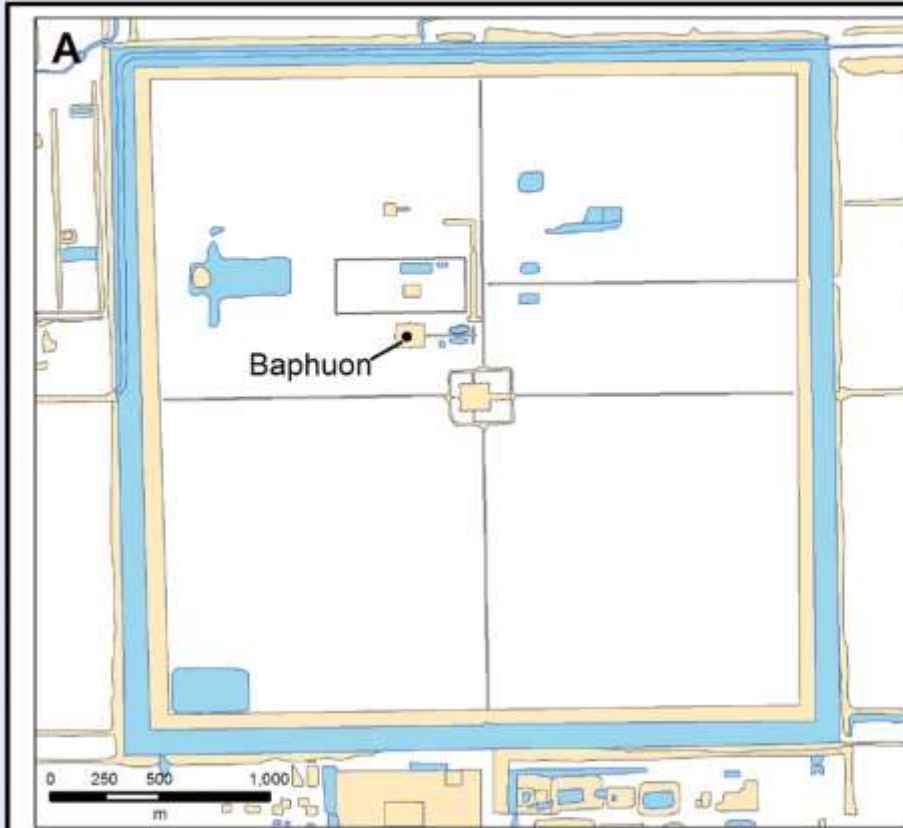
Shape « I »

Shape « T »

Shape « A »



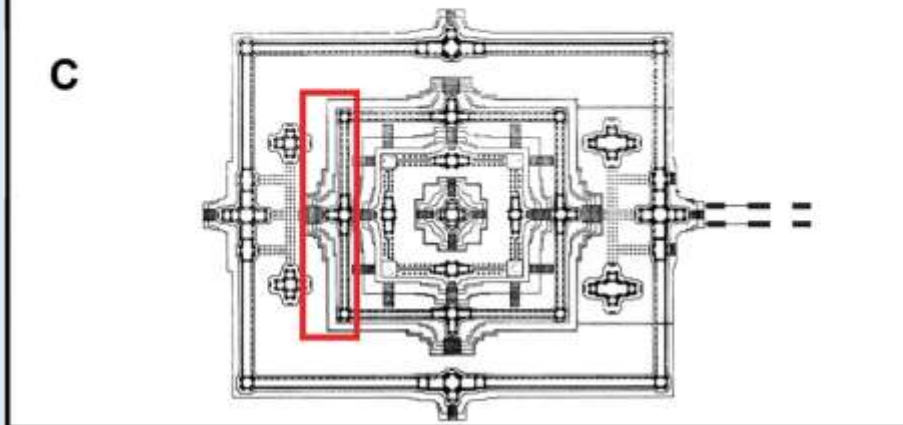
# Baphuon



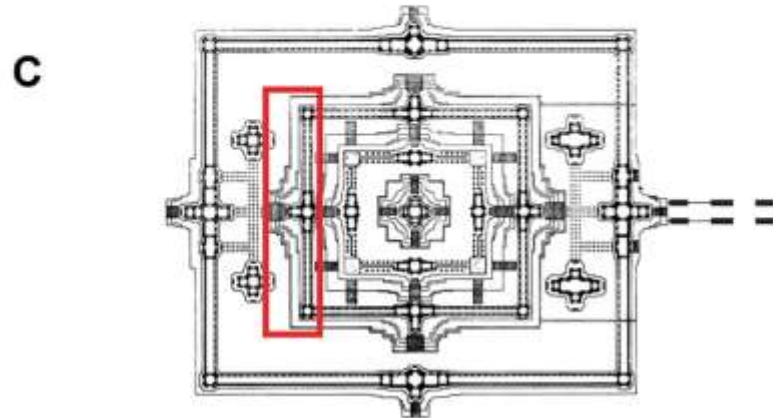
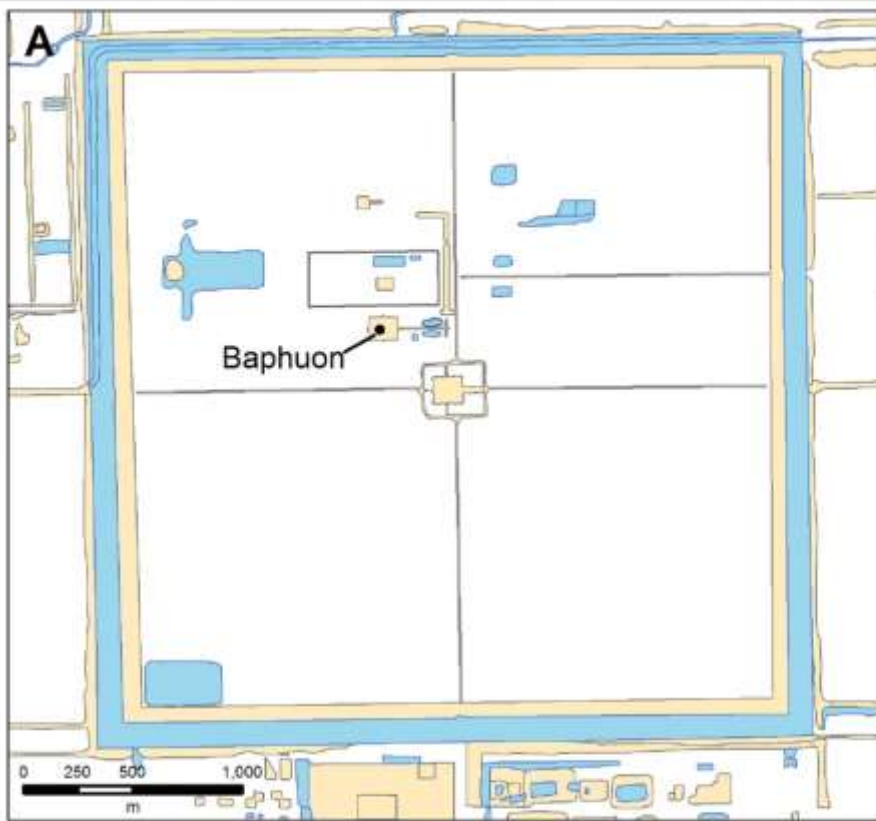
**Construction phase**



**Modification phase**



# Baphuon



## Construction phase

- Indirect historical accounts
- Mistaken associations from unrelated inscriptions



**Work of Udayadityavarman II (1050-1066)**

**Critical examination of this datation**

(P. Royère 2006, W. A. Southworth 2008, ...)

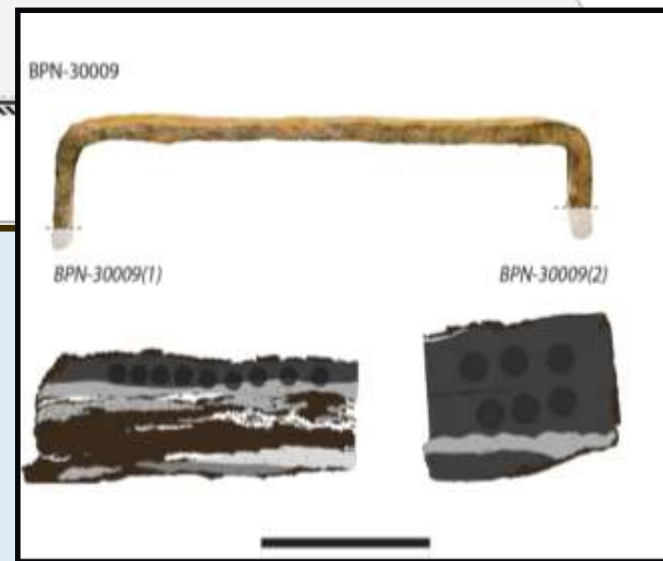
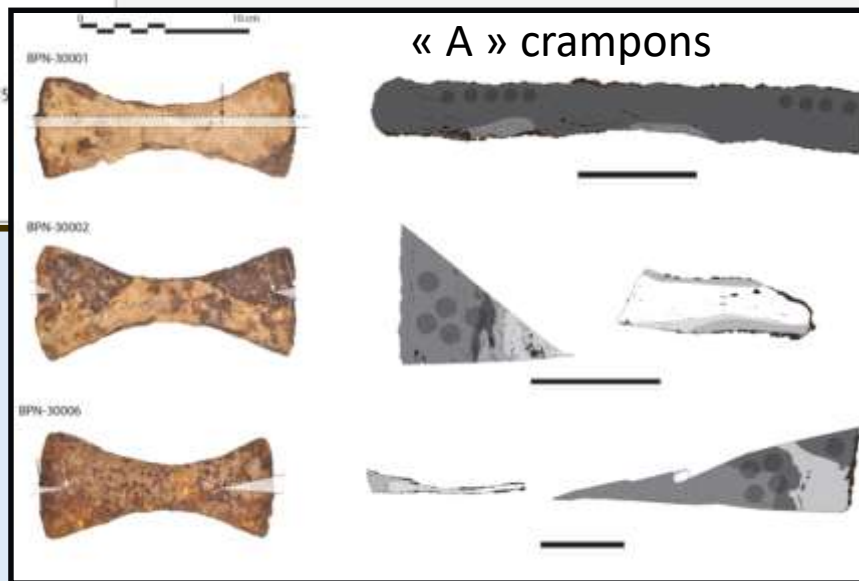
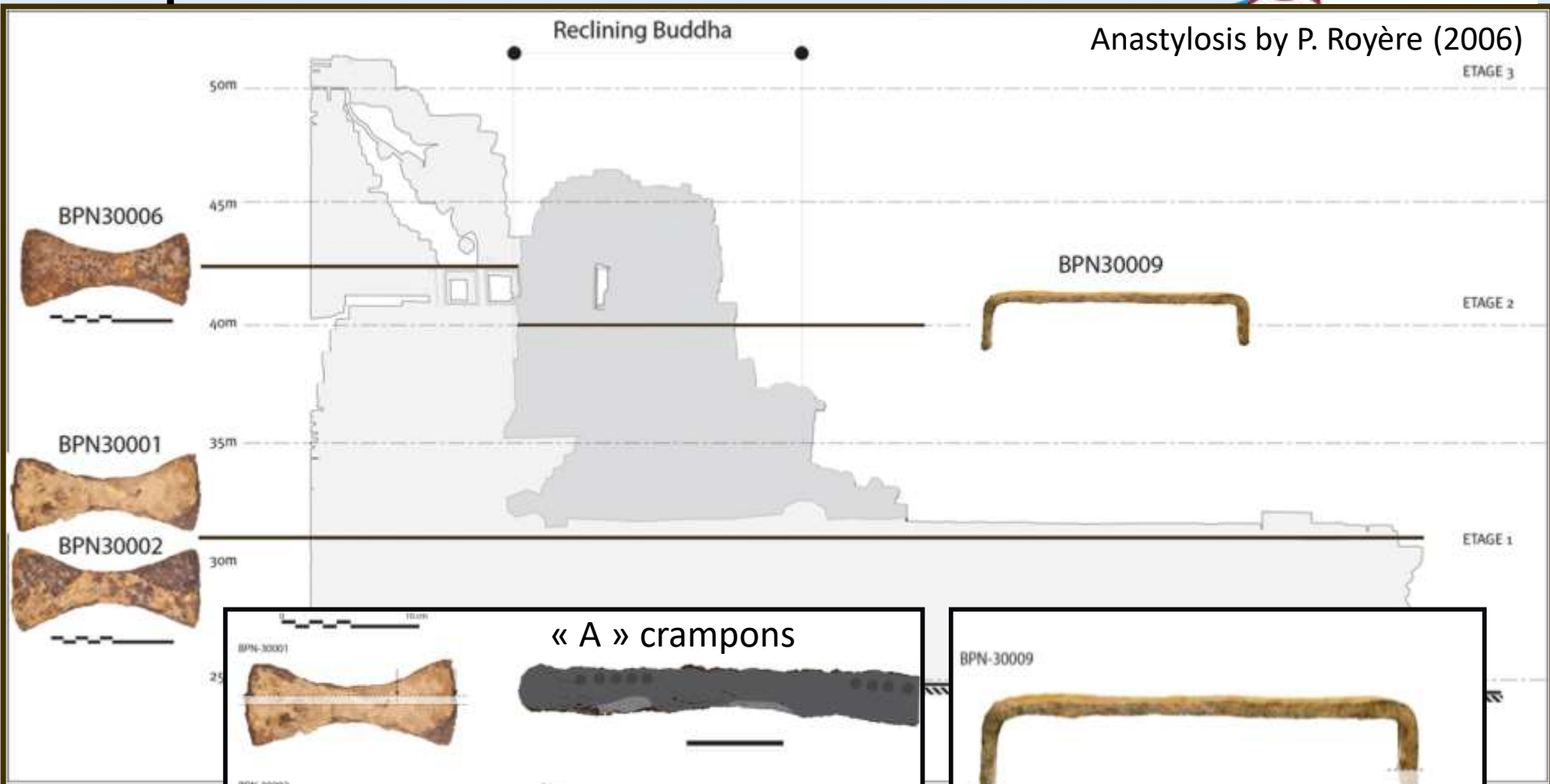
## Modification phase

- Later modification
- No 'official' record
- key evidence of Theravada Buddhist power
- Final moments of the royal presence in Angkor (beg. 16<sup>th</sup> c.)



# Baphuon

Anastylosis by P. Royère (2006)



# Baphuon

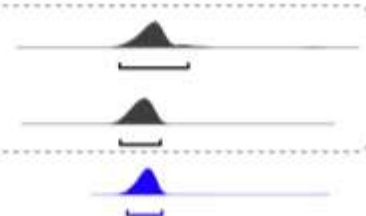
Leroy et al. (2015). PLOS ONE  
Construction and Modification of the Baphuon Temple Mountain in Angkor, Cambodia.

## Reclining Buddha modification

BPN-30009(1)

BPN-30009(2)

**Combine BPN-30009**



## Construction phase

**BPN-30006**

BPN-30002(1)

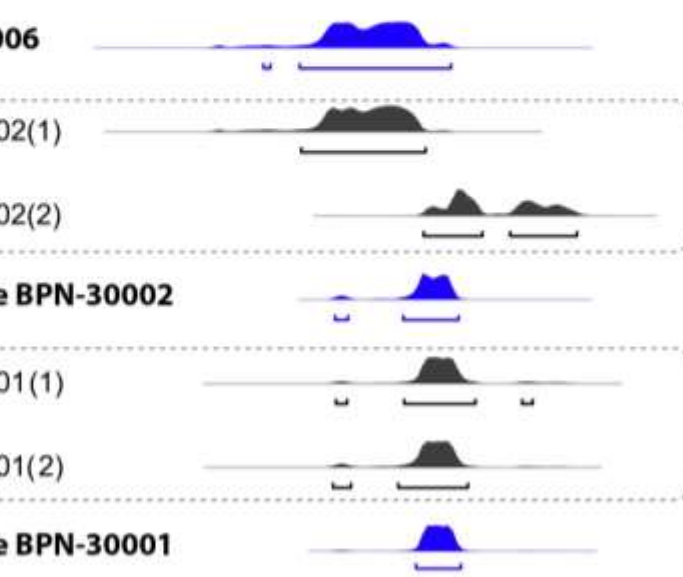
BPN-30002(2)

**Combine BPN-30002**

BPN-30001(1)

BPN-30001(2)

**Combine BPN-30001**



600 800 1000 1200 1400 1600

Calibrated date (calAD)

# Baphuon

Leroy et al. (2015). PLOS ONE

Construction and Modification of the Baphuon Temple Mountain in Angkor, Cambodia.

## Reclining Buddha modification

BPN-30009(1)

BPN-30009(2)

**Combine BPN-30009**

## Construction phase

**BPN-30006**

BPN-30002(1)

BPN-30002(2)

**Combine BPN-30002**

BPN-30001(1)

BPN-30001(2)

**Combine BPN-30001**

Jayavarman V  
Suryavarman I  
Udayadityavarman II

### Standard hypothesis but:

- Indirect historical accounts
- Mistaken associations from unrelated inscriptions
- Brief reign

600 800 1000 1200 1400 1600

Calibrated date (calAD)



# Baphuon

Leroy et al. (2015). PLOS ONE  
Construction and Modification of the Baphuon Temple Mountain in Angkor, Cambodia.

## Reclining Buddha modification

BPN-30009(1)

BPN-30009(2)

Already associated with the  
Ta Keo temple (975- ...)

### Standard hypothesis but:

- Indirect historical accounts
- Mistaken associations from unrelated inscriptions
- Brief reign

## Construction phase

**BPN-30006**

BPN-30002(1)

BPN-30002(2)

**Combine BPN-30002**

BPN-30001(1)

BPN-30001(2)

**Combine BPN-30001**

600

800

1000

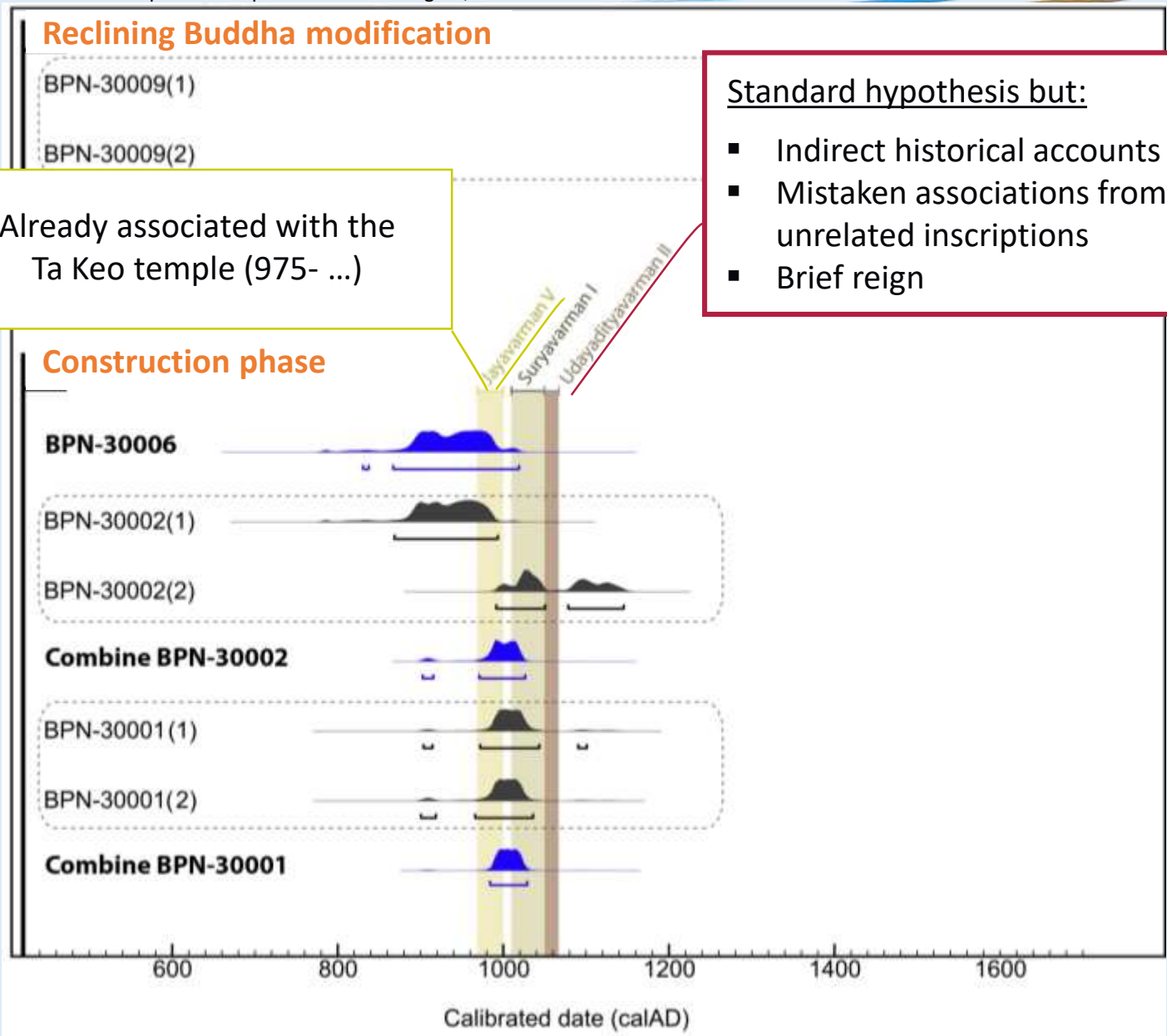
1200

1400

1600

Calibrated date (calAD)

Jayavarman V  
Suryavarman I  
Udayadityavarman II



# Baphuon

Leroy et al. (2015). PLOS ONE  
Construction and Modification of the Baphuon Temple Mountain in Angkor, Cambodia.

## Reclining Buddha modification

BPN-30009(1)

BPN-30009(2)

Already associated with the  
Ta Keo temple (975- ...)

### Standard hypothesis but:

- Indirect historical accounts
- Mistaken associations from unrelated inscriptions
- Brief reign

## Construction phase

BPN-30006

BPN-30002(1)

BPN-30002(2)

- Responsible for re-establishing Khmer dominance
  - Not yet associated with his own temple

BPN-30001(1)

BPN-30001(2)

Combine BPN-30001

600

800

1000

1200

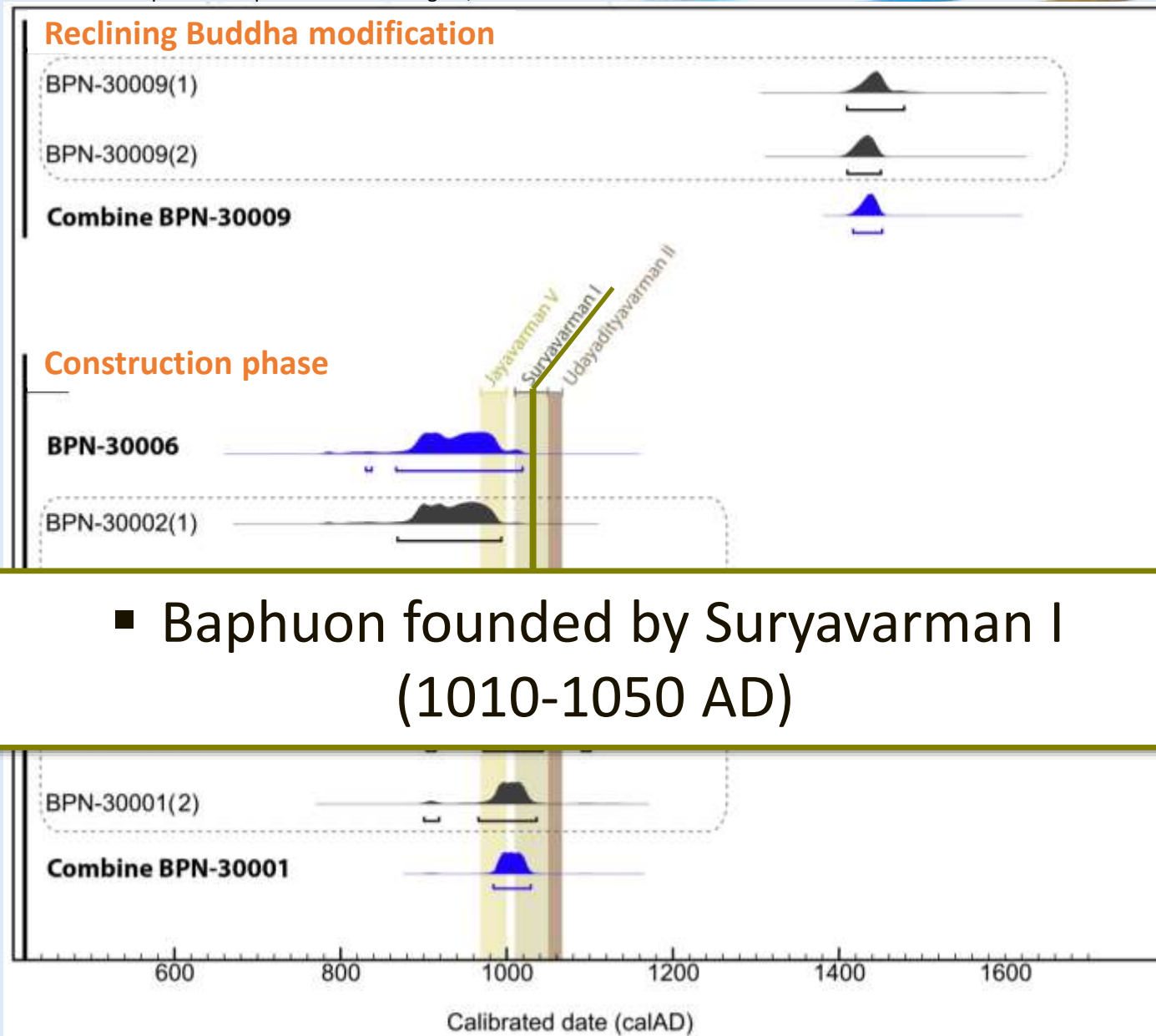
1400

1600

Calibrated date (calAD)

# Baphuon

Leroy et al. (2015). PLOS ONE  
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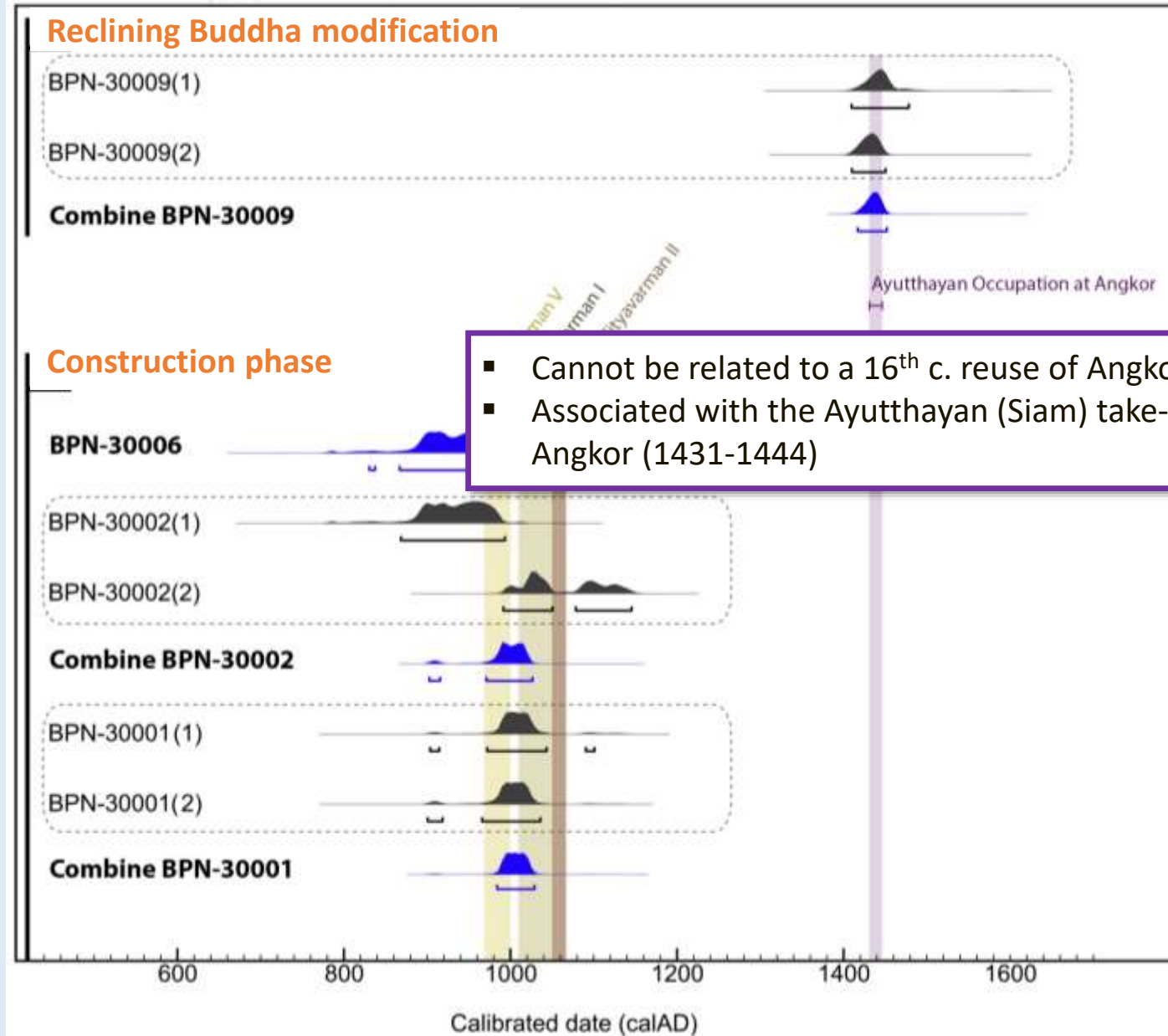




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Leroy et al. (2015). PLOS ONE

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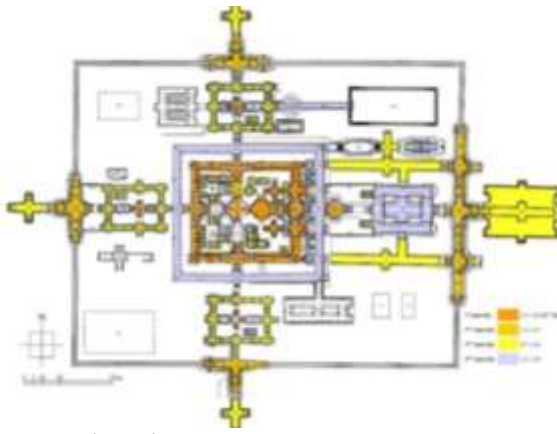


- Cannot be related to a 16<sup>th</sup> c. reuse of Angkor
- Associated with the Ayutthayan (Siam) take-over of Angkor (1431-1444)

# Angkorian architecture

→ Consecration date 1191  
Stele of Preah Khan  
-Jayavarman VII (1181-1218)-

Preah Khan (end of 12th c.)



Cunin (2004)



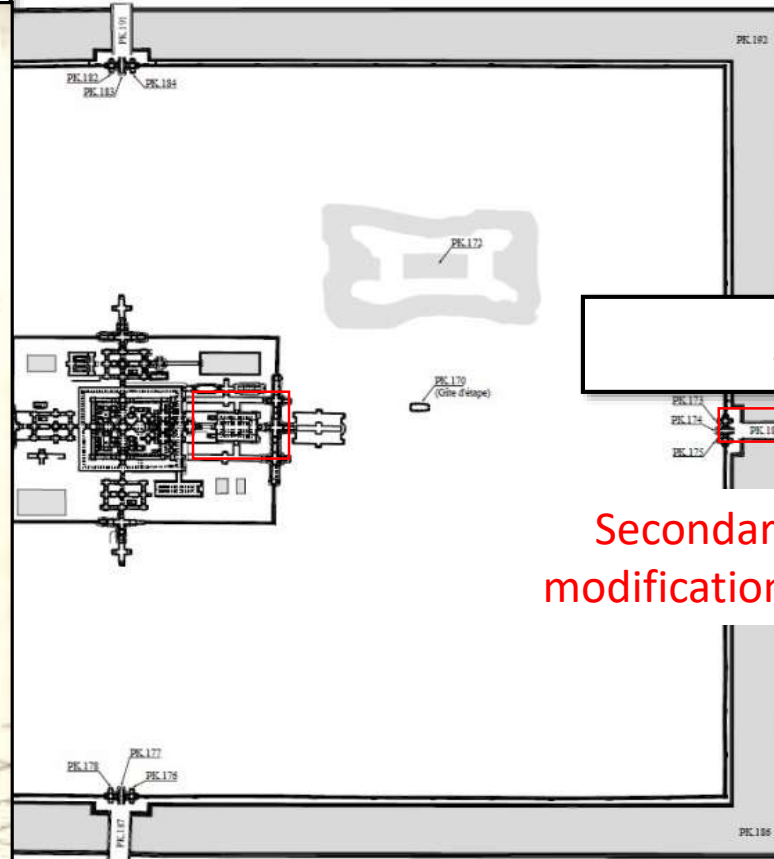
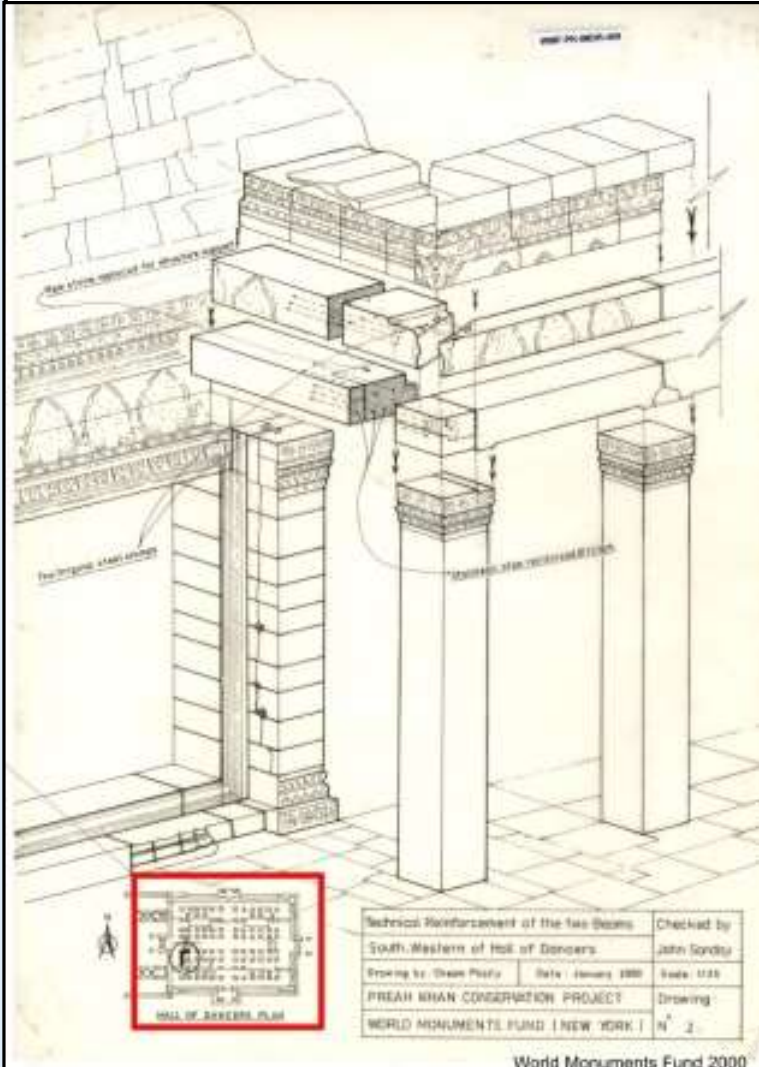
(Coedes, 1941)





# Preah Khan

## Hall of Dancers



Jetty

Secondary architectural modification of Preah Khan ?

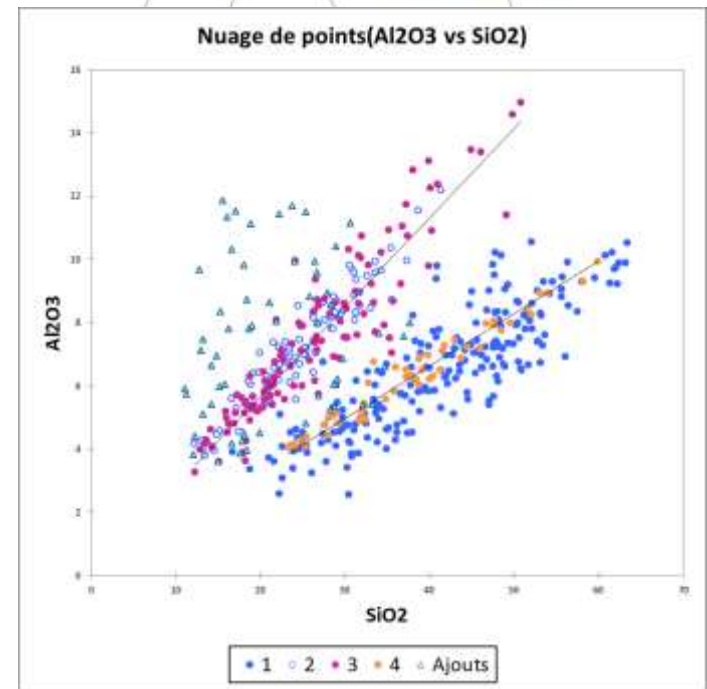
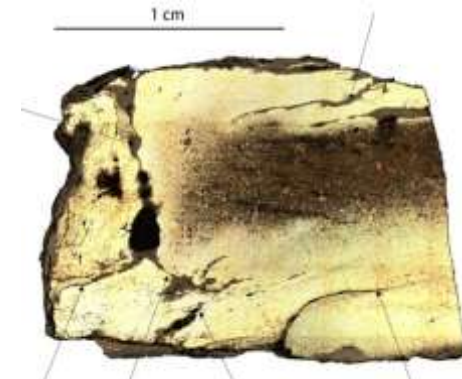




# Preah Khan

## « T » crampons (30 samples)

Crampon	Sample name	Location	Number of PPMs of different origins identified
PK4	4.1	Hall of Dancers	1
	4.2		
PK5	5.1	Hall of Dancers	2
	5.2		
PK7	7.1	Jetty	2
	7.2		
PK9	9.1	Hall of Dancers	2
	9.2		
PK10	10.1	Hall of Dancers	1
	10.2		
PK11	11.1	Hall of Dancers	3
	11.2		
PK12	12.1	Hall of Dancers	2
	12.2		
PK13	13.1	Hall of Dancers	2
	13.2		
PK14	14.1	Hall of Dancers	2
	14.2		
PK15	15.1	Hall of Dancers	1
	15.2		
PK16	16.1	Hall of Dancers	1
	16.2		
PK17	17.1	Hall of Dancers	2?
	17.2		
PK18	18.1	Hall of Dancers	2
	18.2		
PK19	19.1	Hall of Dancers	1
	19.2		
PK20	20.1	Hall of Dancers	1
	20.2		



# Preah Khan

Jayavarman VII

Preah Khan

Stele of Preah Khan 1191 CE

Jetty

Re-used iron ?

Hall of Dancers

Re-used iron ?

PK7-1/2

PK7-1/3

R\_Combine PK 7-1

PK13-2/1

PK13-2/2

R\_Combine PK13-2

PK14-2

PK15-1

PK15-2

PK17-2/1

PK17-2/2

R\_Combine PK17-2

600

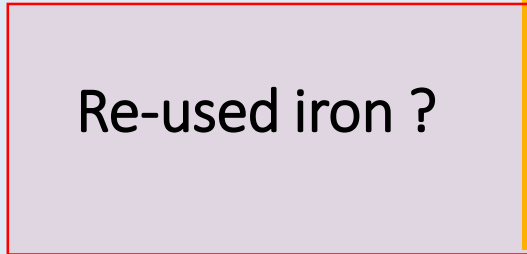
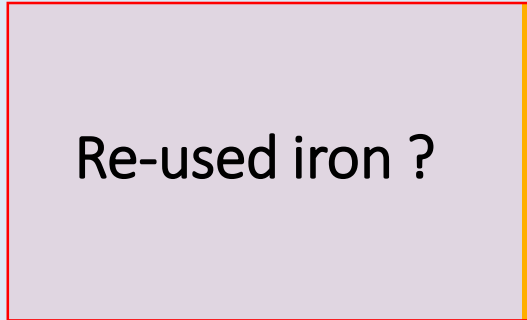
800

1000

1200

1400

Modelled date (CE)





# Preah Khan

Jayavarman VII

Preah Khan

Stele of Preah Khan 1191 CE

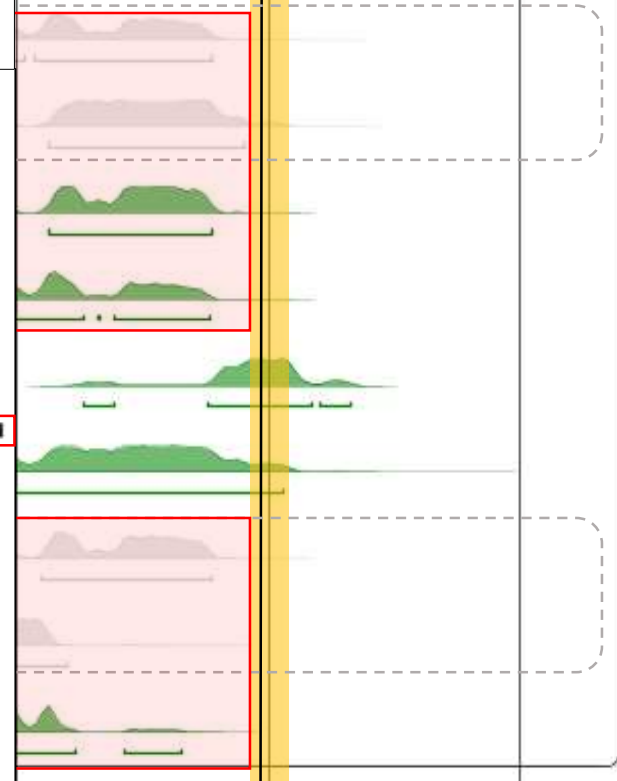
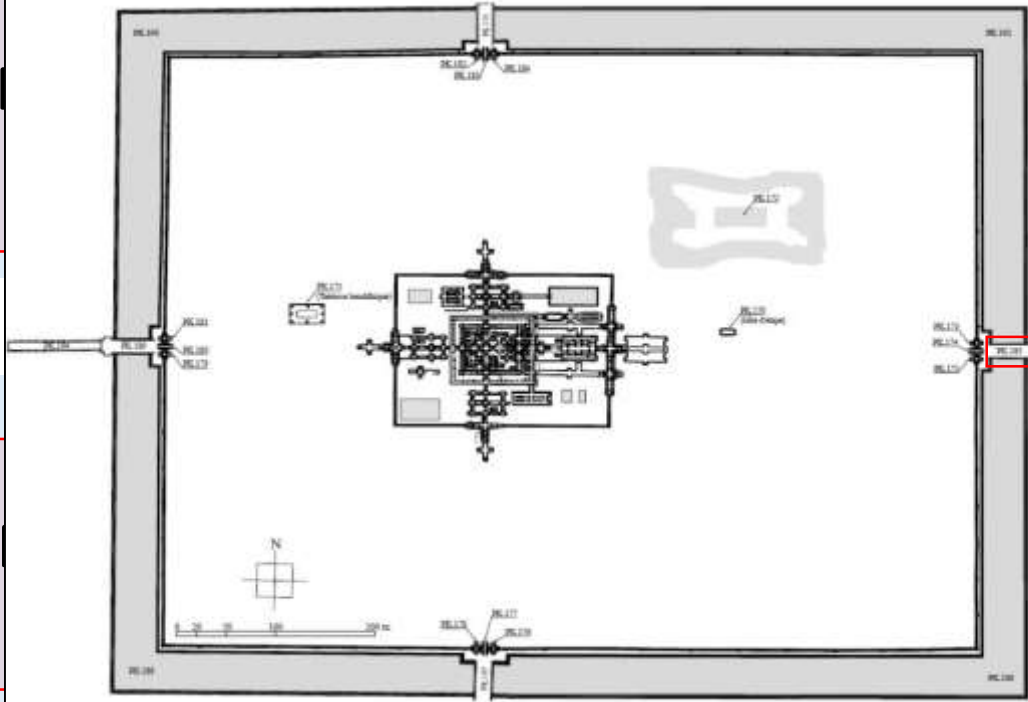
PK7-1/2

PK7-1/3

R\_Combine PK 7-1

Jetty

Jetty not part of the initial constructions:



600

800

1000

1200

1400

Modelled date (CE)

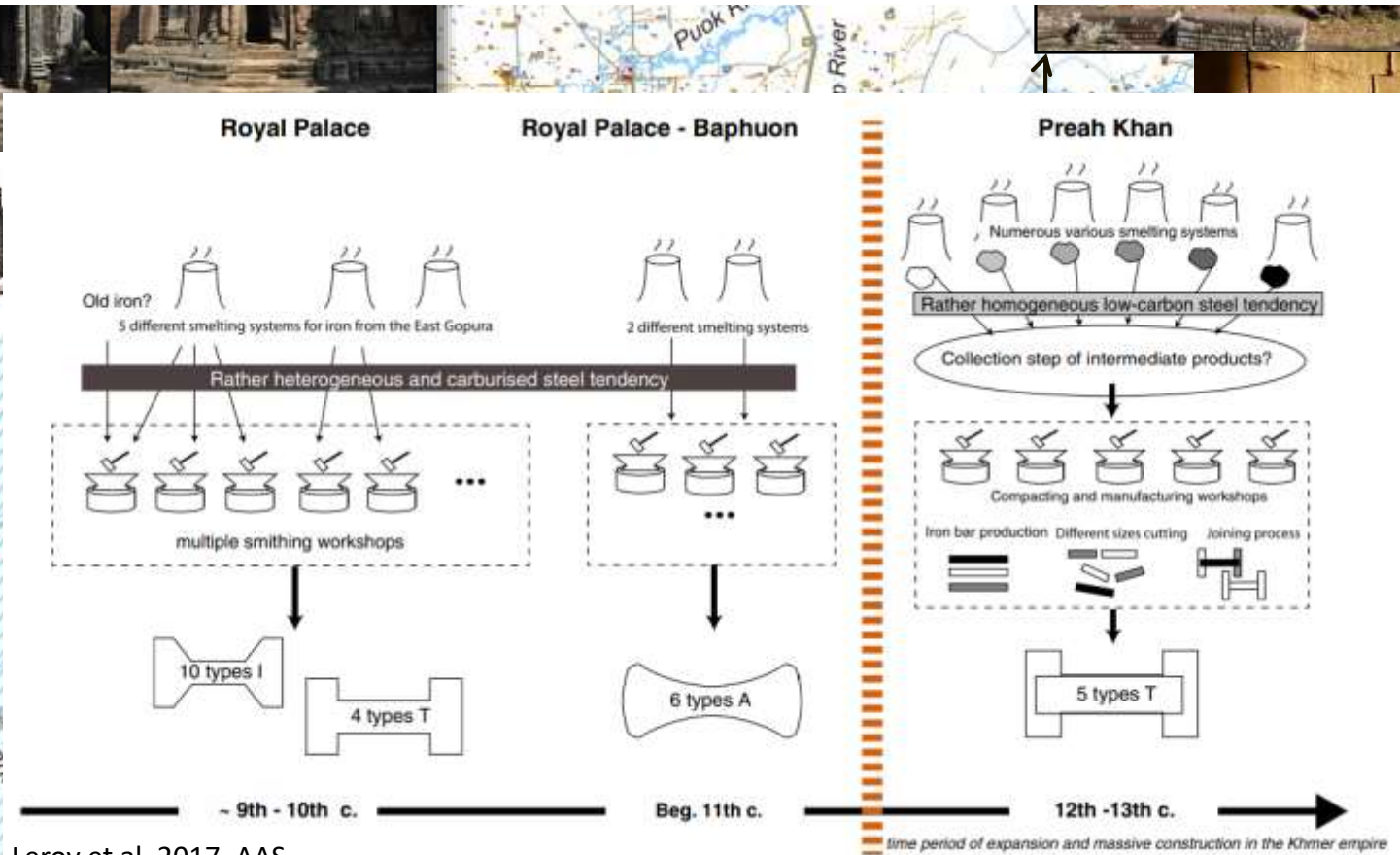
# Radiocarbon dating of iron crampons

Royal Palace (11th c.)

Preah Khan (end of 12th c.)

Radiocarbon dating of iron crampons :

- Dating the construction phases of the Angkor's monuments
- Bring a chronological framework for re-construction of the pre-modern iron economy

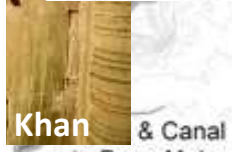
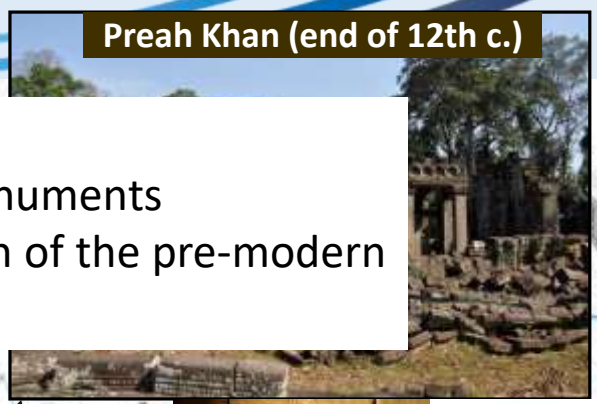
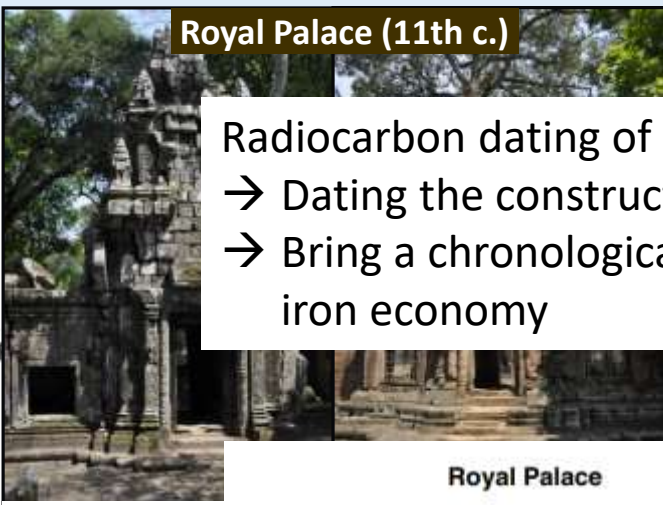


Leroy et al. 2017. AAS

Baphuon

Khan & Canal to Beng Melea

th c.)





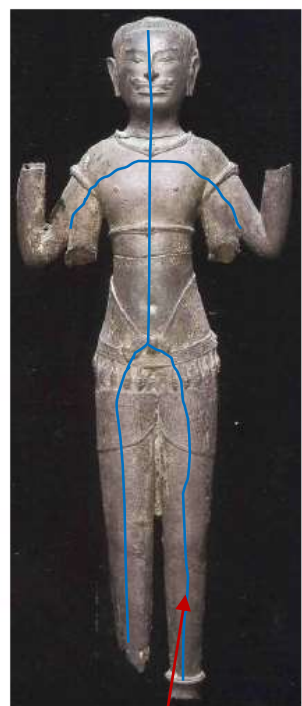
# The bronze statues

**IrAngkor**

A multidisciplinary approach to evaluate the role of iron (production, trade, consumption) in the expansion of the Khmer Empire (9th to 15th c. CE)  
Dir. Stéphanie Leroy



Bodhisattva Avalokiteshvara (B66B14), Asian Art Museum, San Francisco



©RMN-Grand Palais (MNAAG, Paris)/T. Ollivier.

**Iron armature**



Visnu, XIth c., ©National Museum of Cambodia

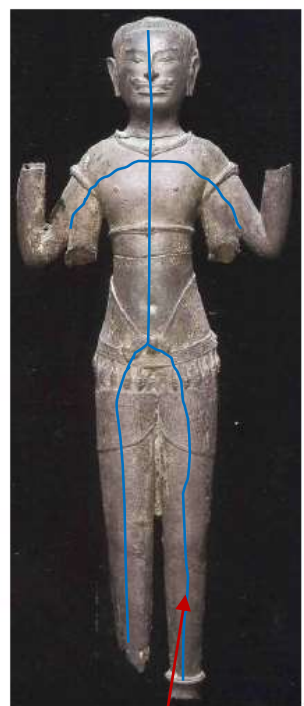
Palanquin fittings (1992,346,1)



© Asian Art Museum of San Francisco



# The bronze statues



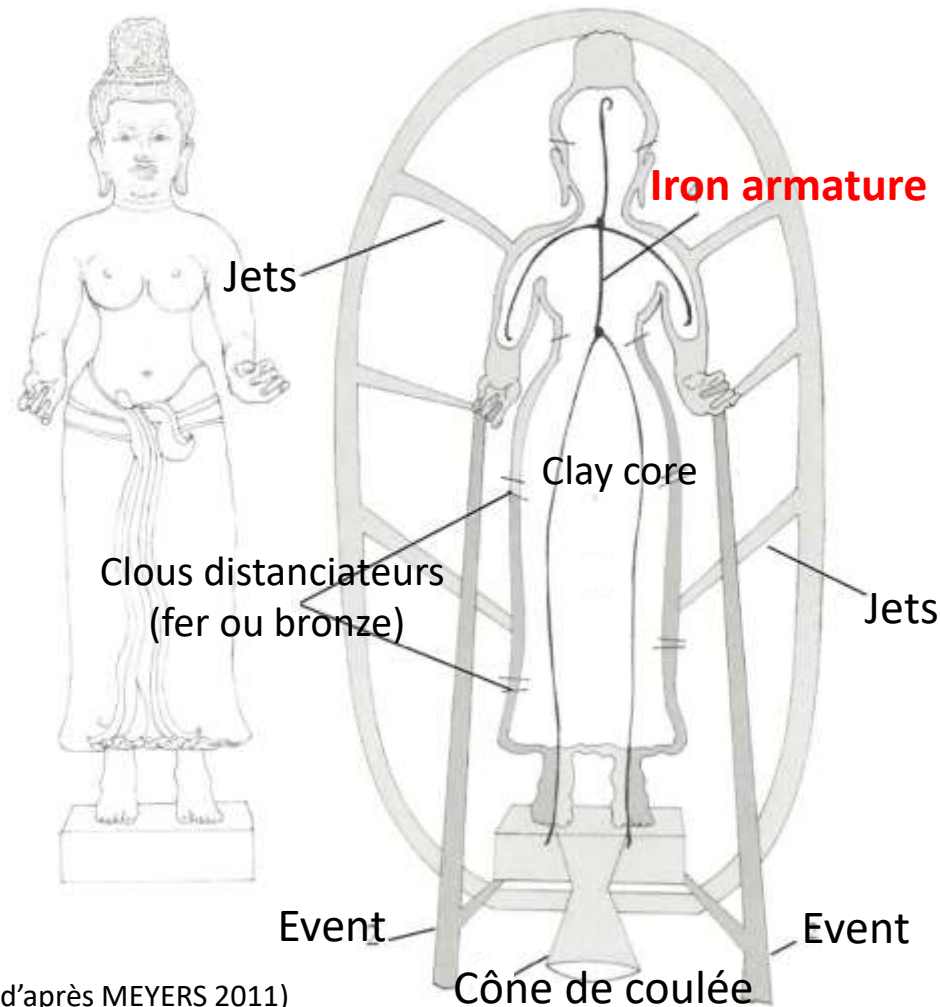
©RMN-Grand Palais (MNAAG, Paris)/T. Ollivier.

**Iron armature**



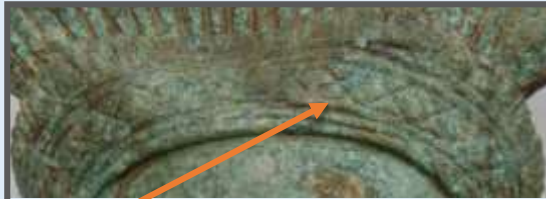
Visnu, XIth c., ©National Mus

## « Lost-wax casting »



(d'après MEYERS 2011)

# Dating bronze statues



Diamonds : 1100-1150 AD

Angkor Vat style : XII<sup>e</sup> s

Flowers : 1175-1200 AD



Photos : B. Vincent

**Iconographic and stylistic criteria** : more complex than in the stone statues

**Engraved stones, stories of chinese pilgrims, rare royal chronicles**



**Archaeological context** : Careful, not necessarily the original location



Seconde campagne de fouilles au Palais Royal d'Angkor Thom menée par B. P. Groslier en 1957-1958

**physico-chemical methods** :

- TL on the clay
- <sup>14</sup>C on organic remains trapped in the clay

→ <sup>14</sup>C dating of iron armatures

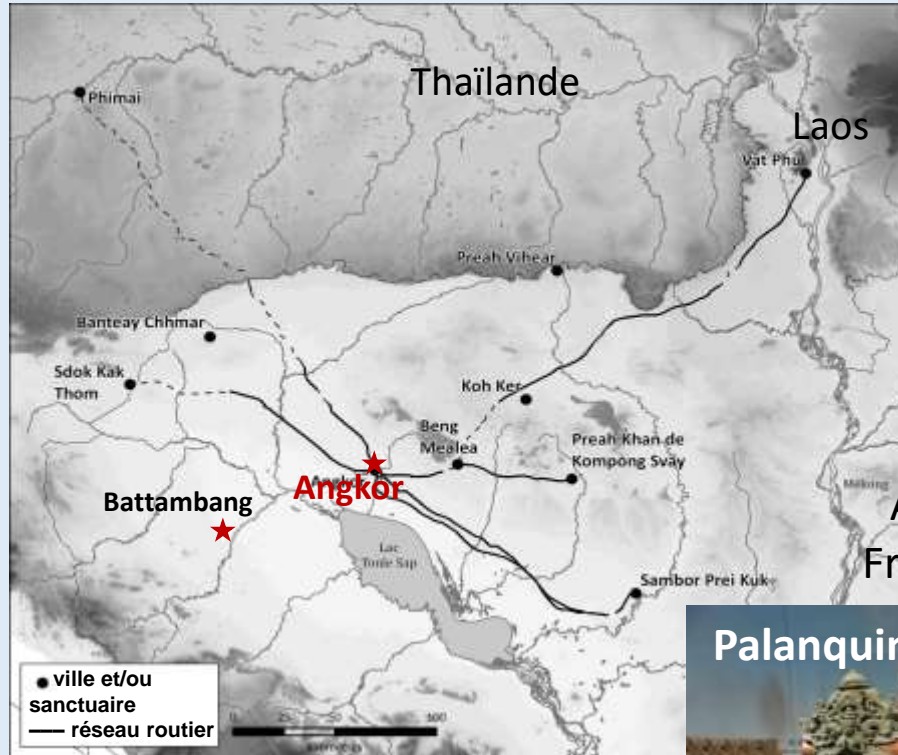
# Dating bronze statues



MA 1339 Vishnu

©RMN-Grand Palais (MNAAG, Paris)/T. Ollivier.

Musée National des Arts  
Asiatiques, Paris, curator P. Baptiste



Asian Art Museum of San  
Francisco, curator F. McGill

Palanquin fittings (inv. 1992.346)





# Vishnu (inv. MA1339)

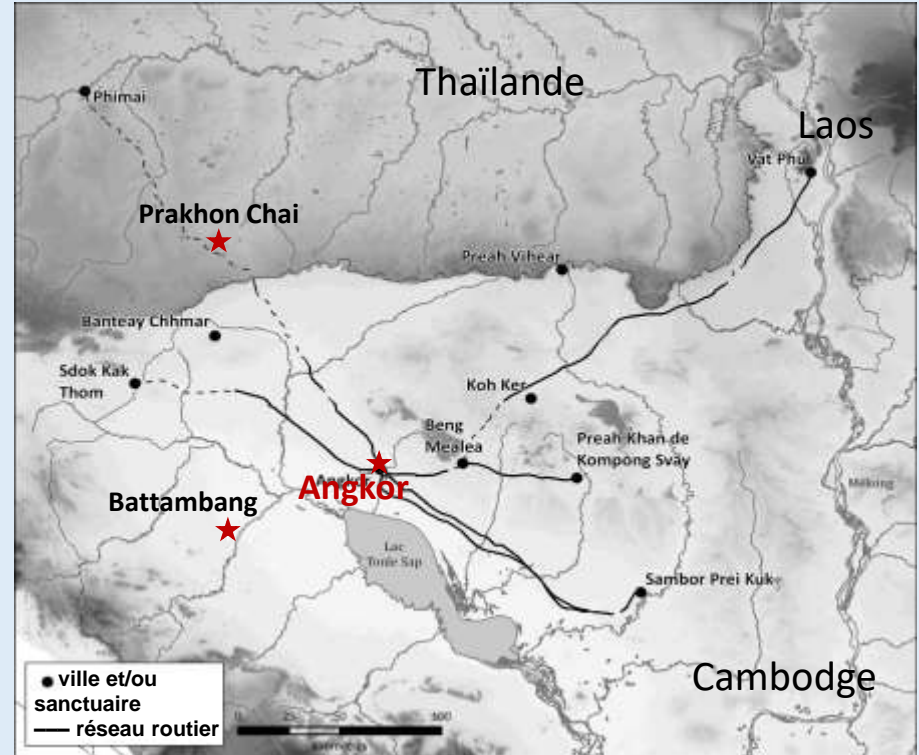
Musée National des Arts Asiatiques, Paris, curator P. Baptiste



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Armature



- Origin : Battambang district ?
- « modern » copy or late XI<sup>st</sup> c. ?

# Vishnu (inv. MA1339)

Musée National des Arts Asiatiques, Paris, curator P. Baptiste



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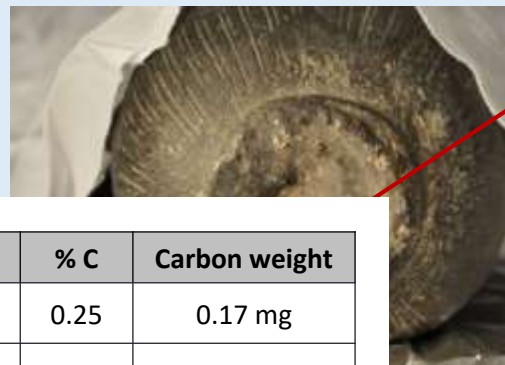
→ Attributed to the Baphuon style, XI<sup>th</sup> c.

# Vishnu (inv. MA1339)

Musée National des Arts Asiatiques, Paris, curator P. Baptiste



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Armature  
#1 cm<sup>2</sup>

Reference	Sample	Sample weight	% C	Carbon weight
SacA 48243	MA1339-2	67 mg	0.25	0.17 mg
SacA 48245	MA1339-4	109 mg	0.22	0.24 mg



→ Attributed to the Baphuon style, XI<sup>th</sup> c.

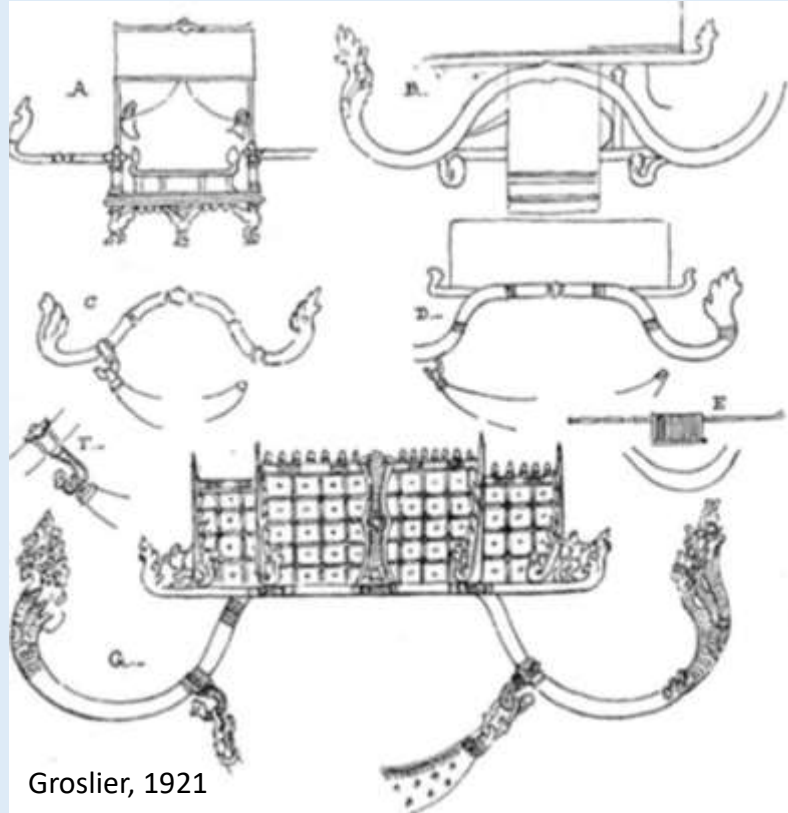
Collaboration





# Palanquin fittings (inv. 1992.346)

Asian Art Museum of San Francisco, curator F. McGill



Groslier, 1921

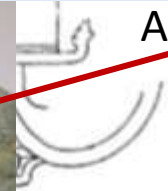


→ Origin : Cambodge

→ late XII<sup>th</sup> to beg. XIII<sup>th</sup> c. or modern copy ?

# Palanquin fittings (inv. 1992.346)

Asian Art Museum of San Francisco, curator F. McGill



→ Origin : Cambodge

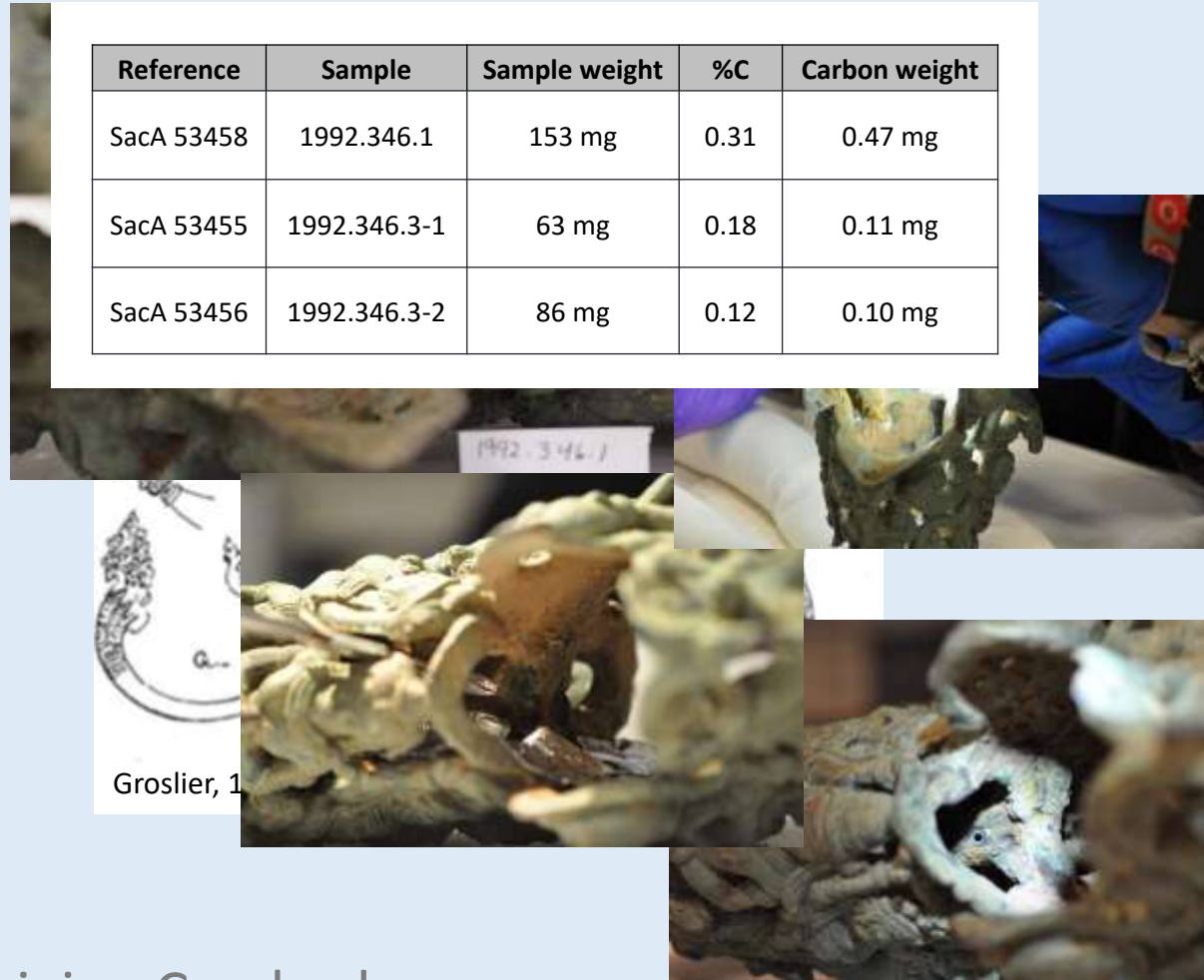
→ late XII<sup>th</sup> to beg. XIII<sup>th</sup> c. or modern copy ?

# Palanquin fittings (inv. 1992.346)

Asian Art Museum of San Francisco, curator F. McGill



Reference	Sample	Sample weight	%C	Carbon weight
SacA 53458	1992.346.1	153 mg	0.31	0.47 mg
SacA 53455	1992.346.3-1	63 mg	0.18	0.11 mg
SacA 53456	1992.346.3-2	86 mg	0.12	0.10 mg



→ Origin : Cambodge

→ late XII<sup>th</sup> to beg. XIII<sup>th</sup> c. or modern copy ?



# Radiocarbon results of the bronze objects



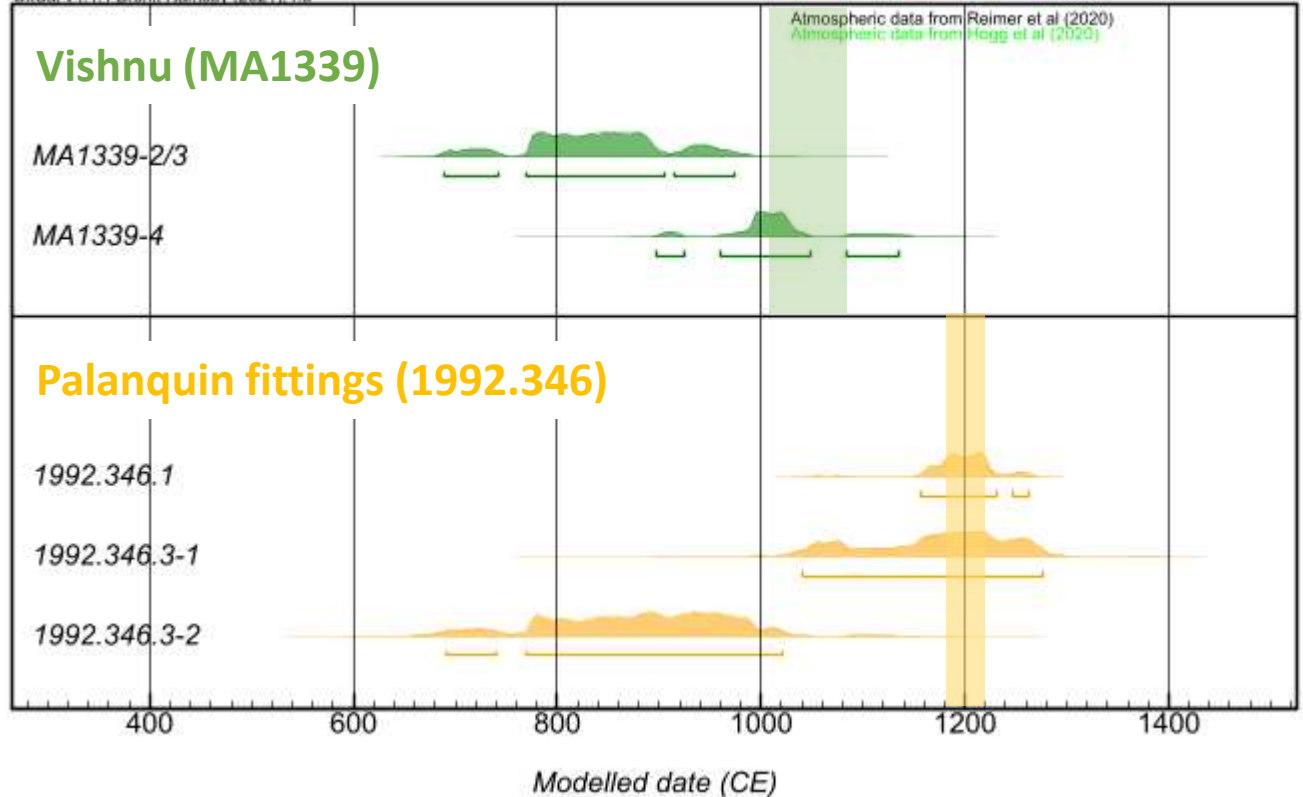
MA 1339 Vishnu

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(MNAAG, Paris)/T.  
Ollivier.



Palanquin fittings - hook

OxCal v4.4.4 Bronk Ramsey (2021): r:5



- ✓ Close collaboration with the conservators
- ✓ Thorough review of the objects before sampling (corrosion of the metal, object safety, preservatives, restorations ?)
- ✓ Small samples → adaptation of the conditions of preparations and measurements

Thanks to :

**APSARA National Authority (Cambodia)**  
**Ministry of Culture and Fine Arts (Cambodia)**



## To go further...

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- Leroy, S., Delqué-Količ, E., Vincent, B., Baptiste, P., Vega, E., McGill, F., Fenn, M., 2021. Le fer comme moyen de datation des bronzes khmers : première approche de prélèvement in situ. *Technè. La science au service de l'histoire de l'art et de la préservation des biens culturels* 82–91. <https://doi.org/10.4000/technè.10073>