Ricardo's Law of Comparative Advantage in Bronze Age, Iron Age, and Early Historic Mainland Southeast Asian Metallurgy: Copper-base Metal Production, Exchange, and Consumption Behaviours at Khao Sai On, Nil Kham Haeng, Non Pa Wai, Phromthin Tai, Sab Champa, and Tha Kae in Central Thailand

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ABSTRACT

Since its late 1970s to early 1980s discovery, the Khao Wong Prachan Valley (KWPV) of central Thailand has been assumed to have been a major supplier of copper in Bronze Age, Iron Age, and Early Historic Southeast Asia. KWPV was the first regional metal production system to be characterised by lead isotope (LI) analysis in the late 2000s, revealing a coherent signature easily distinguished from subsequent analyses of production systems at Phu Lon (northern Thailand) and the Vilabouly Complex (central Laos). Despite KWPV's scale of production, its LI signature has scarcely been detected at Bronze Age metal consumption sites in nearby northeast Thailand and not at all in Iron Age assemblages. We study copper production and copper/bronze consumption behaviours of Iron Age and Early Historic sites in KWPV's immediate vicinity: Khao Sai On, Phromthin Tai, Tha Kae, and Sab Champa. Khao Sai On and Phromthin Tai production signatures are highly consistent with those previously established, whilst the uranogenic tendency at Tha Kae explains outliers from Bronze Age Non Pa Wai and Nil Kham Haeng. Analysis of consumption assemblages reveals little to no consistency with local production signatures. This tendency was tested with LI Iron

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Age and Early Historic datasets for Ban Khu Muang, Ban Mai Chaimongkol, Ban Pong Manao, and Ban Pong Takhob. The pattern is clear: central Thai populations imported copper/bronze, potentially from the Vilabouly Complex or production loci with closely comparable signatures. We examine this counterintuitive behaviour inductively using Ricardo's Law of Comparative Advantage combined with a technological appreciation of the relatively low productivity of central Thai primary copper production. This suggests central Thailand's unattached copper producers freely exchanged copper for exotic goods (bronze, glass, semi-precious stone), with potentially poor terms of exchange, from their desire to participate in wider regional trends in conspicuous consumption. KEYWORDS: Southeast Asia, archaeometallurgy, lead isotope, Ricardo's Law of Comparative Advantage, copper exchange, bronze.

INTRODUCTION

With the aim of better controlling for variation in Mainland Southeast Asian (MSEA) archaeometallurgical lead isotope (LI) data, we explore how Bronze Age and Iron Age primary copper production LI signatures and copper-base consumption behaviours vary within a limited area around the Khao Wong Prachan Valley (KWPV) in Lopburi Province, central Thailand (Fig. 1). The copper production sites referred to in the present study, Khao Sai On (KSO), Nil Kham Haeng (NKH), Non Pa Wai (NPW), Phromthin Tai (PTT), and Tha Kae (TK), range from small (0.5 ha) to medium extent (5 ha), have overlapping chronologies spanning the Bronze Age (ca. 1200–500 B.C.) and Iron Age (ca. 500 B.C.–A.D. 400), and have a maximum inter-site distance of 26 km (KSO-PTT) sites. Southeast Asia is a heavily mineralised region (Hutchison and Taylor 1978; Takimoto 1968; Workman 1977; Zaw, Meffre et al. 2014; Zaw, Santosh et al. 2014) and copper mineralisations are known in the KWPV area (Natapintu 1988; Pryce et al. 2010; Vernon 1988), but due to the presence of military bases in Lopburi Province, collecting geological samples has been problematic and no geochemical data are currently available. Technological analysis of the KSO, PTT, and TK and new elemental analyses for NPW and NKH copper smelting assemblages are reported by Cadet and colleagues in this issue (see Pryce et al. 2010 for NPW and NKH technological analysis). These analyses suggest primary production operated at the scale of communities or even households and was independent of élite control, even in the Late Iron Age on the cusp of state formation. Here we evaluate localised variation in LI ratios for those same samples in geochemical and anthropological terms. Furthermore, we consider how these copper-producing sites, integrated with Sab Champa (SCP, max. distance 70 km, TK-SCP), consumed copper-base metals to better understand the terms of metal exchange for local populations.

Lead isotope-based approaches to metal provenance in Southeast Asia began in the mid-1980s, with the characterisation of lead-bearing mineralisations in Loei Province by the Thailand Archaeometallurgy Project (TAP) (Vincent C. Pigott, pers. comm.). Within a few years, Thai copper-base artifacts from the northern Tak Province were analysed, but these had either been looted or were from private collections, limiting their interpretative value (Kuno et al. 1990). It was not until the early-1990s that the lead isotope analysis (LIA) of excavated Thai bronzes would follow (Hirao and Ro 2013). This was replicated on Vietnamese Iron Age bronzes from the north-central Nghe An Province by the end of the millennium (Imamura 2001) and on Cambodian Iron Age bronzes from the northwestern Banteay Meanchey Province by the mid-2000s (Kakukawa et al. 2008). However, all these studies lacked an appreciation of potential regional source variation, as the typical application of LIA to Southeast Asian

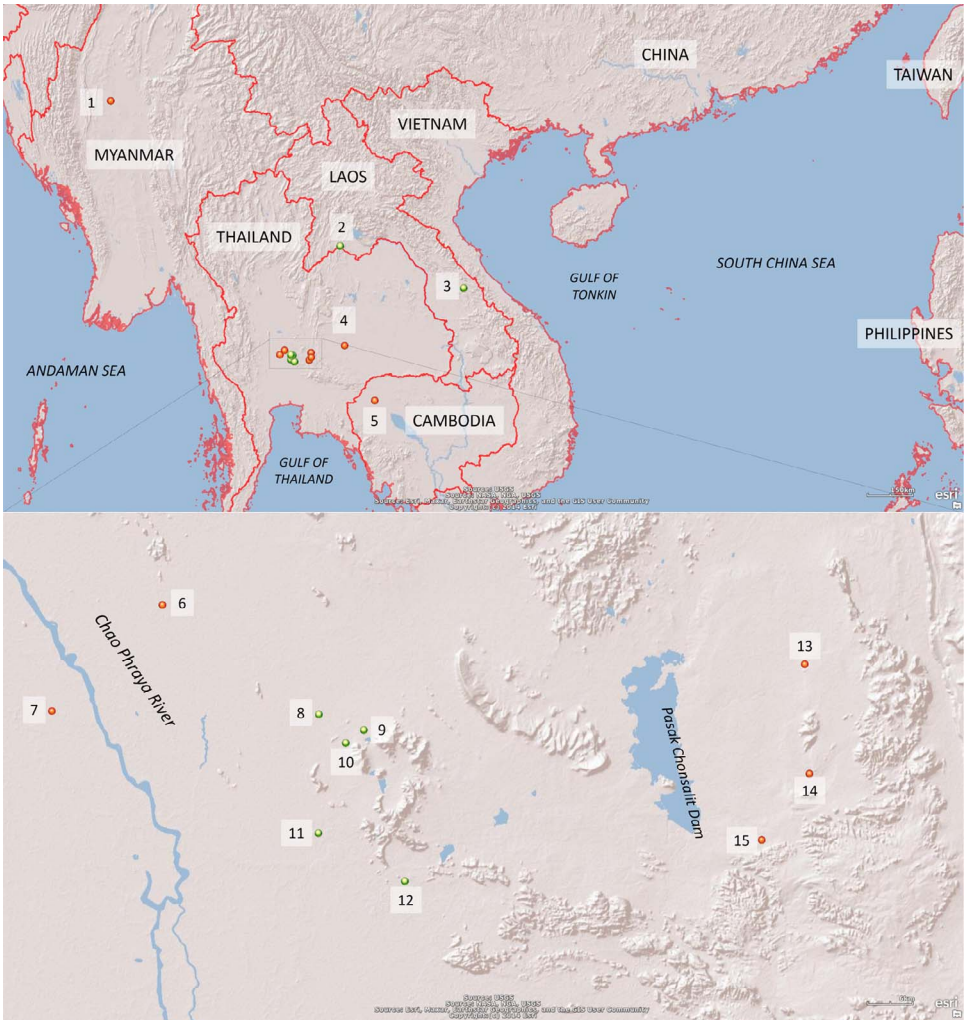

Fig. 1. Map showing Mainland Southeast Asia region of study and location of sites mentioned in text (top); detail of study area in central Thailand and sites (bottom): (1) Oakaie; (2) Phu Lon (PL); (3) Vilabouly Complex (VC); (4) Ban Non Wat (BNW); (5) Phum Snay (PS); (6) Ban Khu Muang (BKM); (7) Ban Mai Chaimongkhon; (8) Phromthin Tai (PTT); (9) Non Pa Wai (NPW); (10) Nil Kham Haeng (NKH); (11) Tha Kae (TK); (12) Khao Sai On (KSO); (13) Sab Champa (SCP); (14) Ban Pong Manao (BPM); (15) Ban Pong Takhob (BPT) (maps produced in ArcGIS Explorer under license, base map ESRI 2014).

copper and lead mineralisations *by geologists for geological purposes* never happened (Killick et al. 2020). This meant initial archaeometric studies had no frame of reference for intra-regional interpretation and could not fulfil the Provenance Hypothesis (*sensu* Wilson and Pollard 2001).

The Southeast Asian Lead Isotope Project (SEALIP) set out to provide this regional frame of reference, with initial LI characterisation of KWPV (Pryce, Pollard et al. 2011) including analysis of 24 samples: 10 copper smelting slag fragments each from NPW and NKH (Pryce et al. 2010), one early Bronze Age axe from NPW, and three

thin copper "cordiform" (heart-shaped) ingots from NKH (Pryce and Pigott 2022:441). To date, SEALIP has incorporated over 1000 copper-base production and copper and lead-base consumption samples from ca. 130 sites spanning ca. 1200 B.C. to A.D. 1700 across MSEA, Island Southeast Asia (ISEA), southern China, India, Sri Lanka, and Papua New Guinea (ANR 2016) to add to the ca. 350 LI results from Iron Age sites in Cambodia and Thailand (Hirao and Ro 2013). However, the 'central Thai copper production signature' has continued to be defined by those original 24 samples from NPW and NKH. This is a potentially critical issue, as despite the KWPV sites still being the largest and densest copper smelting slag deposits known in the region (Pigott et al. 1997) (cf. Cadet et al. 2022 for Vilabouly Complex [VC] in central Laos; Pigott and Weisgerber 1998 and Pryce, Brauns et al. 2011 for Phu Lon [PL] in northern Thailand), the central Thai production signature has never exhibited much consistency with MSEA consumption signatures.

This patterning has been ascribed to sampling bias or recycling (Pryce et al. 2014), which may be an issue as KWPV copper has a low lead content and its signature could be overwhelmed by lead from other sources. The Thai artifacts that may be considered reliably provenanced to KWPV copper production are from BA2 (1000–900 B.C.) Ban Non Wat, ca. 175 km north-northeast of KWPV (Pryce 2011). The one other MSEA instance is from Early Bronze Age (ca. 1000–800 B.C.) Oakaie in north-central Myanmar (Pryce, Htwe et al. 2018), but whilst this provenance attribution is plausible, the lack of any intermediary sites on a ca. 1000 km geodesic route means this network is putative (Pryce, Carrignon et al. 2024). Finally, there is the issue of KWPV dating, which has shifted over the years from a ca. 1500 B.C. Bronze Age transition and copper smelting at NPW (Pigott et al. 1997) to Bronze Age bronze founding at NPW but only Iron Age (post-500 B.C.) copper smelting at NPW and NKH (Rispoli et al. 2013) to a new more comprehensive dating programme that places copper smelting at NPW from ca. 1200–800 B.C. and at NKH from 800–500 B.C. (Higham et al. 2020). The current dating fits with MSEA Iron Age metal consumption patterns, which never exhibit central Thai consistency even when the sites are equidistant or less between the KWPV and the VC in central Laos (Pryce and Higham in press; Pryce et al. 2017). However, what has not yet been taken into account for the 'central Thai copper signature' are the long known but uncharacterised copper production sites in Lopburi Province: KSO, PTT, and TK (Ciarla 2007; Lertcharnrit 2006; Natapintu 1980). Although these deposits are smaller, shallower, and less densely constituted of smelting slag, due to the lack of geological study, it is not known if their LI signatures are compatible with those from NPW and NKH. Are these predominantly later sites consistent with regional copper-base consumption assemblages? Furthermore, the excavations at KSO, PTT, TK, and SCP yielded finished copper-base artifacts as well as ingots. The Early Bronze Age bronze axe at NPW was an import and the NKH ingots were locally made (Pryce, Pollard et al. 2011), but were the KSO, PTT, TK, and SCP artifacts made of local copper, local copper with imported tin, imported bronze, or is the entire picture blurred by recycling and alloying with metallic lead? What can we now say about the socio-economic nature of local copper-base consumption and production?

Previous interpretation for the potentially weaker socio-economic status of KWPV populations was based upon their low labour efficiency in metallurgical behaviours (Pryce 2009:84, 272–273; Pryce et al. 2010:258–259). This argumentation was derived from compositional and microstructural data, as viewed through

anthrochemical (*sensu* Pryce et al. 2014:293) modification of the Weber fraction in complex learning environments (e.g., Eerkens 2000) and inspired by Shennan's (1999) use of Ricardo's Law of Comparative Advantage in Bronze Age Alpine metallurgy. Will the same labour efficiency deficit pertain for the smaller Lopburi-area Iron Age production sites as for the larger Bronze Age ones?

ARCHAEOLOGICAL MATERIALS

This article covers the consumption-only site of SCP and the consumption assemblages of the aforementioned production sites; see Cadet and colleagues (in this issue) for descriptions of KSO, PTT, and TK and their slag assemblages. The ca. 65 ha moated site of SCP is a major settlement, industrial, and funerary site located 15°3'12"N,

Fig. 2. Metal artifacts analysed in the present study, central Thailand: (top row, left, 1 cm scale) fragment (TK/1); two wires (KSO/1, KSO/2); (top row, right, 10 cm scale) bangles (KSO/3, KSO/4 & 15); (centre row, 5 cm scale) animal figurine (SCP/1); bangle (SCP/2); socketed axe (SCP/3); (bottom row, 5 cm scale) six rings (PTT/11–13, PTT/14–16); lead strip (PTT/17).

Table 1. Contextual Information for 38 Slag and Metal Samples Analysed in Present Study, Central Thailand

#	SEALIP ID	SITE	CONTEXT[a]	CATALOGUE	DATE FOUND	PERIOD (DATE)	ARTIFACT	MASS (G)
1	SEALIP/TH/KSO/1	Khao Sai On – Khok Din	Sq. A, SU8 Spit 7	12315	02/12/2007	Late Iron Age (ca. 200 B.C.–A.D. 300)	Wire	
2	SEALIP/TH/KSO/2	Khao Sai On – Khok Din	Sq. A, SU19 Spit 11	12359	09/12/2007	Late Iron Age (ca. 200 B.C.–A.D. 300)	Wire	
3	SEALIP/TH/KSO/3	Khao Sai On – Noen Din	TT2, SU4, Grave 1	12234	24/11/2006	Late Iron Age (ca. 200 B.C.–A.D. 300)	Bangle	
4	SEALIP/TH/KSO/4	Khao Sai On – Noen Din	TT2, SU4, Grave 1	12233	24/11/2006	Late Iron Age (ca. 200 B.C.–A.D. 300)	Bangle[b]	
5	SEALIP/TH/KSO/5	Khao Sai On – Khok Din	Sq. A, Spit 2	12161	24/11/2007	Late Iron Age (ca. 200 B.C.–A.D. 300) to Dvaravati (7th–11th c. A.D.) and later	Slag	145
6	SEALIP/TH/KSO/6	Khao Sai On – Khok Din	Sq. A, area alpha north, Spit 4	12180	26/11/2007	Late Iron Age (ca. 200 B.C.–A.D. 300) to proto-Dvaravati (ca. 3rd–6th c. A.D.)	Slag	17
7	SEALIP/TH/KSO/7	Khao Sai On – Khok Din	TT1, SU1, Spit 3	12208	18/11/2006	Late Iron Age (ca. 200 B.C.–A.D. 300) to proto-Dvaravati (ca. 3rd–6th c. A.D.)	Slag	
8	SEALIP/TH/KSO/8	Khao Sai On – Khok Din	TT1, SU1, Spit 3	12210	18/11/2006	Late Iron Age (ca. 200 B.C.–A.D. 300) to proto-Dvaravati (ca. 3rd–6th c. A.D.)	Slag	
9	SEALIP/TH/KSO/9	Khao Sai On – Khok Din	TT1, SU1, Spit 3	12215	18/11/2006	Late Iron Age (ca. 200 B.C.–A.D. 300) to proto-Dvaravati (ca. 3rd–6th c. A.D.)	Slag	47
10	SEALIP/TH/KSO/10	Khao Sai On – Khok Din	Sq. A, NE, SU24, Spit 17	12497	17/12/2007	Late Iron Age (ca. 200 B.C.–A.D. 300)	Slag	21
11	SEALIP/TH/KSO/11	Khao Sai On – Khok Din	Sq. A, SU25, from section	12745	18/12/2007	Late Iron Age (ca. 200 B.C.–A.D. 300)	Slag	152
12	SEALIP/TH/KSO/12	Khao Sai On – Noen Din	Op.4, SE, SU3, Spit 1	12789	18/11/2008	Late Iron Age (ca. 200 B.C.–A.D. 300) to proto-Dvaravati (ca. 3rd–6th c. A.D.)	Slag	45
13	SEALIP/TH/KSO/13	Khao Sai On – Noen Din	Op.4, SE, SU4–5, contact SU9	12841	20/11/2008	Late Iron Age (ca. 200 B.C.–A.D. 300) to proto-Dvaravati (ca. 3rd–6th c. A.D.)	Slag	49
14	SEALIP/TH/KSO/14	Khao Sai On – Khok Din	Op.1, Sq. A, SU24, Spit 17	12503	17/12/2007	Late Iron Age (ca. 200 B.C.–A.D. 300)	Slag (piece 6)	
15	SEALIP/TH/KSO/15	Khao Sai On – Noen Din	TT2, SU4, Grave 1	12233	24/11/2006	Late Iron Age (ca. 200 B.C.–A.D. 300)	Bangle[b]	
16	SEALIP/TH/PTT/1	Phromthin Tai	PTT/ES/NU/220-230/1			Late Iron Age (200 B.C.–A.D. 100)	Slag	
17	SEALIP/TH/PTT/2	Phromthin Tai	PTT/ES/NU/220-230/2			Late Iron Age (200 B.C.–A.D. 100)	Slag	
18	SEALIP/TH/PTT/3	Phromthin Tai	PTT/ES/NU/220-230/3			Late Iron Age (200 B.C.–A.D. 100)	Slag	
19	SEALIP/TH/PTT/4	Phromthin Tai	PTT/ES/NU/220-230/4			Late Iron Age (200 B.C.–A.D. 100)	Slag	
20	SEALIP/TH/PTT/5	Phromthin Tai	PTT/ES/NU/220-230/5			Late Iron Age (200 B.C.–A.D. 100)	Slag	
21	SEALIP/TH/PTT/6	Phromthin Tai	PTT/WS/SU/260-270/1			Late Iron Age (200 B.C.–A.D. 100)	Slag	
22	SEALIP/TH/PTT/7	Phromthin Tai	PTT/WS/SU/260-270/2			Late Iron Age (200 B.C.–A.D. 100)	Slag	
23	SEALIP/TH/PTT/8	Phromthin Tai	PTT/WS/SU/260-270/3			Late Iron Age (200 B.C.–A.D. 100)	Slag	
24	SEALIP/TH/PTT/9	Phromthin Tai	PTT/WS/SU/260-270/4			Late Iron Age (200 B.C.–A.D. 100)	Slag	
25	SEALIP/TH/PTT/10	Phromthin Tai	PTT/WS/SU/260-270/5			Late Iron Age (200 B.C.–A.D. 100)	Slag	
26	SEALIP/TH/PTT/11	Phromthin Tai	SUAFS 2004 PTT-S2 Burial '49'			Late Iron Age (200 B.C.–A.D. 100)	Ring	1
27	SEALIP/TH/PTT/12	Phromthin Tai	SUAFS 2004 PTT-S2 Burial '49'			Late Iron Age (200 B.C.–A.D. 100)	Ring	1

(*Continued*)

TABLE 1. (*Continued*)

#	SEALIP ID	SITE	CONTEXT[a]	CATALOGUE	DATE FOUND	PERIOD (DATE)	ARTIFACT	MASS (G)
28	SEALIP/TH/PTT/13	Phromthin Tai	SUAFS 2004 PTT-S2 Burial '49'			Late Iron Age (200 B.C.–A.D. 100)	Ring	1
29	SEALIP/TH/PTT/14	Phromthin Tai	SUAFS 2004 PTT-S2 Burial 4			Late Iron Age (200 B.C.–A.D. 100)	Ring	4
30	SEALIP/TH/PTT/15	Phromthin Tai	SUAFS 2004 PTT-S2 Burial 4			Late Iron Age (200 B.C.–A.D. 100)	Ring	3
31	SEALIP/TH/PTT/16	Phromthin Tai	SUAFS 2004 PTT-S2 Burial 4			Late Iron Age (200 B.C.–A.D. 100)	Ring	4
32	SEALIP/TH/PTT/17	Phromthin Tai	LAP 07 PTT-S3 West section, 120-130 cm			Late Iron Age (200 B.C.–A.D. 100)	Lead strip	25
33	SEALIP/TH/SCP/1	Sab Champa	SCP-2-expanded, Level 4, 130–140 cm	SCP-2 6/2002		Iron Age	Animal figurine	12
34	SEALIP/TH/SCP/2	Sab Champa	SCP-3, Level 2, Layer 4, 91 cm	SCP-3 10/2001		Iron Age	Bangle	4
35	SEALIP/TH/SCP/3	Sab Champa	SCP-2, Level 2, Layer 4, 130–140 cm	SCP-3 9/2001		Iron Age	Socketed axe	49
36	SEALIP/TH/TK/1	Tha Kae	Op.1, Sq. D, area a, Spit 7	11001	1990	Dvaravati (7th–11th c. A.D.)	Fragment	
37	SEALIP/TH/TK/2	Tha Kae	Op.1, Sq. B–C, Spit 3	500	1993	Late Iron Age (ca. 200 B.C.–A.D. 300) to proto-Dvaravati (ca. 3rd–6th c. A.D.)	Slag	
38	SEALIP/TH/TK/3	Tha Kae	Op.4, Sq. A area a–b – Sq. B area b, Spit 1	1978	1993	Dvaravati (7th–11th c. A.D.) or later	Slag	
39	SEALIP/TH/TK/4	Tha Kae	Sect. A II/1	2673	1988	Final Iron Age to early proto-Dvaravati (ca. A.D. 0–400)	Slag	
40	SEALIP/TH/TK/5	Tha Kae	Sect. A, III/1	2676	1988	Final Iron Age to early proto-Dvaravati (ca. A.D. 0–400)	Slag	
41	SEALIP/TH/TK/6	Tha Kae	Sect. A, II/2	2690	1988	Final Iron Age to early proto-Dvaravati (ca. A.D. 0–400)	Slag	
42	SEALIP/TH/TK/7	Tha Kae	Op.3, Pit 1, Spit 14	11038	1990	Final Iron Age to early proto-Dvaravati (ca. A.D. 0–400)	Crucible	
43	SEALIP/TH/TK/8	Tha Kae	Op.1 Sq. A, area b, Spit 1	12718	1989	Dvaravati (7th–11th c. A.D.) or later	Slag	
44	SEALIP/TH/TK/9	Tha Kae	Op.1, Sq. A area b, Spit 5	13336	1989	Dvaravati (7th–11th c. A.D.)	Slag	
45	SEALIP/TH/TK/10	Tha Kae	Op.1, Sq. A area b, Spit 14	13337	1989	Proto-Dvaravati (ca. 3rd–6th c. A.D.)	Slag	

[a] Sq. = Square; SU = Stratigraphic Unit; OP = Operation.
[b] Bangles KSO/4 and KSO/15 are the same artifact.

101°14'27"E in Lopburi Province, ca. 16 km east of Pa Sak River and ca. 20 km west of the last mountains separating central Thailand from the Khorat Plateau (Fig. 1). SCP's absolute chronology is vague but is attributed on relative dating grounds to the Bronze Age for basal layers, through Iron Age intermediary layers, to historic Dvaravati for upper layers (Lertcharnrit 2006:259; Lertrit 2004). The three copper-base artifacts analysed include an axe (SCP/3), animal figurine (SCP/1), and bangle (SCP/2), all probably of Iron Age date (Fig. 2, Table 1).

The sole sampled TK metal artifact (TK/1) was fragmentary and of Dvaravati date (ca. A.D. 700–1100). Of the seven PTT late Iron Age metal artifacts, six were copper-base rings (three each from burial 4 [PTT/14–16] and burial 49 [PTT/11–13]) and the seventh (PTT/17) was a strip of lead found at 120–130 cm depth. Of the late Iron Age KSO metal artifacts, two wires (KSO/1–2) were from the Khok Din production locale and two bangles (KSO/3–4) were from Grave 1 at the Noen Din location (Fig. 2, Table 1). Bangles KSO/4 and KSO/15 are the same artifact, sampled a second time due to an unexpected LI result.

METHODOLOGY

Optical Microscopy (OM)

The metal samples were resin-mounted, ground with silicon carbide paper (800–4000 grit) and polished using diamond suspensions (1 and 0.25 μm). After etching with alcoholic ferric chloride, microstructural evidence for thermo-mechanical treatments was investigated using an optical microscope (Zeiss Imager A2 vario Axio system).

X-ray Fluorescence (XRF)

Bulk elemental composition of major, minor, and (some) trace elements for the OM metal samples was done using X-ray fluorescence (XRF) at the Laboratoire Archéomatériaux et Prévision de l'Altération (LAPA-IRAMAT/CEA) in Saclay, France. XRF data were acquired using a NITON XL 3t GOLDD+ portable XRF analyser in 'laboratory' mode (fixed stand), with a maximum 40 kV accelerating voltage in the 'alloys' mode. Accuracy and precision were assessed with eleven Certified Reference Materials (Table 2). Good results for major and minor components were confirmed, but light elements (i.e., phosphorus, silicon, aluminium, magnesium, sulphur) at low concentrations were not reliably detected due to non-vacuum conditions. Analyses were performed on the OM mounted and polished sections using a 3 mm beam diameter, which allowed for reliable results as long as the sample was larger than this. Three such spot analyses were made for each sample.

Scanning Electron Microscopy–Energy Dispersive Spectrometry (SEM-EDS)

Small and/or corroded OM/XRF metal samples were carbon-coated for scanning electron microscopy with energy dispersive spectrometry (SEM-EDS) analysis in a JEOL 7001F instrument in order to establish the bulk composition of samples less than 3 mm in diameter or with intergranular corrosion, and study any inclusions. Both secondary electron (SE) and backscattered electron (BSE) modes were used with an Oxford Silicon Drift Detector set at 20 kV accelerating voltage and 10 mm working distance; data were processed using Oxford Instruments Aztec software.

Table 2. Certified Reference Materials for Present Study, Analysed with pXRF and SEM-EDS, with Certified Values Given (to 1 d.p.)

SAMPLE	Sb	Sn	Bi	Pb	Zn	Cu	Ni	Co	Fe	Mn	Al	S
B10 pXRF	1.2	7.2	bdl	4.1	2.9	83.2	1.1	bdl	0.2	bdl	bdl	bdl
B10 SEM-EDS	1.7	6.6	bdl	3.6	3.0	82.7	1.0	bdl	bdl	bdl	bdl	bdl
B10 certified value	**1.1**	**7.0**	**0.0**	**4.1**	**2.8**	**83.7**	**1.0**	**0.0**	**0.2**	**0.0**	**0.2**	**0**
B12 pXRF	0.1	10.1	bdl	0.2	0.7	85.2	2.8	bdl	0.2	0.2	bdl	bdl
B12 SEM-EDS	bdl[a]	9.5	bdl	bdl	0.9	84.9	3.1	bdl	bdl	bdl	bdl	bdl
B12 certified value	**0.1**	**9.6**	**0.0**	**0.2**	**0.6**	**85.7**	**2.6**	**0.0**	**0.2**	**0.2**	**0.1**	**0.0**
51.13-4 pXRF	bdl	0.3	bdl	0.1	0.4	91.0	bdl	bdl	1.9	0.9	4.9	bdl
51.13-4 SEM-EDS	bdl	bdl	bdl	bdl	0.7	87.7	bdl	bdl	1.9	1.1	7.8	bdl
51.13-4 certified value	**0.0**	**0.3**	**0.0**	**0.0**	**0.3**	**88.8**	**0.1**	**0.0**	**1.8**	**0.9**	**7.3**	**0.0**
71.32-4 pXRF	0.3	6.4	bdl	4.3	7.1	80.5	0.8	bdl	0.4	bdl	bdl	bdl
71.32-4 SEM-EDS	bdl	6.4	bdl	3.1	7.3	81.8	0.8	bdl	0.4	bdl	bdl	bdl
71.32-4 certified value	**0.3**	**6.5**	**0.1**	**4.4**	**6.5**	**80.5**	**0.7**	**0.0**	**0.4**	**0.1**	**0.1**	**0.0**
SRM-500 pXRF	bdl	bdl	bdl	bdl	0.1	99.7	0.1	bdl	bdl	bdl	bdl	bdl
SRM-500 SEM-EDS	bdl	bdl	bdl	bdl	0.4	99.4	bdl	bdl	bdl	bdl	bdl	bdl
SRM-500 certified value	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**99.7**	**0.1**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
C1123 pXRF	bdl	bdl	bdl	bdl	bdl	97.4	bdl	2.5	bdl	bdl	bdl	bdl
C1123 SEM-EDS	bdl	bdl	bdl	bdl	bdl	96.5	bdl	3.4	bdl	bdl	bdl	bdl
C1123 certified value	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**97.4**	**0.0**	**2.3**	**0.0**	**0.0**	**0.0**	**0.0**
SRM1275 pXRF	bdl	bdl	bdl	bdl	bdl	86.9	10.7	bdl	1.6	0.4	bdl	bdl
SRM1275 SEM-EDS	bdl	bdl	bdl	bdl	bdl	87.9	10.1	bdl	1.5	0.5	bdl	bdl
SRM1275 certified value	**0.0**	**0.0**	**0.0**	**0.0**	**0.1**	**88.2**	**9.8**	**0.0**	**1.5**	**0.4**	**0.0**	**0.0**
L-20-1 pXRF	bdl	0.5	bdl	0.3	14.4	84.2	0.2	bdl	bdl	0.1	bdl	bdl
L-20-1 SEM-EDS	bdl	0.5	bdl	bdl	14.6	84.0	bdl	bdl	bdl	bdl	bdl	bdl
L-20-1 certified value	**0.0**	**0.5**	**0.0**	**0.3**	**13.3**	**85.2**	**0.2**	**0.0**	**0.0**	**0.1**	**0.1**	**0.0**
B21 pXRF	0.2	5.3	bdl	3.7	6.5	82.2	1.3	bdl	0.3	bdl	bdl	bdl
B21 SEM-EDS	bdl	5.2	bdl	3.9	7.0	82.2	1.3	bdl	bdl	bdl	bdl	bdl
B21 certified value	**0.2**	**5.1**	**0.0**	**3.8**	**6.2**	**83.0**	**1.2**	**0.0**	**0.3**	**0.0**	**0.1**	**0.0**
B31 pXRF	0.5	8.0	bdl	10.6	0.8	79.4	0.6	bdl	bdl	bdl	bdl	bdl
B31 SEM-EDS	1.8	8.0	bdl	9.9	1.1	78.6	0.5	bdl	bdl	bdl	bdl	bdl
B31 certified value	0.5	7.7	0.0	11.8	0.8	78.6	0.5	0.0	0.0	0.0	0.0	0.0
UZ-52-3 pXRF	0.1	1.0	bdl	0.1	18.0	80.3	0.1	bdl	0.3	bdl	bdl	bdl
UZ-52-3 SEM-EDS	bdl	1.0	bdl	bdl	18.2	80.2	bdl	bdl	bdl	bdl	bdl	bdl
UZ-52-3 certified value	**0.1**	**1.1**	**0.0**	**0.1**	**17.0**	**81.1**	**0.1**	**0.0**	**0.3**	**0.0**	**0.0**	**0.0**

[a] bdl = below detection level of instrument.

The detection limit was fixed at 0.5 wt.% with a count rate of 4000/s (detection time of 40 s), which gave good spectral resolution with respect to background noise. Relative quantification error (2σ) is ca. 10 percent of the measured value. SEM-EDS accuracy was evaluated using the same Certified Reference Materials (CRMs) as for the XRF analysis. We obtained good results for the major elements (Table 2). Bulk compositions for each sample were obtained by a mean of 3–4 areas scan (0.4 mm^2) per sample. When possible, the analyses were performed in areas without corrosion products.

Multi Collector – Inductively Coupled Plasma – Mass Spectrometer (MC-ICP-MS)

Lead isotope analysis (LIA) was conducted at the Service d'Analyse des Roches et des Minéraux of the Centre for Petrographic and Geochemical Research (SARM-CRPG) in Nancy, France, using an Multi Collector – Inductively Coupled Plasma – Mass Spectrometer (MC-ICP-MS) after lead extraction (Aebischer et al. 2015; Cloquet et al. 2006). Thallium NIST SRM 997 was used to correct for instrumental mass bias and all parameters were adjusted to obtain the closest values relative to lead NIST SRM 981, as determined by DS-TIMS (Thirlwall 2002).

As per the SEALIP and BROGLASEA (ANR 2016) programmes, LIA was used to look for consistency with known and characterised production systems, in recognition that there could be other as yet uncharacterised primary and/or secondary production systems or that interpretation could be impacted by mixing, alloying, or recycling (e.g., Budd et al. 1993; Pryce et al. 2014; Pryce, Brauns et al. 2011; Wilson and Pollard 2001). These consistencies were judged by proximity of data points on $^{206}Pb/^{204}Pb$ (uranium-238 series divided by primeval lead ratio, known as 'uranogenic' or 'radium series' variation) versus $^{207}Pb/^{204}Pb$ (uranium-235 series divided by primeval lead ratio, known as 'actinium series' variation) and $^{206}Pb/^{204}Pb$ versus $^{208}Pb/^{204}Pb$ (thorium-232 decay series divided by primeval lead ratio, known as 'thorogenic' or 'thorium series' variation) biplots for manual interpretation.

RESULTS

Technological

As can be seen in Figure 3 and Table 3, eleven of the fifteen metal samples had an as-cast structure, whilst two were hammered and annealed, one was too corroded, and the last was difficult to determine in a pure lead matrix. The thermo-mechanical treatments correspond to the typologies, with all the bangles and rings (including PTT/13 in Table 4) being as-cast and thus left to cool in their moulds, whilst the socketed axe and the wire were hammered and annealed to shape them and prevent brittleness, respectively. The animal figurine's microstructure was too corroded to identify but, given the form, was most likely as-cast. Given that all the samples are from the Iron Age (Late Iron Age or Historic), it is to be expected that technology correlates with typology. However, since none of the objects was particularly sophisticated, there is nothing to indicate that any of the producing workshops were especially skilled.

Elemental

As indicated by XRF analysis (Table 3), and slightly revised for some samples with SEM-EDS data (Table 4), eight of the study samples were made from leaded copper,

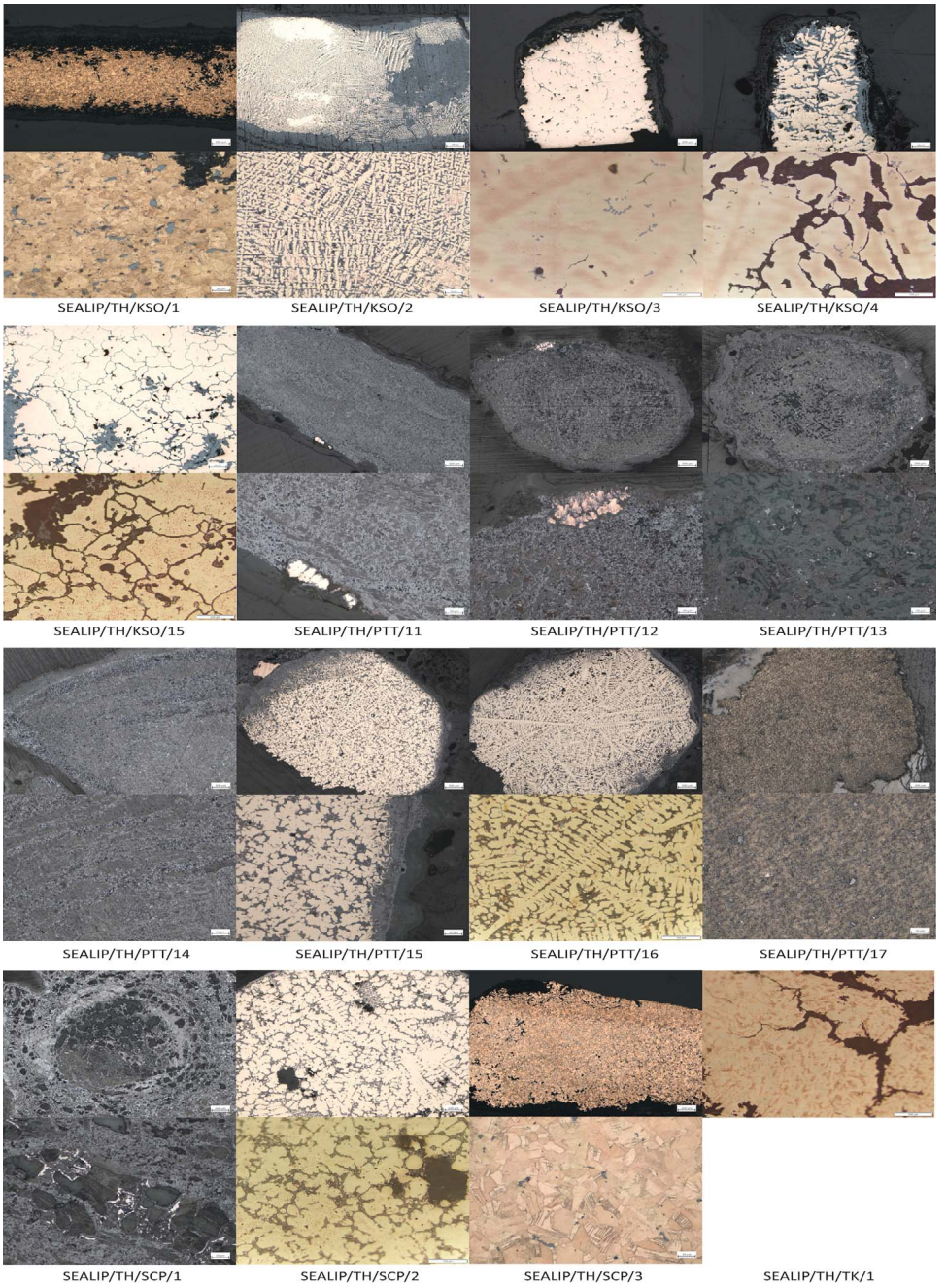

Fig. 3. Reflected light optical micrographs of the central Thai study samples, etched or not according to corrosion.

five from bronze, and one each from copper and lead. As per the technological analysis, there is a good correspondence between alloy and typology, with all the rings, one bangle, and the animal figurine having been made from leaded bronze for greater

Table 3. Normalised pXRF Data with Analytic Totals and Optical Microscopy Data for Central Thai Metal Samples

SEALIP ID	Sb[a]	Sn	Cd	Pb	As	Au	W	Zn	Cu	Ni	Fe	Cr	V	Al	S	P	Si	ANALYTIC TOTAL	CORROSION	ALLOY	WORKING TREATMENT	OBJECT
SEALIP/TH/KSO/1	bdl	12.4	bdl	bdl	0.1	bdl	bdl	bdl	81.9	bdl	0.5	bdl	bdl	bdl	0.7	bdl	4.3	100.0	Medium	Bronze	Hammered/ annealed	Wire
SEALIP/TH/KSO/2	bdl	18.9	bdl	bdl	bdl	bdl	bdl	bdl	78.4	bdl	0.1	bdl	bdl	bdl	0.3	bdl	2.2	100.0	Medium	Bronze	As cast	Wire
SEALIP/TH/KSO/3	bdl	7.9	bdl	bdl	0.1	bdl	0.5	1.2	85.9	bdl	0.1	bdl	bdl	bdl	0.5	bdl	3.8	103.0	Low	Bronze	As cast	Bangle
SEALIP/TH/KSO/4	bdl	10.0	0.1	0.1	0.2	bdl	bdl	0.2	84.8	0.1	0.2	bdl	bdl	bdl	0.3	bdl	4.0	100.2	Medium	Bronze	As cast	Bangle[b]
SEALIP/TH/KSO/15	bdl	6.9	bdl	0.2	bdl	bdl	bdl	bdl	92.6	0.1	0.1	bdl	bdl	bdl	bdl	bdl	bdl	99.6	Medium	Bronze	As cast	Bangle[b]
SEALIP/TH/PTT/11	bdl	22.2	bdl	0.9	0.1	bdl	bdl	bdl	72.0	bdl	1.3	bdl	bdl	bdl	bdl	0.1	3.5	100.0	High	Bronze	As cast	Ring
SEALIP/TH/PTT/12	bdl	13.6	bdl	0.8	bdl	bdl	0.1	0.5	56.0	bdl	6.1	bdl	bdl	1.8	bdl	0.4	20.7	100.3	High	Bronze	As cast	Ring
SEALIP/TH/PTT/14	bdl	33.4	bdl	1.0	bdl	bdl	bdl	bdl	64.0	bdl	0.6	bdl	bdl	bdl	bdl	bdl	0.8	100.0	High	Leaded bronze	As cast	Ring
SEALIP/TH/PTT/15	bdl	18.5	bdl	5.7	0.2	bdl	bdl	bdl	75.2	bdl	0.3	0.1	bdl	bdl	bdl	bdl	bdl	99.8	Low	Leaded bronze	As cast	Ring
SEALIP/TH/PTT/16	bdl	17.6	bdl	5.0	0.2	0.1	bdl	bdl	75.8	bdl	0.9	bdl	bdl	bdl	bdl	bdl	0.5	99.9	Low	Leaded bronze	As cast	Ring
SEALIP/TH/PTT/17	bdl	bdl	bdl	99.7	bdl	bdl	bdl	bdl	0.1	bdl	bdl	bdl	0.1	bdl	bdl	bdl	bdl	99.9	Low	Lead	?	Lead strip
SEALIP/TH/SCP/1	bdl	19.4	bdl	3.2	bdl	bdl	bdl	bdl	72.2	bdl	0.2	bdl	bdl	1.0	bdl	bdl	3.8	100.5	High	Leaded bronze	Corroded	Animal figurine
SEALIP/TH/SCP/2	bdl	15.8	bdl	3.7	0.2	bdl	bdl	bdl	73.5	bdl	0.7	bdl	bdl	bdl	bdl	bdl	6.1	99.7	Low	Leaded bronze	As cast	Bangle
SEALIP/TH/SCP/3	bdl	4.6	bdl	bdl	bdl	bdl	bdl	bdl	95.2	bdl	0.2	bdl	bdl	bdl	bdl	bdl	bdl	100.0	Low	Bronze	Hammered/ annealed	Socketed axe
SEALIP/TH/TK/1	0.4	0.2	bdl	0.2	0.2	bdl	bdl	bdl	95.6	bdl	bdl	bdl	bdl	bdl	0.7	0.1	2.5	102.5	Low	Copper	As cast	Metal?

[a] bdl = below detection level of instrument; O, Pd, Ag, Ru, Mo, Nb, Zr, Bi, Se, Co, Mn, Ti, Cl, and Mg were scanned for but were systematically BDL.
[b] Bangles KSO/4 and KSO/15 are the same artifact.

Table 4. Normalised SEM-EDS Data with Analytic Totals for Central Thai Metal Samples

SEALIP ID	O[a]	Si	S	Cl	Fe	Cu	Sn	Pb	Ca	ANALYTIC TOTAL	ALLOY	OBJECT
SEALIP/TH/KSO/1	2.2	bdl	0.6	0.3	bdl	88.9	8.1	bdl	bdl	100.0	Bronze	Wire
SEALIP/TH/KSO/2	8.3	0.1	0.2	bdl	bdl	73.5	17.9	0.1	bdl	100.0	Bronze	Hook
SEALIP/TH/KSO/3	4.2	bdl	0.2	0.1	bdl	88.6	6.8	bdl	bdl	100.0	Bronze	Bangle
SEALIP/TH/KSO/4	bdl	bdl	0.1	bdl	bdl	94.2	5.7	bdl	bdl	100.0	Bronze	Bangle[b]
SEALIP/TH/KSO/15	2.2	0.1	0.1	bdl	bdl	92.2	5.5	bdl	bdl	100.0	Bronze	Bangle[b]
SEALIP/TH/PTT/11	27.4	1.1	0.1	0.2	0.3	50.4	20.1	0.3	bdl	100.0	Leaded bronze	Ring
SEALIP/TH/PTT/12	26.8	0.7	0.1	0.5	bdl	45.1	25.9	1.0	bdl	100.0	Leaded bronze	Ring
SEALIP/TH/PTT/13	33.8	0.7	bdl	bdl	bdl	39.7	24.7	1.1	bdl	100.0	Leaded bronze	Ring
SEALIP/TH/PTT/14	28.9	0.4	bdl	bdl	bdl	44.3	25.2	1.1	bdl	100.7	Leaded bronze	Ring
SEALIP/TH/PTT/15	7.1	0.1	bdl	0.1	bdl	69.7	18.4	4.6	bdl	100.0	Leaded bronze	Ring
SEALIP/TH/PTT/16	6.4	0.3	bdl	0.5	bdl	70.9	17.8	4.2	bdl	100.5	Leaded bronze	Ring
SEALIP/TH/PTT/17	9.7	2.9	bdl	bdl	bdl	bdl	bdl	87.2	0.2	99.9	Lead	Lead strip
SEALIP/TH/SCP/1	29.2	0.3	0.1	bdl	bdl	36.6	31.1	2.7	bdl	100.2	Leaded bronze	Animal figurine
SEALIP/TH/SCP/2	4.2	bdl	bdl	0.3	bdl	74.7	17.6	3.2	bdl	100.0	Leaded bronze	Bangle
SEALIP/TH/SCP/3	0.7	bdl	bdl	bdl	bdl	95.9	3.4	bdl	bdl	100.0	Bronze	Socketed axe
SEALIP/TH/TK/1	1.5	bdl	bdl	0.1	bdl	98.4	bdl	bdl	bdl	100.0	Copper	Fragment

[a] bdl = below detection level of instrument.
[b] Bangles KSO/4 and KSO/15 are the same artifact.

casting fidelity. For the KSO metal artifacts, the use of bronze for the bangles is somewhat atypical for MSEA Iron Age ornaments; it could simply have been a whimsy of the manufacturer based on lead availability at the workshop that day, rather than a meaningful "technological choice" (Pryce et al. 2010:251, 262). Conversely, the SCP socketed axe, which is most likely Iron Age, represents a probable technological choice in the selection of bronze for toughness rather than leaded bronze for castability. The Tha Kae fragment being made of copper suggests it is raw metal, whether smelted on site or imported for processing on site or consumption as is.

The high tin values seen in some artifacts are almost certainly the result of post-depositional modification, as seen in the corroborating Fe, Al, and Si values and highly corroded microstructures. As none of these artifacts presents a high-tin bronze microstructure, they are identified as 'bronzes' and 'leaded bronzes' only. It is also salutary to note the variation in elemental results for KSO/4 (10 wt.% Sn, 85 wt.% Cu, Zn detected) and KSO/15 (7 wt.% Sn, 93 wt.% Cu, no Zn detected), two samples from the same bangle. As we have observed in sampling and analysing many hundreds of MSEA copper-base artifacts, this reflects frequent significant intra-sample compositional heterogeneity, whether induced during potentially multiple production

Table 5. Raw Lead Isotope Data for Central Thai Study Samples

SEALIP ID	OBJECT	$^{206}Pb/^{204}Pb$	ERR (2σ)	$^{207}Pb/^{204}Pb$	ERR (2σ)	$^{208}Pb/^{204}Pb$	ERR (2σ)	$^{207}Pb/^{206}Pb$	ERR (2σ)
SEALIP/TH/KSO/1	Wire	18.472	0.001	15.624	0.002	38.451	0.004	0.84570	0.00002
SEALIP/TH/KSO/2	Hook	18.347	0.002	15.622	0.002	38.511	0.005	0.85139	0.00001
SEALIP/TH/KSO/3	Bangle	18.531	0.002	15.584	0.002	38.239	0.005	0.84151	0.00003
SEALIP/TH/KSO/4	Bangle[a]	18.715	0.001	15.704	0.001	38.932	0.003	0.83960	0.00002
SEALIP/TH/KSO/5	Slag	18.386	0.001	15.542	0.001	37.913	0.004	0.84580	0.00002
SEALIP/TH/KSO/6	Slag	18.207	0.001	15.529	0.001	37.889	0.003	0.85344	0.00002
SEALIP/TH/KSO/7	Slag	18.404	0.001	15.559	0.001	38.026	0.002	0.84591	0.00002
SEALIP/TH/KSO/8	Slag	18.057	0.001	15.528	0.001	37.918	0.003	0.86044	0.00002
SEALIP/TH/KSO/9	Slag	18.248	0.001	15.536	0.001	37.918	0.002	0.85185	0.00002
SEALIP/TH/KSO/10	Slag	18.298	0.001	15.568	0.001	37.905	0.003	0.85128	0.00002
SEALIP/TH/KSO/11	Slag	18.327	0.001	15.549	0.001	37.958	0.003	0.84886	0.00002
SEALIP/TH/KSO/12	Slag	18.584	0.001	15.569	0.001	38.015	0.003	0.83823	0.00002
SEALIP/TH/KSO/13	Slag	18.468	0.001	15.554	0.001	37.972	0.003	0.84275	0.00002
SEALIP/TH/KSO/14	Slag	18.151	0.001	15.533	0.001	37.951	0.004	0.85621	0.00002
SEALIP/TH/KSO/15	Bangle[a]	18.716	0.001	15.704	0.001	38.928	0.005	0.83955	0.00002
SEALIP/TH/PTT/1	Slag	18.222	0.001	15.535	0.001	37.960	0.003	0.85300	0.00002
SEALIP/TH/PTT/2	Slag	18.256	0.001	15.543	0.001	38.005	0.003	0.85190	0.00003
SEALIP/TH/PTT/3	Slag	18.992	0.001	15.590	0.001	38.115	0.004	0.82135	0.00002
SEALIP/TH/PTT/4	Slag	18.604	0.001	15.583	0.001	38.126	0.003	0.83811	0.00002
SEALIP/TH/PTT/5	Slag	18.431	0.001	15.568	0.001	38.058	0.003	0.84518	0.00002
SEALIP/TH/PTT/6	Slag	18.337	0.001	15.550	0.001	38.032	0.004	0.84849	0.00002
SEALIP/TH/PTT/7	Slag	18.476	0.001	15.559	0.001	38.065	0.004	0.84257	0.00002
SEALIP/TH/PTT/8	Slag	18.398	0.001	15.567	0.001	38.057	0.004	0.84663	0.00002
SEALIP/TH/PTT/9	Slag	18.083	0.001	15.514	0.001	37.861	0.003	0.85846	0.00002

(*Continued*)

TABLE 5. (*Continued*)

SEALIP ID	OBJECT	$^{206}Pb/^{204}Pb$	ERR (2σ)	$^{207}Pb/^{204}Pb$	ERR (2σ)	$^{208}Pb/^{204}Pb$	ERR (2σ)	$^{207}Pb/^{206}Pb$	ERR (2σ)
SEALIP/TH/PTT/10	Slag	18.598	0.001	15.561	0.001	38.049	0.003	0.83724	0.00002
SEALIP/TH/PTT/11	Ring	18.414	0.002	15.703	0.002	38.965	0.005	0.853	0.00001
SEALIP/TH/PTT/12	Ring	18.413	0.001	15.703	0.001	38.963	0.003	0.853	0.00001
SEALIP/TH/PTT/13	Ring	18.415	0.001	15.704	0.001	38.966	0.004	0.853	0.00001
SEALIP/TH/PTT/14	Ring	18.414	0.001	15.711	0.001	38.917	0.003	0.853	0.00002
SEALIP/TH/PTT/15	Ring	18.494	0.001	15.731	0.001	38.948	0.003	0.851	0.00001
SEALIP/TH/PTT/16	Ring	18.494	0.001	15.732	0.001	38.948	0.004	0.851	0.00001
SEALIP/TH/PTT/17	Lead strip	18.257	0.001	15.748	0.001	38.501	0.003	0.863	0.00002
SEALIP/TH/SCP/1	Animal figurine	18.260	0.001	15.753	0.001	38.523	0.003	0.86279	0.00001
SEALIP/TH/SCP/2	Bangle	18.412	0.001	15.702	0.001	38.954	0.004	0.85289	0.00001
SEALIP/TH/SCP/3	Socketed axe	18.150	0.002	15.626	0.003	38.259	0.007	0.86093	0.00003
SEALIP/TH/TK/1	Fragment	18.357	0.001	15.725	0.001	38.772	0.004	0.85659	0.00002
SEALIP/TH/TK/2	Slag	18.223	0.001	15.532	0.001	37.901	0.003	0.85280	0.00002
SEALIP/TH/TK/3	Slag	18.494	0.001	15.683	0.001	38.508	0.004	0.84850	0.00002
SEALIP/TH/TK/4	Slag	18.990	0.001	15.587	0.001	38.020	0.004	0.82126	0.00002
SEALIP/TH/TK/5	Slag	20.039	0.002	15.676	0.002	38.187	0.004	0.78269	0.00002
SEALIP/TH/TK/6	Slag	19.320	0.001	15.604	0.001	38.056	0.002	0.80813	0.00002
SEALIP/TH/TK/7	Crucible	20.380	0.002	15.699	0.002	38.390	0.005	0.77076	0.00002
SEALIP/TH/TK/8	Slag	19.083	0.001	15.606	0.001	38.041	0.003	0.81830	0.00002
SEALIP/TH/TK/9	Slag	19.017	0.001	15.590	0.001	37.984	0.003	0.82025	0.00002
SEALIP/TH/TK/10	Slag	21.176	0.003	15.749	0.002	38.430	0.006	0.74417	0.00002

[a] Bangles KSO/4 and KSO/15 are the same artifact.

cycles, by analytical instrumental parameters, or, more likely, from post-depositional modification, as indicated in the divergent Si determinations (4 vs. 0 wt.%) of the KSO bangle in question. This experience guides our scepticism regarding claims of ancient preferences for bronze versus copper in upper versus lower northeast Thailand on the basis of tenths of a percent of analysed tin concentration (cf. White and Hamilton 2021:14).

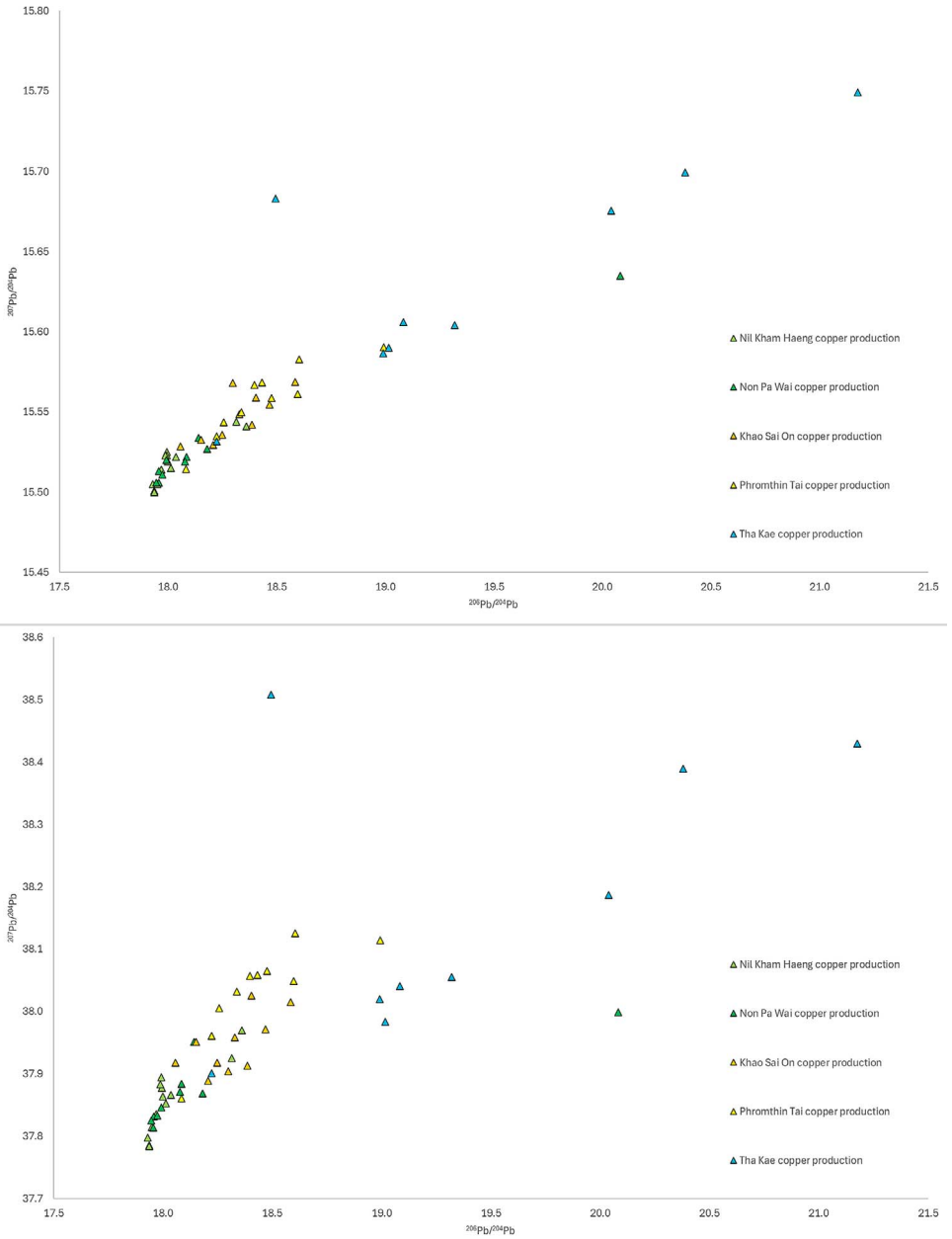

Fig. 4. Raw LI ratios for slag samples from KSO, PTT, and TK, with previously published NPW and NKH slag data (Pryce, Pollard et al. 2011): $^{207/204}$Pb plotted against $^{206/204}$Pb ratios (top); $^{208/204}$Pb plotted against $^{206/204}$Pb ratios (bottom).

Isotopic

Starting with production data (Table 5), we can see a good degree of compatibility for KSO and PTT slag samples with the pre-existing data constituting the central Thai copper production signature, though perhaps with a slightly higher uranogenic trend (Fig. 4). This tendency is marginally noticeable for the two KSO-ND slag samples

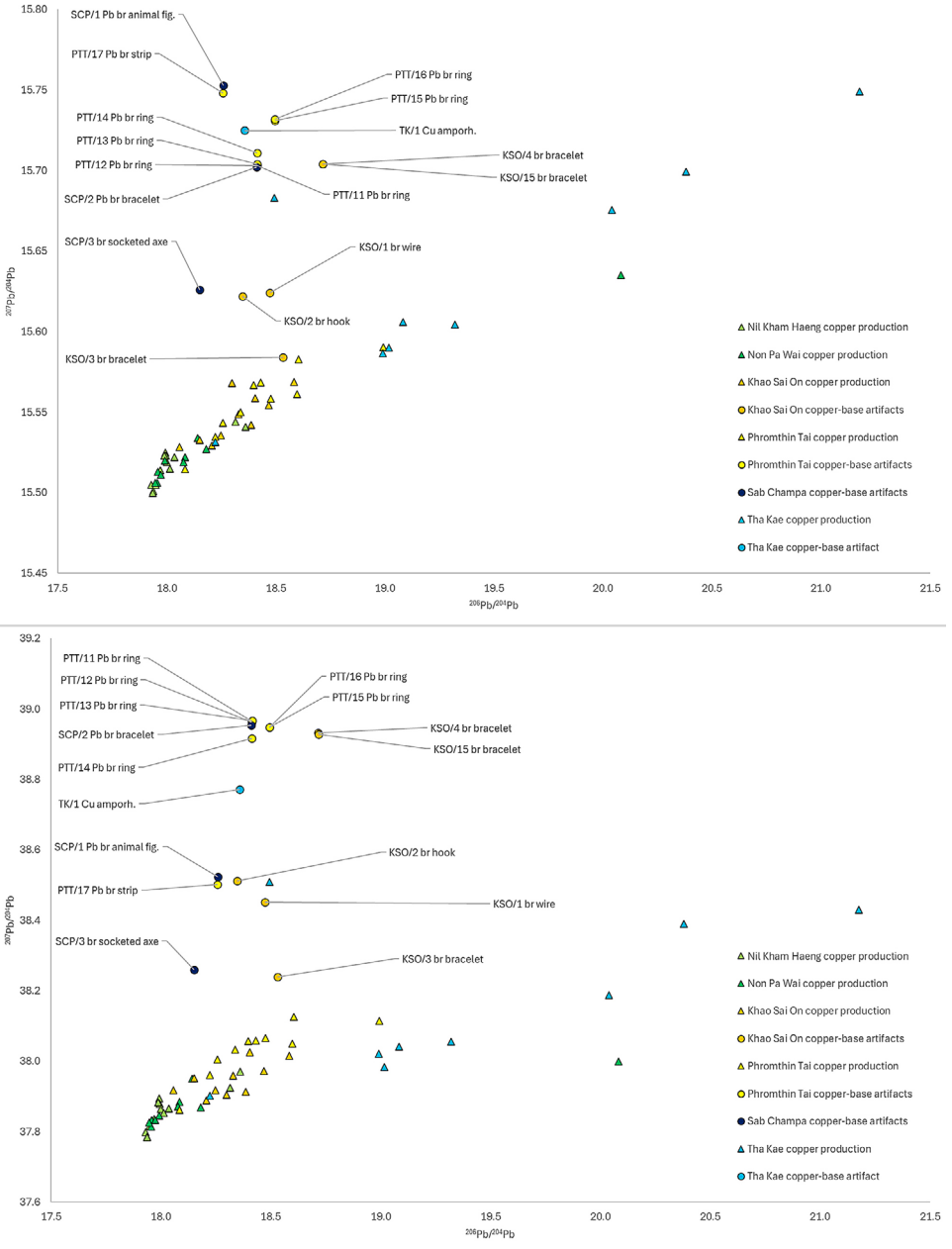

Fig. 5. Raw LI ratios for slag and metal samples from KSO, PTT, and TK, and metal from SCP, with previously published NKH and NPW slag and metal data (Pryce, Brauns et al. 2011): $^{207/204}$Pb plotted against $^{206/204}$Pb ratios (top); $^{208/204}$Pb plotted against $^{206/204}$Pb ratios (bottom).

(KSO/12, KSO/13), and may be related to bronze recycling (Cadet et al. this issue) but the difference is minimal and well within the range of central Thai copper smelting slags. Though overlapping the NPW and NKH slag LI ratios, we can see some TK slag samples have significantly higher uranogenic values, which themselves overlap the previously anomalous NPW/1 slag sample (Pryce, Pollard et al. 2011). However, the lack of a horizontal orientation when plotted against thorogenic variation (Fig. 4 bottom) suggests that the TK samples may not be more 'radiogenic' in the sense of being derived from copper ores with more uranium-238. A single sample (TK/3) plots apart on actinium and thorium series values; this could represent the use of copper ores from other mineralisations or the exchange of slag between primary production centres, as has previously been proposed for crossed signatures between PL and the VC (Pryce et al. 2014). However, it could also represent: (1) a non-ore component of the smelt, like a flux, contributing lead to the smelting system; (2) slag deriving from secondary copper-base production processes that has been contaminated by recycling; or (3) a slag unrelated to copper-base production. As TK/3 has a very low copper content but does have precipitated Fe^{2+} iron oxides (wüstite) and inclusions of metallic iron (Cadet et al. this issue), it is conceivably the result of iron smelting activities.

Several interesting patterns crystallise from these new consumption data (Fig. 5). The PTT metal samples are all leaded alloys, so it is not possible to test for consistency with our slag-defined copper production signature. For the KSO samples, all of which are bronze, only one (KSO/3) is marginally consistent with the local copper production signature. KSO/4's total inconsistency with the central Thai signatures was surprising, so a second sample was analysed, KSO/15, which furnished an almost identical result. This highlights the analytical consistency of our LI methodology even when samples are partly corroded and subsequently have variable elemental compositions. The two wire samples, KSO/1 and KSO/2, plot relatively closely and could conceivably have been made with metal from a shared source, whether primary or secondary. For the SCP samples, as expected, the leaded alloys are inconsistent with the local copper production signature; of course, the copper may have been local and the lead imported. However, the unleaded socketed bronze axe, SCP/3, is not consistent with the central Thai copper production signature either. Finally, the sole TK metal sample, a fragment of copper, is incompatible with local production and was seemingly imported.

DISCUSSION

Present Study Data Versus Known Bronze Age and Iron Age MSEA Production Signatures

As has recently been demonstrated for much smaller Bronze Age datasets (Pryce, Carrignon et al. 2024), it is not yet feasible to compare this study's data algorithmically against the full MSEA Iron Age metals dataset. However, we can answer some simple questions, and pose some harder ones, by plotting against other known MSEA copper and lead production signatures (Fig. 6). Firstly, it is important to point out that although the TK and PL copper production signatures appear to overlap when comparing $^{207/204}$Pb ratios (Fig. 6 top), they are clearly inconsistent when plotting for $^{208/204}$Pb variation (Fig. 6 bottom). Secondly, the signatures for KSO metal samples, with the exception of KSO/3, are inconsistent with any of the known MSEA primary copper production (mining and/or smelting) signatures; it is possible these samples represent secondary production (refining, alloying, and/or recycling loci) signatures.

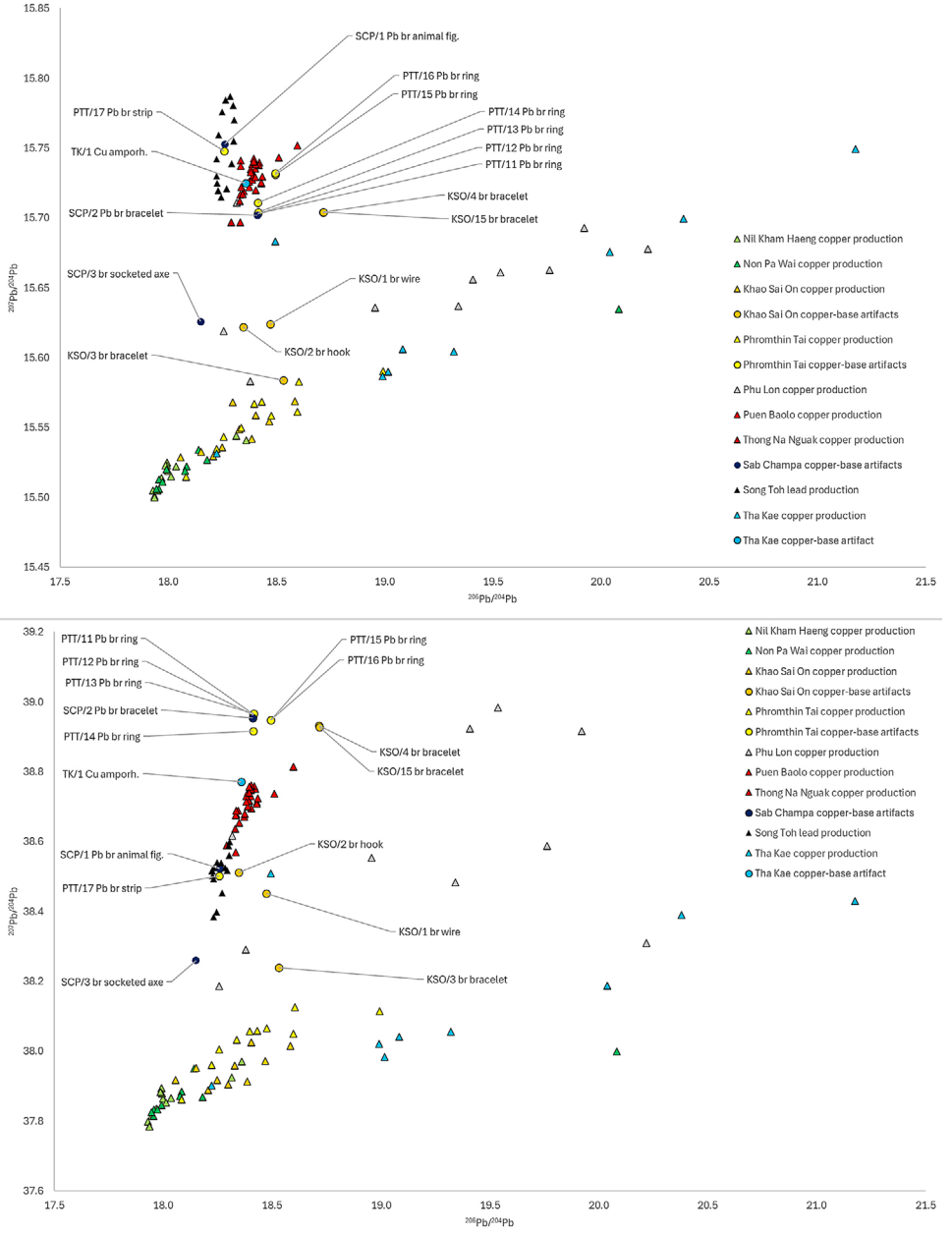

Fig. 6. Raw LI ratios for slag and metal samples from KSO, PTT, and TK, and metal from SCP, with previously published NKH, NPW, and VC slag and metal data (Cadet et al. 2019; Pryce, Pollard et al. 2011; Pryce et al. 2014) and Song Toh lead mineral data (Hirao and Ro 2013): $^{207/204}$Pb plotted against $^{206/204}$Pb ratios (top); $^{208/204}$Pb plotted against $^{206/204}$Pb ratios (bottom).

For PTT, the leaded bronze rings (PTT/11–16) plot in two groups within an isospace densely occupied by MSEA leaded alloys (not plotted here for legibility) for which no potential source is known due to a lack of study of regional lead producers (Pryce 2012), but the lead strip (PTT/17) does fall within the lead ore mineral field defined for Song Toh in western Thailand (Hirao and Ro 2013).

For SCP, we note the bronze axe (SCP/3) is not compatible with known MSEA copper production signatures; though it does offer limited consistency with the Early Bronze Age bronze axe from Non Pa Wai, which is thought to be imported (Pryce, Pollard et al. 2011). The leaded bronze bangle (SCP/2) with PTT/11–14 hints at an unknown shared lead source, while the leaded bronze figurine (SCP/1) joins PTT/17 in having a possible Song Toh provenance, which would be a logical attribution of the constituent lead metal at least – the copper and tin being methodologically unknowable. Finally, for TK, we note that the copper fragment (TK/1) is highly consistent with the primary copper production signature of the VC in central Laos, some 625 km geodesic to the east. This latter pattern, of the VC dominating MSEA supply has been noted many times before but never at such proximity to the KWPV (Pigott and Pryce 2022; Pryce 2014; Pryce et al. 2014; Pryce, Htwe et al. 2018; Pryce et al. 2017; Pryce and Pigott 2022).

Present Study Data Versus Pre-existing Datasets for Central Thailand

Having identified a consistent and long-term pattern for central Thai non-ferrous base metal production and consumption in the SEALIP dataset, how do local pre-existing datasets compare (see also Pryce et al. 2017)? These data are for artifacts from the following sites: Ban Mai Chaimongkhon (BMC), including a bronze axe and 'plate' of prehistoric date; Ban Khu Muang (BKM), including six historic (Dvaravati) lead fragments; Ban Pong Manao (BPM), including 23 bronze, 1 copper, 11 leaded bronze, and 35 leaded copper artifacts, predominantly bracelets, but some finger, toe, and earrings and two weapons, all of probable Iron Age or Early Historic date; Ban Pong Takhob (BPT), including one leaded copper fragment of unknown date; and Tha Kae (TK), including two leaded bronze fragments of unknown date. These sites are distributed within 42 km west and 62 km east of KWPV and constitute a coherent group with the SEALIP sites.

Hirao and Ro's (2013) data exhibit the same pattern: little to no compatibility with central Thai copper sources for the unleaded alloys and mostly very different lead signatures for leaded alloys (Fig. 7). The BPM copper 'lump' (BP1766) appears somewhat consistent with KWPV copper production on the $^{207/206}$Pb plot (Fig. 7 top) but is clearly distinguished as incompatible using $^{208/206}$Pb (Fig. 7 bottom). The BPM copper arrowhead (BP1767) is inconsistent with any known primary or secondary source. However, BMC, a residential and funerary site without radiometric chronology but attributed to the Bronze and Iron Ages (Onsuwan 2003; Onsuwan-Eyre 2006), and cited as potentially relevant to the Southeast Asian 'origins of metallurgy' debate (Higham 2021; Pryce, Carrignon et al. 2024; Pryce et al. 2010; White and Hamilton 2009), offers two intriguing results. BP1794, a socketed bronze axe, shows solid consistency with KWPV copper production, which is perfectly reasonable given the proximity (ca. 30 km) and overlapping sequences (Onsuwan-Eyre 2006:table 5.1; Higham et al. 2020; cf. White and Hamilton 2009:363). Conversely, BP1780, a bronze 'plate' (referred to as a bronze "bar" in

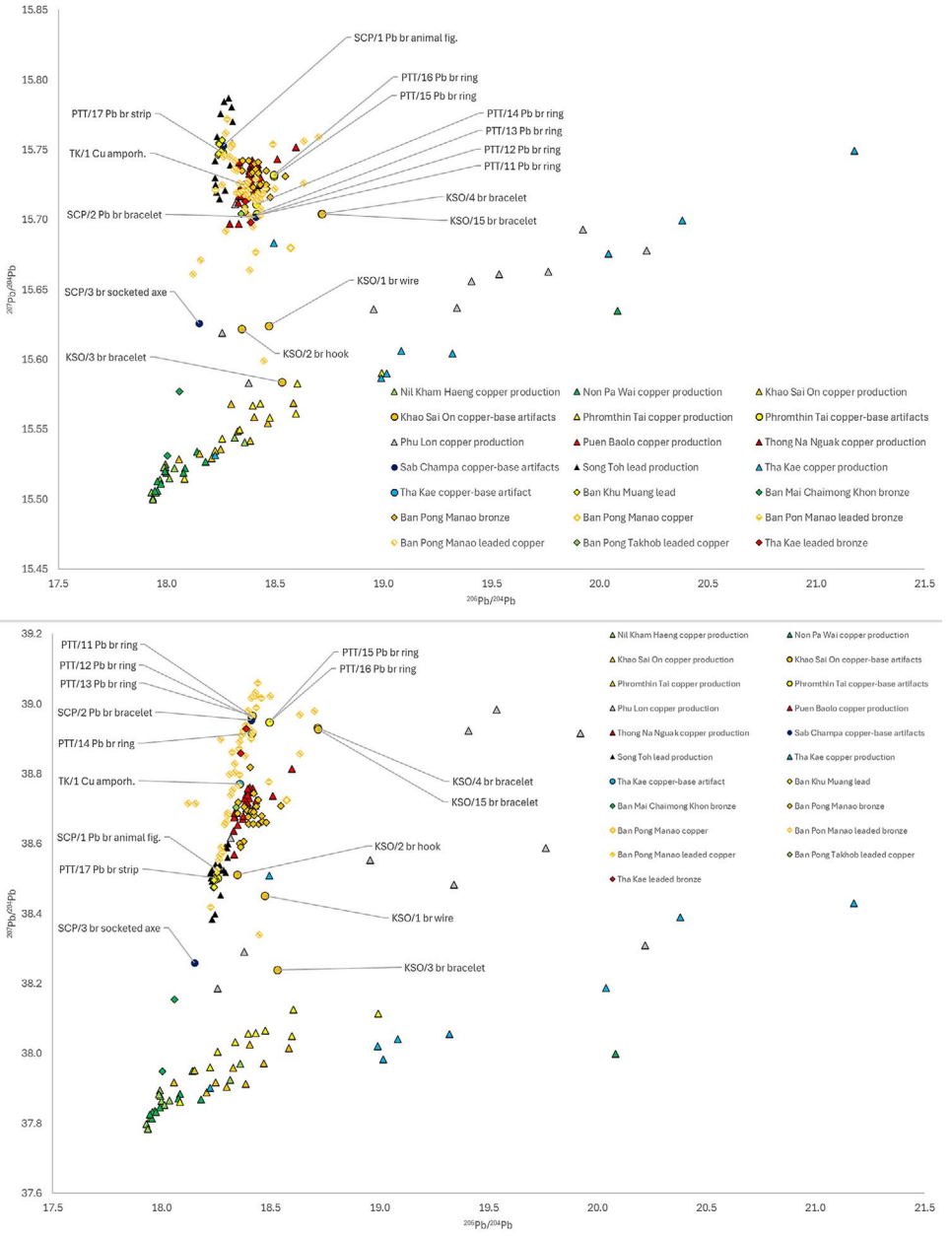

Fig. 7. Raw LI data plots for present study data, plus the Vilabouly Complex (Cadet et al. 2019; Pryce, Brauns et al. 2011) and the central Thai site assemblages studied by Hirao et al. (2013): $^{207/204}$Pb plotted against $^{206/204}$Pb ratios (top); $^{208/204}$Pb plotted against $^{206/204}$Pb ratios (bottom).

White and Hamilton 2009:363), is relatively compatible (within the quantitative measure used in Pryce, Carrignon et al. 2024) with the aforementioned early Bronze Age axe (NPW/11) from Non Pa Wai. As the latter has been interpreted as an import (Pryce, Pollard et al. 2011), it follows that the BMC 'bar' or 'plate' might also be an

import, potentially from the same, as yet unknown, source. There is a potential dating discrepancy because the NPW axe is dated to the late second millennium B.C. by radiometric statistical probability (Higham et al. 2020), whereas White and Hamilton (2009:363) claim:

> [The bar] has been cross-dated to some time during the early second millennium BC, based on its position in the Ban Mai Chai Mong Khon [a.k.a. Ban Mai Chaimongkol] ceramic sequence relative to dated ceramic sequences from other sites in central Thailand.

Whilst we are content to accept the bar as Early Bronze Age, we consider a late second or early first millennium B.C. date far more likely, given that the premise for an early second millennium B.C. MSEA Bronze Age is currently completely untenable (Higham 2021; Higham et al. 2015; Higham et al. 2020; Pryce, Kyaw et al. 2018; Pryce, Pradier et al. 2024).

For Ban Pong Manao, none of the 23 bronze artifacts are consistent with central Thai copper, but the majority are highly compatible with copper produced at the Villabouly Complex in central Laos (Fig. 7), which is very much in line with MSEA Iron Age consumption trends (Pryce 2014; Pryce and Pigott 2022). The 46 BPM leaded bronze and copper artifacts largely overlap each other, which is understandable given that our copper/bronze distinction of 1 wt.% alloying agent is not absolute (cf. White and Hamilton 2019; cf. White and Hamilton 2021 for their 2 wt.% fixation). On the $^{207/206}$Pb plot, the BPM leaded alloys appear consistent with the Vilabouly Complex signature, but this is a copper production locale and the $^{208/206}$Pb plot clearly confirms incompatibility (Fig. 7). The sole leaded copper fragment from BPT follows this pattern, which is coherent since the sites are broadly contemporary and only 11 km geodesic apart. The same applies to the two leaded bronzes from TK, some 67 km geodesic distant. Finally, the six lead fragments from Early Historic BKM are not only highly consistent with each other, they are also entirely compatible with the PTT lead strip, SCP leaded bronze figurine, and the Song Toh lead production signature.

Whatever the potential misgivings about their analysis of surficial corrosion products (Hirao and Ro 2013:260–262; Pryce et al. 2017), the pre-existing LI datasets confirm the patterns identified by SEALIP, both in past (Pryce, Pollard et al. 2011) and present studies. First, there is very little compatibility between central Thai copper-base metal consumption and central Thai copper-base metal production, with scant Bronze Age exceptions (e.g., BMC axe). Second, of the other Bronze Age artifacts, some may share an as yet unknown source (e.g., BMC 'bar', NPW axe) (Pryce, Pollard et al. 2011). Third, the vast majority of local copper-base consumption is consistent with a primary production source in or around the VC in central Laos (Cadet et al. 2019; Pryce, Brauns et al. 2011). Fourth, most leaded artifacts have an unknown lead source, with the exception of several highly compatible Dvararati Period artifacts from BKM, PTT, and SCP.

Given these patterns, we must attempt to explain the near absence of the central Thai primary copper production signature in copper-base consumption assemblages, but instead of at the scale of MSEA, now within central Thailand itself. A decade ago, Pryce and colleagues (2014:289) were able to offer the alternatives of "sampling coverage versus intensive recycling" to explain the regional lacuna, but, over one thousand samples later, the sampling coverage option is no longer viable. Instead, we

must turn to the nature of central Thai primary (mining, smelting) and secondary (refining, mixing, alloying and recycling) metallurgical behaviours evidenced in the available dataset. What were MSEA Bronze Age, and in particular Iron Age, metalworkers doing that would have almost systematically erased the central Thai copper production signature?

Whence Central Thai Copper?

Although we do not yet have central Thai geochemical data for local mineralisations, our technological reconstructions (Cadet et al. this issue; Pryce et al. 2010) mean we can be provisionally confident that mining was taking place during the Bronze and Iron Ages, and that the local minerals were being locally smelted to produce copper with a coherent sub-regional geochemical signature. We can also discern that the scale and intensity of such primary production had enormous chronospatial variation, with vast numbers of small unit scale rudimentary crucible smelting at Bronze Age NPW, followed by improved product recovery but still very labour intensive crucible smelting at Bronze Age NKH (Pryce et al. 2010), followed by the widespread but limited scale crucible smelting identified for Iron Age KSO, PTT, and TK (Cadet et al. this issue), which likely continued well into historic periods around KSO at least (Pryce, Bevan et al. 2011). However, there is little to no indication of large scale central Thai copper production in the Iron Age or later. We might not see the central Thai copper signature in post-Bronze MSEA metal networks if contemporary production was for local consumption only, but this would not explain the dominance of extraneous copper signatures – potentially central Lao on the basis of current archaeological slag-based production signatures (Cadet et al. 2019; Pryce, Brauns et al. 2011) – in local copper/bronze consumption assemblages.

Turning to secondary production, only the crucibles from NPW and NKH have undergone technological analysis; the results gave no indication of refining, mixing, alloying, or recycling activities (Pryce et al. 2010). However, NKH slags, probably dating to the Late Bronze Age (Higham et al. 2020), did have irregular traces of tin, suggesting that occasional recycling was taking place (Pryce et al. 2010), since no tin minerals are reported in the local geology (Vernon 1988). KSO had crucibles but, until they are technologically studied, we have no direct evidence of Iron Age central Thai secondary production behaviours (Ciarla 2007, 2008). We are thus required to work by geochemical deduction alone. The lead concentration of tin minerals is typically, though not always (see Molofsky et al. 2014 for South African cassiterites), orders of magnitude lower than that for copper minerals (Begemann et al. 1999; Berger et al. 2019). As such, if central Thai metalworkers had access – either because they were free to visit or conduct exchange by whatever market mechanism one favours – to tin minerals or tin metal smelted at one of the MSEA's extensive, but least 200 km geodesic distant, stanniferous mineral reserves, then the resulting alloy would still have a central Thai copper LI signature because it would overwhelm the tin LI signature. However, with the possible but unlikely exception of bronze bracelet KSO/3, this is not what the bronze artifact consumption LI data show us (Fig. 7).

The limits of lead isotope methodology dictate we can say nothing explicit about the source of copper used in the central Thai leaded copper and bronze consumption assemblage, because the signature of the added lead metal would utterly swamp that of trace lead in the copper. However, as none of the 24 copper or bronze artifacts from

BPM are consistent with central Thai copper signature, we consider it unlikely that local copper was alloyed with imported lead for the 46 BPM, two SCP, two TK, and the single BPT and leaded artifacts.

Thus, we are led inexorably to mixing – the combination of copper from two or more sources – as our preferred explanation for central Thai lead isotope data patterning. If two primary copper production loci have LI signatures that can be reliably distinguished, then mixing copper from each source will produce a composite signature representing the weighted average of their trace lead contents – in other words, a mixing line (Longman et al. 2018; Pollard 2009; Stos-Gale and Gale 2009). Because mixing equal amounts of copper with equal trace lead concentrations will result in a composite signature lying at the midpoint of a line bisecting the two source signatures, it follows that variations in copper quantity and lead concentration will shift the composite signature up and down that bisecting line – *potentially to the point where the composite signature and one of the source signatures will merge.*

The technological analysis of formally excavated VC copper ingots gives us a mean Pb content of ca. 600 ppm (Cadet et al. 2019) and the coefficient of variation of 104 percent seems largely related to artifact corrosion levels based on correlations in Sn, Cu, and Fe concentrations. To date, only three central Thai copper ingots, from NKH, have been analysed with instruments capable of detecting trace lead (previous proton-induced X-ray emission [PIXE] analyses had a detection limit of 0.023 wt.% Pb [Wang et al. 1994]), giving Pb concentrations averaging 150 ppm, with a 47 percent coefficient of variation (Pryce, Pollard et al. 2011). Therefore, raw smelted VC copper has approximately four times as much trace lead as raw smelted KWPV copper, which should produce a composite LI signature about 80 percent towards the VC signature along the VC-KWPV mixing line *if equal quantities of copper were mixed*. However, this linear mixing patterning is not what we observe in the central Thailand or MSEA copper/bronze consumption data. This suggests sufficient central Lao copper was mixed with putative central Thai copper to completely overwhelm the signature of the latter. The LI data patterning is extremely clear and leads us inexorably to our overriding sub-regional observation: however much raw copper was produced in and potentially exported from KWPV/central Thailand, far more non-local copper/bronze was imported in the form of raw metal or, as the data suggest, finished alloyed products.

This situation seems analogous to the "Three-sector" model of trade in primary raw materials, secondary manufactured goods, and tertiary service industries between developed and developing nations (Fisher 1939; Fourastié 1949), but as there would certainly be objections to projecting mid-twentieth century Dependency Theory (Prebisch 1950; Singer 1949) onto late prehistoric and early historic Thailand, we revert to economic first principles in Southeast Asian metallurgy. Apart from implausibly long-term gifting relationships, and with no evidence for complex industrial organisation or external coercion in the context of "community craft production" (Cadet et al. this issue; White and Pigott 1996), why would arduous copper mining and smelting persist unless it was ultimately in the metal producers' self-interest? To answer, we turn to David Ricardo's (1817) nineteenth century Law of Comparative Advantage, which was derived from the thinking of the eighteenth century Scottish classical economist, Adam Smith:

> If a foreign country [community] can supply us with a commodity cheaper than we ourselves can make it, better buy it off them with some part of the produce of our own industry employed in a way in which we have some advantage. (Smith 1776:218)

Terms of Exchange

In demonstrably producing copper yet importing bronze in a metal-rich landscape with limited social stratification, the central Thai metallurgical data closely fit the Ricardian model recently adopted in White and Hamilton's (2018:134–135, 2019) re-evaluation of prehistoric Thai metallurgy:

> [C]ommunities specialize in producing certain goods in order to participate in the regional exchange system and gain access to products: 1) they cannot produce, 2) cannot produce at sufficient quantities to meet local demand, or 3) choose not to produce because they see their efforts are better spent in producing other products to exchange for desired goods made in other villages or regions. (White and Hamilton 2021:2)

This economic configuration for central Thai metallurgy result was anticipated based upon technological analyses of KWPV copper production assemblages using the identical theoretical framework, source article, and economic argument (Pryce 2009:84, 272–273):

> Up to now, we have made a case for low-efficiency NPW and higher-efficiency NKH copper production, which would superficially suggest that NKH metalworkers may have been able to exchange copper on improved terms relative to their NPW antecedents. However, the definition of 'efficiency' we have previously employed has related to the loss of copper product and not necessarily to labour efficiency as per Shennan's (1999) hypothesis. Whilst NKH copper production was certainly more effective in reducing metal loss, this 'efficiency' probably came at the price of a much increased labour input, e.g. as required by the higher temperatures and the potential crushing and re-smelting of slag. Therefore, we cannot currently estimate whether the shift in [Khao Wong Prachan] Valley metallurgical ethos coincided with a modification of metalworkers' participation in regional exchange systems or whether this had an effect on their relative social status. (Pryce et al. 2010:258–259)

Productivity, in terms of input (capital, labour) cost per unit of output (product), is a concept associated with market economics, and is often poorly received by prehistorians; we nevertheless consider it a fundamental in evaluating long-term human energy expenditure. A 'productive' behaviour might be considered simply one that offers high output for low input. As such, Early Bronze Age copper smelting activities at NPW (moderate intensity, low-effort, high copper loss) or Late Bronze Age NKH (high intensity, high effort, low copper loss) (Pryce et al. 2010), or Iron Age KSO, PTT, and TK (lower intensity, lower effort, moderate metal loss) (Cadet et al. this issue) are all variations of sub-optimal productivity. The persistence of a variably-laborious and toxic copper production tradition for well over a thousand years based on gifting or altruism alone seems extremely unlikely to us. We have previously acknowledged the possibility of and even advocated for gifting-type behaviours between prehistoric MSEA copper producers (Pryce, Brauns et al. 2011:3320), so in this instance we are *adding* to the proposed range of regional exchange mechanisms and

not offering a monolithic interpretation unsuited to either prehistory generally or MSEA's ethnographically-recorded past (Bouté et al. 2021). Given there is no evidence for élite control of central Thai primary copper production, which might enforce low productivity smelting behaviours via slavery, tribute, or taxation, Ricardian relative productivity is our null hypothesis for considering terms of exchange for central Thai copper against tin/bronze in protohistoric Thailand. Ergo, over the long timeframes evidenced in LI-based metal exchange research, and due to evidence of sub-optimal productivity, KSO, NKH, NPW, PTT, and TK smelters probably did not get much bronze for each unit of copper they offered in exchange. Furthermore, given the apparent swamping of the central Thai copper LI signature, the metal supply (whether or not driven by market dynamics) was likely buffered by an excess of presumably cheaper copper from central Laos (or a mining region with a similar LI signature); this could be as simple as the Lao copper minerals being of higher grade, giving more copper for less extraction and smelting effort. Due to lacunae in the VC metallurgical assemblage and stratigraphy, this option could not be fully demonstrated in Cadet and colleagues' (2022) technological reconstruction of mostly Iron Age primary production behaviours, but the crucible-based smelting process evidenced was certainly a relatively efficient reduction of relatively high grade minerals. That said, just because an exchange does not appear equal to us, if it was entered into freely, then both parties must have benefited to some extent.

Comparanda for Local Productivity and Multiscalar Exchange

We know bronze was entering central Thailand whilst copper was being produced at lower productivity, but what else is known to have been imported and potentially exchanged for copper or other local products? Recent elemental analyses of glass beads from PTT burials (Carter et al. 2022) indicated a predominant presence of potash compositions, which are known to represent Early Iron Age South China Sea networks linking peninsular Thailand with central and northern Vietnam, southeast Cambodia, and central and peninsular Myanmar (Dussubieux and Bellina 2017; Dussubieux and Pryce 2016). Also identified at PTT were a number of compositions especially linked to peninsular Thai sites, from which we can read a probable indirect South Asian connection (Dussubieux and Bellina 2018), whilst still others had "high alumina mineral soda" compositions associated with the Late Iron Age Mekong Interaction Sphere (Carter et al. 2022:172). All of which goes to show that the PTT community had access to extensive exchange networks of goods, some of which may have had exotic appeal. However, of the 35 PTT burials concerned in the bead study, only 12 had stone or glass beads, the former being highly indicative of long-range interactions (Bellina 2003; Bellina et al. 2019). This is not to suggest PTT's discontinuous funerary assemblage was indicative of differential wealth accumulation or significant social complexity, just that artifacts that were likely to have been exchanged over considerable distances were not frequently encountered.

Likewise, the KSO funerary assemblage gives the impression of a small peripheral agricultural community practicing part-time or seasonal metallurgy and only loosely integrated into the wider MSEA Iron Age interaction sphere (Ciarla 2008). Unfortunately, such a consideration of TK is complicated by much of the site's 80–85 ha extent having been destroyed by construction and looting prior to the arrival of the Lopburi Regional Archaeological Project (LoRAP) in 1987 (Natapintu 1984;

Rispoli et al 2013:138–149). However, there is an impression of a thriving Late Iron Age (ca. A.D. 0–400) farming community having made a substantial investment in earthworks and accessory primary copper production. Almost all TK adult burials contain iron/steel agricultural tools (and at least one bracelet), some of which were solid, heavy (50–100 g), and ornate, unlike the lighter (10–20 g) examples interred with subadult individuals. LoRAP's analysis of carnelian and glass beads to establish what networks TK inhabitants were interacting with is ongoing, but the site gives the impression of having been a wealthy community, with respect to central Thai comparators, but there is no indication of significant social stratification (Rispoli et al. 2013). This is in contrast with some contemporary communities in the upper Mun river valley of lower northeast Thailand such as Ban Non Wat (Higham and Kijngam 2012), Noen U-Loke (Higham 2007), Non Ban Jak (Higham and Kijngam 2020), and Non Muang Kao (Higham 2007), where social complexity was rising sharply, though in a chronospatially highly discontinuous fashion, during the first millennium B.C. and early first millennium A.D. (Higham 2014; Higham and Rispoli 2014). The central and lower northeast Thai sequences can be summarised as follows.

Bronze Age Phase 1 (BA1, ca. 1200–1000 B.C.) — Sparse metal artifacts in funerary contexts at NPW and BNW, with primary production (smelting) uncertain at the former and no evidence of secondary production (founding) at the latter (Higham and Cawte 2021; Higham and Kijngam 2011; Higham et al. 2020; Pryce et al. 2010). Thus far, LI data indicate that at least the constituent metal of BA1 artifacts was imported, if not the finished products themselves (Pryce, Carrignon et al. 2024).

BA2 (ca. 1000–900 B.C.) — Extensive copper smelting at NPW (Higham et al. 2020), an innovation perhaps stimulated by metal imports (Pryce, Pollard et al. 2011), concurrent with BNW, evidencing regionally-unprecedented socially-aggrandising élites in the form of significant funerary consumption, including finished metal products but no foundry accoutrements (Higham and Cawte 2021). This conspicuous consumption of metal cannot be attributed to the entire BNW BA2 cemetery population, and is absent during the same period at nearby BLK, at which latter site there were nevertheless crucibles and moulds in habitation contexts (Higham and Cawte 2021; Higham and Rispoli 2014). Several of the BNW BA2 copper-base artifacts can be confidently attributed to central Thai primary production signatures (Pryce 2011; Pryce, Carrignon et al. 2024).

BA3 (ca. 900–800 B.C.) — Decreasing primary copper production at NPW in favour of it increasing at NKH (Higham et al. 2020), with an associated shift in metallurgical production behaviours towards greater extraction efficiency at the cost of greater effort (Pryce et al. 2010). At BNW, significant mortuary offerings continued during phase BA3a but declined sharply in BA3b. The single BNW copper-base artifact sampled from this phase, an axe (BNW/9), comes from an unknown source (Pryce 2011).

BA4 (ca. 800–700 B.C.) — Continued intensive copper smelting at NKH, with some primary production activity extant at NPW (Higham et al. 2020), whereas for the first time at BNW there is extensive evidence for secondary production in the form of furnaces, crucibles, and moulds in habitation contexts as well as founders' graves (Higham 2008; Higham and Cawte 2021). However, the BNW foundry data contrast sharply with the near absence of copper-base mortuary artifacts; there are just two

copper-base bangles and one arrowhead (BNW/10) and analysis of the latter suggests an unknown source similar to that of BA3 axe BNW/9.

BA5 (ca. 700–420 B.C.) — Decline of copper smelting activity at NKH (Higham et al. 2020), whilst copper-base founding continued unabated at BNW, and that in light of almost no metal consumption in funerary practices (Higham and Cawte 2021). The dearth of consumption implied there were no mortuary samples available for LIA with SEALIP (Pryce 2011), but of the ca. 600 non-mortuary copper-base metal fragments, all but one were leaded (Higham and Cawte 2021). As such, the copper source would be unknowable, but the lead source should still be investigated (Pryce 2012).

Iron Age Phase 1 (IA1, ca. 420–100 B.C.) and Phase 2 (IA2, ca. 100 B.C.–A.D. 200) — Primary copper production at NPW and NKH is thought to have ceased (Higham et al. 2020) and the KSO and TK phasing suggests no primary copper production, though it conceivably existed at PTT with its less refined chronology (Cadet et al. this issue). At BNW, secondary copper-base production continued at some considerable scale, but there was a remarkable increase in the quantities of copper-base metal in funerary contexts, though without the differential wealth distribution indicative of potential aggrandisers (Higham and Cawte 2021). The LI consumption data for IA1 BNW suggest consistency with the VC for unleaded artifacts, as well as some compatibility for Song Toh lead production for the leaded artifacts (Figure 8).

IA3 (ca. A.D. 200–400) and IA4 (ca. A.D. 400–500) — Lower intensity primary copper production at KSO, PTT, and TK in central Thailand (Cadet et al. this issue) concurrent with an explosion of copper-base metal consumption at Noen U-Loke (NUL) and Non Ban Jak (NBJ) (Higham and Cawte 2021), whilst copper-base materials at IA3–4 BNW continue to be consistent with the VC signature (Pryce et al. 2014). The absence of foundry evidence from these sites suggests the metal artifacts were imported as finished products (Higham and Cawte 2021). Both central Thai production and lower northeast Thai consumption behaviours continued into the early historic periods, with regional transitions to statehood and institutionalised Hindu-Buddhism associated with architectural and statuary monumentalism (Higham 2014).

Copper for Salt, Food, or Exotic Goods?

Northeast Thailand does not host cupric/cuprous (Cu, copper), plumbous (Pb, lead), or stannic (Sn, tin) (Workman 1977; Zaw, Meffre et al. 2014) metal reserves nor ferrous (Fe, iron) reserves in any significant quantity and quality (Pryce and Natapintu 2009). The SEALIP database indicates the almost exclusive consumption of central Lao/VC copper or that with a comparable LI signature. What northeast Thailand did have was salt (Yankowski et al. 2015), an essential exchange commodity for the preservation of proteins, and, from the mid-Iron Age (IA3+), agriculture enhanced by irrigation and animal traction. The role of agricultural production relative to central Thai metallurgy, including the possibility that copper might have been exchanged for foodstuffs, was considered nearly 30 years ago (Mudar 1995; Mudar and Pigott 2003). Agriculture was certainly weighed in light of technological evidence for low productivity (Pryce et al. 2010:258) and then recent KWPV archaeobotanical data

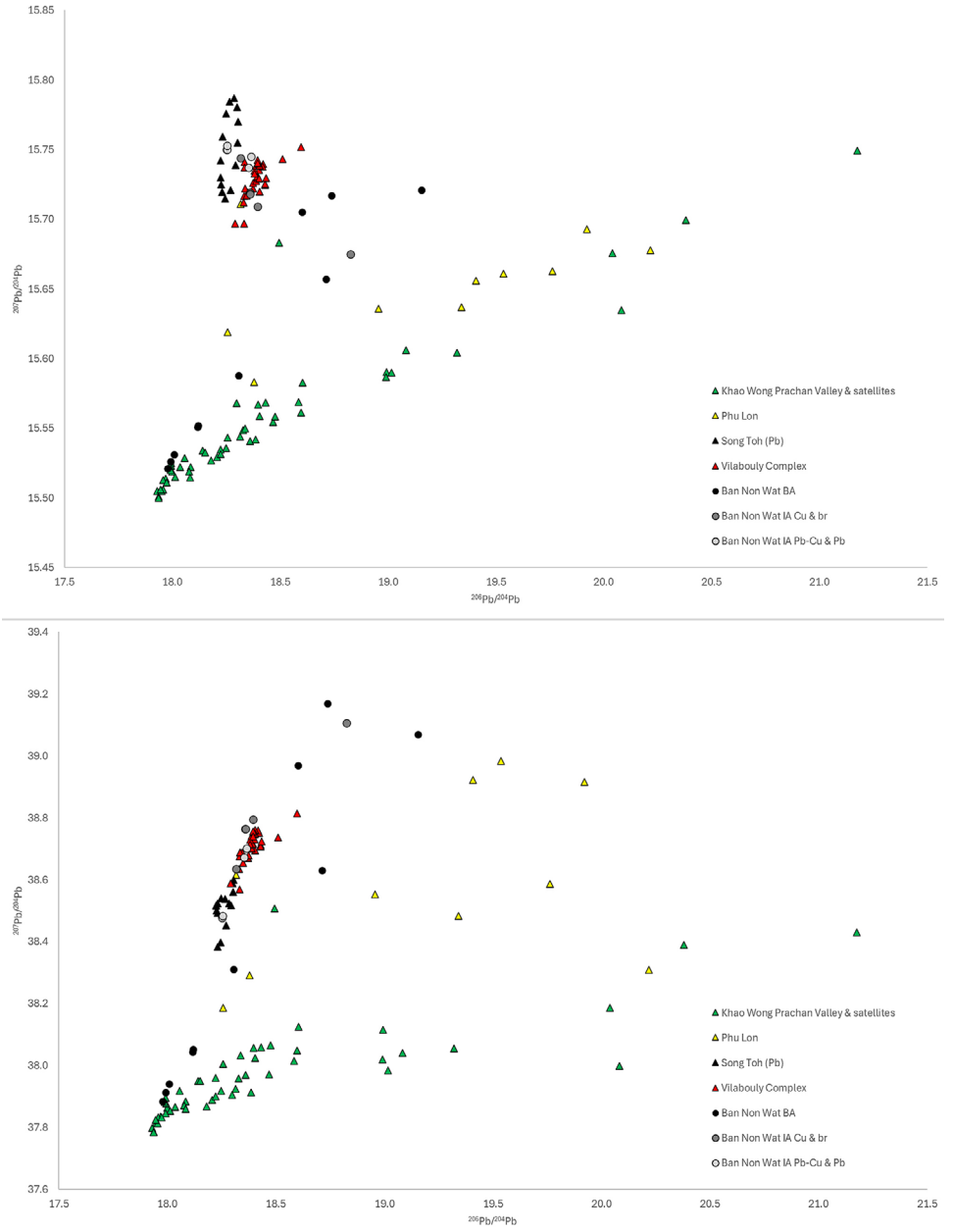

Fig. 8. Raw LI data plots for regional copper and lead production centres (Cadet et al. 2019; Hirao and Ro 2013; Pryce, Brauns et al. 2011; Pryce, Pollard et al. 2011), plus Ban Non Wat BA and IA consumption signatures (Pryce 2011; Pryce et al. 2014): $^{207/204}$Pb plotted against $^{206/204}$Pb ratios (top); $^{208/204}$Pb plotted against $^{206/204}$Pb ratios (bottom).

(Weber et al. 2010). Weber and colleagues (2010) discerned a predominance of upland/dryland foxtail millet (*Setaria italica*) cultivation during the second millennium B.C., giving way to rice (*Oryza sativa japonica*) during the first millennium B.C. Their

data have been substantiated by recent research by d'Alpoim-Guedes and colleagues at PTT (d'Alpoim Guedes et al. 2019; d'Alpoim Guedes et al. 2020) and NPW, NKH, and Non Mak La (d'Alpoim Guedes et al. 2020). Compared with datasets in southern China (Dal Martello et al. 2018) and northeast Thailand (Castillo et al. 2018), d'Alpoim-Guedes and colleagues emphasise initial foxtail millet cultivation giving way to rice, "grown in a rain-fed upland and not in an irrigated paddy environment" (d'Alpoim Guedes et al. 2020:976), without the benefit of animal traction, and supplemented by persistent foraging and hunting. With the possible exception of TK (see below), this as opposed to northeast Thailand, where from the mid-Iron Age (ca. A.D. 200) communities built and maintained extensive hydraulic earthworks, so they could practice intensive irrigated rice agriculture, aided by buffalo, during an increasingly dry climatic phase (Castillo et al. 2018; Wohlfarth et al. 2016). Phytolith studies from TK do indicate large quantities of rice from the Late Iron Age to Early Historic period in the early to mid-first millennium A.D., which, combined with TK's large size and earthworks, could suggest irrigated wet rice agriculture contemporary with the Mun river valley sites, though with no evidence of animal traction (Kealhofer 1997).

These archaeobotanical findings eliminate the notion that central Thai communities were deficient in foodstuffs at any period in question and thus never needed to produce copper to obtain staples. This leaves the possibility of copper being exchanged for salt for food preservation or for other non-locally available products like glass and semi-precious ornaments. One must then consider the terms of exchange. The import and consumption of exotic finished products, edible or otherwise (e.g., bronze, carnelian, glass), could have played a variable but generally increasing role in driving central Thai primary copper production. Ergo, the desire to participate in late prehistoric interaction spheres at the regional or inter-regional scale (Bellina et al. 2019; Carter et al. 2022) could have driven predominantly agricultural central Thai communities, who had long had access to and experience in exploiting local mineral resources, to produce copper as a means of exchange, rather than as a commodity to be alloyed and consumed directly.

CONCLUSION

The central Thai metal production data are consistent with 'community craft production' (Cadet et al. this issue; Pryce et al. 2010; White and Pigott 1996), with no sign of control of primary resources and every indication of 'independent' exploitation of copper reserves during the Bronze and Iron Ages. This suggests incipient élites, who were certainly present by the mid-late Iron Age in northeast Thailand, either did not care who controlled arguably rustic and dirty primary production, were unable to project their power into primary producing areas, or were more concerned with controlling secondary production, that is, the conversion of raw metal to desirable finished forms with perceived artisanal value (Bauvais et al. 2021). This is indicated by Iron Age founders' graves at Ban Non Wat (Higham 2008), in an area without metal resources, as opposed to the atypical founders' graves in central Thailand, where such activity must have been frequent if not common (Ciarla 2008).

Whilst technological and geochemical variation exists in central Thai copper production, the product is nevertheless easily distinguished from other known MSEA copper producer signatures. That we did not identify the central Thai signature in

MSEA consumption assemblages, nor at the central Thai copper producing sites themselves, indicates that those sites, however large and impressive they are (NPW and NKH especially), were massively outproduced by other suppliers. Following the Ricardian productivity principle, the low efficiency of central Thai copper smelting would imply that they were exchanging copper on relatively poor terms; given local agricultural self-sufficiency, it was presumably not being exchanged for staples but possibly in part for northeast Thai salt or other products not locally available.

As awkward as it may seem, given the scale and longevity of primary copper production in and around the KWPV, we propose that, whilst initial Early Bronze Age smelting was likely a technological innovation based on experience with secondary production behaviours from potentially immigrant metalworkers and their imported wares (Pryce et al. 2010; Pryce, Pollard et al. 2011), and driven by demand from relatively nearby northeast Thai aggrandisers at BA2 (ca. 1000–900 B.C.) Ban Non Wat (Higham and Cawte 2021; Higham and Higham 2009; Pryce 2011) and potentially further afield north-central Myanmar (Pryce, Carrignon et al. 2024; Pryce, Htwe et al. 2018), as the first millennium B.C. progressed into the early first millennium A.D., central Thai primary copper production became less about furnishing metal for immediate consumption and more about a means of exchange for accessing regional and inter-regional markets in exotic finished goods.

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REFERENCES CITED

Aebischer, Stéphane, Christophe Cloquet, Jean Carignan, Charles Maurice, and Reinhard Pienitz
2015 Disruption of the geochemical metal cycle during mining: Multiple isotope studies of lake sediments from Schefferville, subarctic Québec. *Chemical Geology* 412:167–178.

ANR [Agence National de la Recherche]
2016 Bronze and Glass as Cultural Catalysts and Tracers in Early Southeast Asia – BROGLASEA (webpage), *Agence National de la Recherche* (website). URL: https://anr.fr/Project-ANR-16-CE27-0011/.

Bauvais, Sylvain, Marion Berranger, Alexandre Disser, Philippe Dillmann, Stéphanie Leroy, and Philippe Fluzin
2021 Le fer des principautés: "L'Économie du fer" dans le nord-est de la France au Hallstatt D et à La Tène A1 [Iron in the Principalities: "The Iron Economy" in Northeastern France in Hallstatt D and La Tène A1], in *Vix et le phénomène princier: Colloque international de Vix, 27–28 octobre*

2016 [Vix and the Princely Phenomenon: International Vix Colloquium 27–28 October 2016]: 219–257, ed. Patrice Brun, Bruno Chaume, and Federica Sacchetti. Bordeaux: Ausonius Éditions.

Begemann, Friedrich, Kalfas Kallas, Sigrid Schmitt-Strecker, and Ernst Pernicka
1999 Tracing ancient tin via isotope analyses, in *The Beginnings of Metallurgy*: 277–284, ed. Andreas Hauptmann, Ernst Pernicka, Thilo Rehren, and Ünsal Yalcin. Der Anschnitt Beiheft 9. Bochum: Deutsches Bergbau-Museum.

Bellina, Bérénice
2003 Beads, social change and interaction between India and Southeast Asia. *Antiquity* 77 (296):285–297.

Bellina, Bérénice, Aude Favereau, and Laure Dussubieux
2019 Southeast Asian early Maritime Silk Road trading polities' hinterland and the sea-nomads of the Isthmus of Kra. *Journal of Anthropological Archaeology* 54:102–120.

Berger, Daniel, Jeffrey S. Soles, Alessandra R. Giumlia-Mair, Gerhard Brügmann, Ehud Galili, Nicole Lockhoff, and Ernst Pernicka
2019 Isotope systematics and chemical composition of tin ingots from Mochlos (Crete) and other Late Bronze Age sites in the eastern Mediterranean Sea: An ultimate key to tin provenance? *PLOS One* 14(6):e0218326, DOI: https://doi.org/10.1371/journal.pone.0218326.

Bouté, Vanina, Stéphen Huard, and Emmanuel Pannier, eds.
2021 Studying non-commercial transfers from fields in Southeast Asia and beyond. *Moussons: Recherche en sciences humaines sur l'Asie du Sud-Est* 37:n.p., DOI: https://doi.org/10.4000/moussons.8753.

Budd, P., D. Gale, A. M. Pollard, R. G. Thomas, and P. A. Williams
1993 Evaluating lead isotope data: Further observations. *Archaeometry* 35(2):241–263. DOI: https://doi.org/10.1111/j.1475-4754.1993.tb01038.x.

Cadet, Mélissa, T. O. Pryce, Philippe Dillmann, Thongsa Sayavongkhamdy, Viengkeo Souksavatdy, Thonglith Luangkhoth, and Nigel Chang
2022 Technological reconstruction of the late prehistoric primary copper production of the Vilabouly Complex (central Laos). *Archaeological and Anthropological Sciences* 14(8):141, DOI: https://doi.org/10.1007/s12520-022-01608-0.

Cadet, Mélissa, Thongsa Sayavongkhamdy, Viengkeo Souksavatdy, Thonglith Luangkhoth, Philippe Dillmann, Christophe Cloquet, Justine Vernet, Paolo Piccardo, Nigel Chang, John Edgar, Eddy Foy, and T. O. Pryce
2019 Laos' central role in Southeast Asian copper exchange networks: A multi-method study of bronzes from the Vilabouly Complex. *Journal of Archaeological Science* 109:104988, DOI: https://doi.org/10.1016/j.jas.2019.104988.

Carter, Alison, Laure Dussubieux, Thomas R. Fenn, Thanik Lertcharnrit, and T. O. Pryce
2022 The exchange of beads in Central Thailand in the protohistoric period: Glass objects from Phromthin Tai, in *The Elemental Analysis of Glass Beads: Technology, Chronology and Exchange*: 161–176, ed. Laure Dussubieux and Heather Walder. Leuven: Leuven University Press, DOI: https://doi.org/10.2307/j.ctv2z9fzr0.13.

Castillo, Cristina C., Charles F. W. Higham, Katie Miller, Nigel Chang, Katerina Douka, Tom F. G. Higham, and Dorian Q. Fuller
2018 Social responses to climate change in Iron Age north-east Thailand: New archaeobotanical evidence. *Antiquity* 92(365):1274–1291, DOI: https://doi.org/10.15184/aqy.2018.198.

Ciarla, Roberto
2007 A preliminary report on Lo.R.A.P. archaeological excavations at prehistoric Khao Sai On, Lopburi Province, Central Thailand. *East and West* 57(1):395–401.

2008 The Thai-Italian 'Lopburi Regional Archaeological Project' (LoRAP): Excavation at Khao Sai On-Noen Din 2008 preliminary report. *East and West* 58(1):313–336.

Cloquet, Christophe, Jean Carignan, and Guy Libourel
2006 Atmospheric pollutant dispersion around an urban area using trace metal concentrations and Pb isotopic compositions in epiphytic lichens. *Atmospheric Environment* 40(3):574–587, DOI: https://doi.org/10.1016/j.atmosenv.2005.09.073.

Dal Martello, Rita, Rui Min, Chris Stevens, Charles Higham, Tom Higham, Ling Qin, and Dorian Q. Fuller
2018 Early agriculture at the crossroads of China and Southeast Asia: Archaeobotanical evidence and radiocarbon dates from Baiyangcun, Yunnan. *Journal of Archaeological Science: Reports* 20:711–721, DOI: https://doi.org/10.1016/j.jasrep.2018.06.005.

d'Alpoim Guedes, Jade, Sydney Hanson, Charles Higham, Tom Higham, and Thanik Lertcharnrit
2019 The wet and the dry, the wild and the cultivated: Subsistence and risk management in ancient Central Thailand. *Archaeological and Anthropological Sciences* 11:6473–6484, DOI: https://doi.org/10.1007/s12520-019-00794-8.

d'Alpoim Guedes, Jade, Sydney Hanson, Thanik Lertcharnrit, Andrew D. Weiss, Vincent C. Pigott, Charles F. W. Higham, Tom F. G. Higham, and Steven A. Weber
2020 Three thousand years of farming strategies in central Thailand. *Antiquity* 94(376):966–982, DOI: https://doi.org/10.15184/aqy.2020.8.

Dussubieux, Laure, and Bérénice Bellina
2017 Glass from an early Southeast Asian producing and trading centre, in *Khao Sam Kaeo: An Early Industrial Port City between the Indian Ocean and the South China Sea*: 549–585, ed. Bérénice Bellina. Mémoires Archéologiques 28. Paris: École Française D'Extrême-Orient.

2018 Glass ornament production and trade polities in the Upper-Thai Peninsula during the Early Iron Age. *Archaeological Research in Asia* 13:25–36, DOI: https://doi.org/10.1016/j.ara.2017.08.001.

Dussubieux, Laure, and T. O. Pryce
2016 Myanmar's role in Iron Age interaction networks linking Southeast Asia and India: Recent glass and copper-base metal exchange research from the Mission Archéologique Française au Myanmar. *Journal of Archaeological Science Reports* 5:598–614, DOI: https://doi.org/10.1016/j.jasrep.2016.01.005.

Eerkens, Jelmer C.
2000 Practice makes within 5% of perfect: Visual perception, motor skills, and memory in artifact variation. *Current Anthropology* 41(4):663–668, DOI: https://doi.org/10.1086/317394.

Fisher, Allan. G. B.
1939 Production, primary, secondary and tertiary. *Economic Record* 15(1):24–38, DOI: https://doi.org/10.1111/j.1475-4932.1939.tb01015.x.

Fourastié, Jean
1949 *Le grand espoir du XXe siècle – Progrès technique, progrès économique, progrès social* [The Great Hope of the 20th Century: Technical Progress, Economic Progress, Social Progress]. Paris: Presses Universitaires de France.

Higham, Charles F. W.
2007 *The Origins of the Civilization of Angkor (vol. 2): The Excavation of Noen U-Loke and Non Muang Kao.* Bangkok: Fine Arts Department of Thailand.

2008 Recasting Thailand: New discoveries at Ban Non Wat. *Current World Archaeology* 31:38–41.

2014 From the Iron Age to Angkor: New light on the origins of a state. *Antiquity* 88(341):822–835, DOI: https://doi.org/10.1017/S0003598X00050717.

2021 The later prehistory of Southeast Asia and southern China: The impact of exchange, farming and metallurgy. *Asian Archaeology* 4(2):63–93, DOI: https://doi.org/10.1007/s41826-021-00040-y.

Higham, Charles F. W., and Hayden Cawte
2021 Bronze metallurgy in Southeast Asia with particular reference to northeast Thailand. *Journal of World Prehistory* 34(1):1–46, DOI: https://doi.org/10.1007/s10963-020-09151-3.

Higham, Charles F. W., Katerina Douka, and Tom F. G. Higham
2015 A new chronology for the Bronze Age of northeastern Thailand and its implications for Southeast Asian prehistory. *PLOS ONE* 10:e0137542, DOI: https://doi.org/10.1371/journal.pone.0137542.

Higham, Charles F. W., and Thomas Higham
2009 A new chronological framework for prehistoric Southeast Asia, based on a Bayesian model from Ban Non Wat. *Antiquity* 83(319):125–144, DOI: https://doi.org/10.1017/S0003598X00098136.

Higham, Charles F. W., and Ampham Kijngam, eds.
2011 *The Origins of the Civilization of Angkor (vol. 5): The Excavation of Ban Non Wat (part 3): The Bronze Age*. Bangkok: Fine Arts Department of Thailand.

2012 *The Origins of the Civilization of Angkor (vol. 6): The Excavation of Ban Non Wat (part 4): The Iron Age*. Bangkok: Fine Arts Department of Thailand.

2020 *The Origins of the Civilization of Angkor (vol. 7): The Excavation Non Ban Jak*. Bangkok: Fine Arts Department of Thailand.

Higham, Charles F. W., and Fiorella Rispoli
2014 The Mun Valley and Central Thailand in prehistory: Integrating two cultural sequences. *Open Archaeology* 1:2–28, DOI: https://doi.org/10.2478/opar-2014-0002.

Higham, Tom F. G., Andrew D. Weiss, Charles F. W. Higham, Chris B. Ramsey, Jade d'Alpoim Guedes, Sydney Hanson, Steven A. Weber, Fiorella Rispoli, Roberto Ciarla, T. O. Pryce, and Vincent C. Pigott
2020 A prehistoric copper-production centre in central Thailand: Its dating and wider implications. *Antiquity* 94(376):948–65, DOI: https://doi.org/10.15184/aqy.2020.120.

Hirao, Yoshimitsu, and Ji-Hyun Ro
2013 Chemical composition and lead isotope ratios of bronze artifacts excavated in Cambodia and Thailand, in *Water Civilisation: From Yangtze to Khmer Civilisations*: 247–312, ed. Yoshinori Yasuda. Tokyo: Springer.

Hutchison, C. S., and D. Taylor
1978 Metallogenesis in SE Asia. *Journal of the Geological Society* 135:407–428, DOI: https://doi.org/10.1144/gsjgs.135.4.0407.

Imamura, Kenji
2001 Lead isotope analysis of bronze tools unearthed from the Lang Vac sites, Vietnam. *Bulletin of the National Museum of Japanese History* 86:47–64.

Kakukawa, Shigeru, Sadaomi Hieda, and Yoshimitsu Hirao
2008 Preliminary report for the excavation in Phum Snay 2007, in *Chemical Analysis on Bronze Bracelets Unearthed from the Phum Snay Archaeological Site in Cambodia and the Identification of their Production Area*: 60–65, ed. Yoshinori Yasuda and Chuch Phoeurn. Kyoto: Institute Research Center for Japanese Studies.

Kealhofer, Lisa
1997 Evidence of cultural impact on the environment in the Holocene: Two phytolith sequences from the Lopburi Region, Thailand, in *Southeast Asian Archaeology 1992: Proceedings of the Fourth International Conference of the European Association of Southeast Asian Archaeologists, Rome, 28th September–4th October 1992*: 9–27. Rome: Istituto Italiano per l'Africa e l'Oriente.

Killick, David J., Jay A. Stephens, and Tom R. Fenn
2020 Geological constraints on the use of lead isotopes for provenance in archaeometallurgy. *Archaeometry* 62(S1):86–105, DOI: https://doi.org/10.1111/arcm.12573.

Kuno, Yuichiro, Kazuo Yamasaki, Masayo Murozumi, and Rujaya Abhakorn
1990 Metallographic and lead isotope studies on metal objects unearthed in the Tak Area, Thailand. *Journal of the Siam Society* 78(2):51–60.

Lertcharnrit, Thanik
2006 The moated site of Promtin Tai and the transition from late prehistory to early history in central Thailand, in *Uncovering Southeast Asia's Past: Selected Papers from the 10th International Conference of the European Association of Southeast Asian Archaeologists*: 257–264, ed. Elizabeth A. Bacus, Ian C. Glover, and Vincent C. Pigott. Singapore: National University of Singapore.

Lertrit, Sawang
2004 Sab Champa revisited: Results of recent archaeological field investigations, in *Southeast Asian Archaeology – Wilhelm G. Solheim II Festschrift*: 504–521, ed. Victor Paz. Quezon City: University of the Philippines Press.

Longman, Jack, Daniel Veres, Vasile Ersek, Donald L. Phillips, Catherine Chauvel, and Calin G. Tamas
2018 Quantitative assessment of Pb sources in isotopic mixtures using a Bayesian mixing model. *Scientific Reports* 8:6154, DOI: https://doi.org/10.1038/s41598-018-24474-0.

MOLOFSKY, LISA J., DAVID KILLICK, MIHAI N. DUCEA, MONICA MACOVEI, JOHN T. CHESLEY, JOAQUIN RUIZ, ALYSON THIBODEAU, AND GHEORGHE C. POPESCU
2014 A novel approach to lead isotope provenance studies of tin and bronze: Applications to South African, Botswanan and Romanian artifacts. *Journal of Archaeological Science* 50:440–450, DOI: https://doi.org/10.1016/j.jas.2014.08.006.

MUDAR, KAREN
1995 Evidence for prehistoric dryland farming in mainland Southeast Asia: Results of regional survey in Lopburi Province, Thailand. *Asian Perspectives* 34(2):157–194.

MUDAR, KAREN, AND VINCENT C. PIGOTT
2003 Subsistence changes and community-based craft production in prehistoric Thailand, in *Fishbones and Glittering Emblems*: 149–160, ed. Anna Källén and Anna Karlström. Stockholm: Östasiatiska Museet.

NATAPINTU, SURAPOL
1980 Preliminary Report on Ta Kae Excavation in 1980 (in Thai). Unpublished report archived at Fine Arts Department of Thailand in Bangkok.

1984 Ancient settlement at Ban Tha Khae in Lopburi. *Muang Boran* 10(4):26–40.

1988 Current research on ancient copper-base metallurgy in Thailand, in *Prehistoric Studies: The Stone and Metal Ages in Thailand*: 107–124, ed. P. Charoenwongsa and B. Bronson. Bangkok: Thai Antiquity Working Group.

ONSUWAN, CHUREEKAMOL
2003 Metal age complexity in Thailand: Socio-political development and landscape use in the Upper Chao Phraya Basin. *Bulletin of the Indo-Pacific Prehistory Association* 23(1):7–13.

ONSUWAN-EYRE, CHUREEKAMOL
2006 Prehistoric and Proto-historic Communities in the Eastern Upper Chao Phraya River Valley. Unpublished Ph.D. thesis. University of Pennsylvania.

PIGOTT, VINCENT C., AND T. O. PRYCE
2022 Prehistoric copper production and exchange in Southeast Asia, in *The Oxford Handbook of Early Southeast Asia*: 430–457, ed. C.F.W. Higham and N. C. Kim. Oxford: Oxford University Press.

PIGOTT, VINCENT C., AND GERD WEISGERBER
1998 Mining archaeology in geological context: The prehistoric copper mining complex at Phu Lon, Nong Khai Province, northeast Thailand, in *Metallurgica Antiqua: In Honour of Hans-Gert Bachmann and Robert Maddin*: 135–161, ed. Thilo Rehren, Andreas Hauptmann, and James D. Muhly. Bochum: Deutsches Bergbau-Museum Bochum.

PIGOTT, VINCENT C., ANDREW WEISS, AND SURAPOL NATAPINTU
1997 Archaeology of copper production: Excavations in the Khao Wong Prachan Valley, central Thailand, in *South-east Asian Archaeology 1992: Proceedings of the Fourth International Conference of the European Association of South-east Asian Archaeologists. Rome, 28th September–4th October 1992*: 119–157, ed. Roberto Ciarla and Fiorella Rispoli. Rome: Istituto Italiano per l'Africa e l'Oriente.

POLLARD, A. MARK
2009 From mine to microscope: Advances in the study of ancient technology, in *What a Long Strange Trip It's Been: Lead Isotopes and Archaeology*: 181–189, ed. Andrew Shortland, Ian C. Freestone, and Thilo Rehren. Oxford: Oxbow Books.

PREBISCH, RAUL
1950 *The Economic Development of Latin America and Its Principal Problems*. New York: United Nations Department of Economic Affairs.

PRYCE, T. O.
2009 Prehistoric Copper Production and Technological Reproduction in the Khao Wong Prachan Valley of Central Thailand. Unpublished Ph.D. thesis. University College London.

2011 Technical analysis of Bronze Age Ban Non Wat copper-base artifacts, in *The Excavation of Ban Non Wat: The Bronze Age*: 489–498, ed. Charles F. W. Higham and Amphan Kijngam. Bangkok: Fine Arts Department.

2012 A flux that binds? The Southeast Asian Lead Isotope Project, in *Proceedings of the 5th Forbes Symposium on Ancient Asian Bronzes*: 115–123, ed. Paul Jett, Blythe McCarthy, and Janet G. Douglas. Washington, D.C.: Smithsonian.

2014 Metallurgy in Southeast Asia, in *Encyclopaedia of the History of Science, Technology, and Medicine in Non-Western Cultures*: n.p. Dordrecht: Springer Science and Business Media, DOI: https://doi.org/10.1007/978-94-007-7747-7_10178.

Pryce, T. O., Sandrine Baron, Bérénice H. M. Bellina, Peter S. Bellwood, Nigel Chang, Pranab Chattopadhyay, Eusebio Dizon, Ian C. Glover, Elizabeth Hamilton, Charles F. W. Higham, Aung Aung Kyaw, Vin Laychour, and 11 others
2014 More questions than answers: The Southeast Asian Lead Isotope Project 2009–2012. *Journal of Archaeological Science* 42:273–294, DOI: https://doi.org/10.1016/j.jas.2013.08.024.

Pryce, T. O., Andrew H. Bevan, Roberto Ciarla, Fiorella Rispoli, Cristina Castillo, Brenna Hassett, and Julie L. Malakie
2011 Intensive archaeological survey in tropical environments: Methodological and metallurgical insights from Khao Sai On, central Thailand. *Asian Perspectives* 50(1–2):53–69.

Pryce, T. O., Michael Brauns, Nigel Chang, Ernst Pernicka, A. Mark Pollard, Christopher Ramsey, Thilo Rehren, Viengkeo Souksavatdy, and Thongsa Sayavongkhamdy
2011 Isotopic and technological variation in prehistoric primary Southeast Asian copper production. *Journal of Archaeological Science* 38:3309–3322, DOI: https://doi.org/10.1016/j.jas.2011.07.016.

Pryce, T. O., Simon Carrignon, Mélissa Cadet, Kay Thwe Oo, Saw Naing Oo, Thu Thu Win, Arkar Aye, Baptiste Pradier, Bérénice Bellina, Clémence Le Meur, Peter Petchey, and Miljana Radivojević
2024 A partial prehistory of the Southwest Silk Road: Archaeometallurgical networks along the sub-Himalayan corridor. *Cambridge Archaeological Journal* 34(2):173–212, DOI: https://doi.org/10.1017/S0959774323000185.

Pryce, T. O., and Charles F. W. Higham
in press Differential metal supply networks between central and northeast Thailand, and northwest Cambodia during the mid-late Iron Age: Silver, copper and lead artefacts from 2nd–8th c. AD Non Ban Jak. *Archaeological and Anthropological Sciences*.

Pryce, T. O., Kalayar Myat Myat Htwe, Myrto Georgakopoulou, Tiffany Martin, Enrique Vega, Thilo Rehren, Tin Tin Win, Thu Thu Win, Peter Petchey, Jitlada Innanchai, and Baptiste Pradier
2018 Metallurgical traditions and metal exchange networks in late prehistoric central Myanmar, c. 1000 BC to c. AD 500. *Archaeological and Anthropological Sciences* 10:1087–1109, DOI: https://doi.org/10.1007/s12520-016-0436-7.

Pryce, T. O., Aung Aung Kyaw, Myo Min Kyaw, Tin Tin Win, Thu Thu Win, Khin Htwe Win, May Myat Mon, Mar Mar Aye, Su Hlaing Htay, Aye Aye Mar, Bérénice Bellina, R. Alexander Bentley, and 18 others
2018 A first absolute chronology for Late Neolithic to Early Bronze Age Myanmar: New AMS ^{14}C dates from Nyaung'gan and Oakaie. *Antiquity* 92(363):690–708, DOI: https://doi.org/10.15184/aqy.2018.66.

Pryce, T. O., and Surapol Natapintu
2009 Smelting iron from laterite: Technical possibility or ethnographic aberration? *Asian Perspectives* 48(2):249–264.

Pryce, T. O., Dougald O'Reilly, and Louise Shewan
2017 Copper-base metallurgy in Late Iron Age Cambodia: Evidence from Lovea. *Journal of Archaeological Science: Reports* 13:395–402, DOI: https://doi.org/10.1016/j.jasrep.2017.04.005.

Pryce, T. O., and Vincent C. Pigott
2022 Metal exchange networks in prehistoric Southeast Asia, in *Oxford Research Encyclopedia of Asian History*: 430–457. Oxford: Oxford University Press.

Pryce, T. O., Vincent C. Pigott, Marcos Martinón-Torres, and Thilo Rehren
2010 Prehistoric copper production and technological reproduction in the Khao Wong Prachan Valley of Central Thailand. *Archaeological and Anthropological Sciences* 2:237–264, DOI: https://doi.org/10.1007/s12520-010-0043-y.

Pryce, T. O., A. Mark Pollard, Marcos Martinòn-Torres, Vincent C. Pigott, and Ernst Pernicka
2011 Southeast Asia's first isotopically-defined prehistoric copper production system: When did extractive metallurgy begin in the Khao Wong Prachan Valley of central Thailand? *Archaeometry* 53:146–163, DOI: https://doi.org/10.1111/j.1475-4754.2010.00527.x.

PRYCE, T. O., BAPTISTE PRADIER, AUDE FAVEREAU, U SAW NAING OO, CLÉMENCE LE MEUR, DAW KAY THWE OO, U ARKAR AYE, DAW THU THU WIN, KINGA ALINA LANGOWSKA, KASPER HANUS, YOSHIYUKI IIZUKA, CLOÉ GEORGON, AND 14 OTHERS
2024 Late prehistoric and early historic chronology of Myanmar: A four-millennia sequence from Halin. *Antiquity* 98(397):30–47, DOI: https://doi.org/10.15184/aqy.2023.190.

RICARDO, DAVID,
1817 *On the Principles of Political Economy and Taxation*. London: John Murray.

RISPOLI, FIORELLA, ROBERTO CIARLA, AND VINCENT C. PIGOTT
2013 Establishing the prehistoric cultural sequence for the Lopburi region, central Thailand. *Journal of World Prehistory* 26(2):101–171, DOI: https://doi.org/10.1007/s10963-013-9064-7.

SHENNAN, STEPHEN J.
1999 Cost, benefit, and value in the organization of early European copper production. *Antiquity* 73:352–363, DOI: https://doi.org/10.1017/S0003598X0008830X.

SINGER, HANS W.
1949 *Relative Prices of Exports and Imports of Under-developed Countries*. New York: United Nations Department of Economic Affairs.

SMITH, ADAM
1776 *An Inquiry into the Nature and Causes of the Wealth of Nations*. London: Penguin Classics.

STOS-GALE, ZOFIA A., AND NOEL H. GALE
2009 Metal provenancing using isotopes and the Oxford archaeological lead isotope database (OXALID). *Archaeological and Anthropological Sciences* 1(3):195–213, DOI: https://doi.org/10.1007/s12520-009-0011-6.

TAKIMOTO, KIYOSHI, ED.
1968 *Geology and Mineral Resources in Thailand and Malaya*. Kyoto: Dobosha Co.

THIRLWALL, MATTHEW F.
2002 Multicollector ICP-MS analysis of Pb isotopes using a ^{207}Pb-^{204}Pb double spike demonstrates up to 400 ppm/amu systematic errors in Tl-normalization. *Chemical Geology* 184(3–4):255–279, DOI: https://doi.org/10.1016/S0009-2541(01)00365-5.

VERNON, WILLIAM W.
1988 Field Notes from Geological Survey of the Khao Wong Prachan Valley, 18th–23rd February 1988. Unpublished report archived at MASCA, University of Pennsylvania, Philadelphia.

WANG, DONG N., VINCENT C. PIGOTT, AND MICHAEL. R. NOTIS
1994 The Archaeometallurgical Analysis of Copper-base Artifacts from Prehistoric Nil Kham Haeng, Central Thailand: A Preliminary Report. Archived at Museum Applied Science Center for Archaeology, University of Pennsylvania Museum, Phildadelphia.

WEBER, STEVEN, HEATHER LEHMAN, TIMOTHY BARELA, SEAN HAWKS, AND DAVID HARRIMAN
2010 Rice or millets: Early farming strategies in prehistoric central Thailand. *Archaeological and Anthropological Sciences* 2:79–88, DOI: https://doi.org/10.1007/s12520-010-0030-3.

WHITE, JOYCE C., AND ELIZABETH G. HAMILTON
2009 The transmission of early bronze technology to Thailand: New perspectives. *Journal of World Prehistory* 22(4):357–397, DOI: https://doi.org/10.1007/s10963-009-9029-z.

2018 Metals in economic context, in *Ban Chiang, Northeast Thailand (vol. 2A): Background to the Study of the Metal Remains*: 117–136, ed. J. C. White and E. G. Hamilton. Philadelphia: University of Pennsylvania Press.

2019 Conclusions: Placing metals in social contexts in prehistoric Thailand, in *Ban Chiang, Northeast Thailand (vol. 2C): The Metal Remains in Regional Context*: 155–183, ed. J. C. White and E. G. Hamilton. Philadelphia: University of Pennsylvania Press.

2021 The metal age of Thailand and Ricardo's Law of Comparative Advantage. *Archaeological Research in Asia* 27:100305, DOI: https://doi.org/10.1016/j.ara.2021.100305.

WHITE, JOYCE C., AND VINCENT C. PIGOTT
1996 From community craft to regional specialisation: Intensification of copper production in pre-state Thailand, in *Craft Specialization and Social Evolution: In Memory of V. Gordon Childe*: 151–175, ed. B. Wailes. Philadelphia: University Museum Publications.

Wilson, Lyn, and A. Mark Pollard
2001 The provenance hypothesis, in *Handbook of Archaeological Sciences*: 507–517, ed. David R. Brothwell and A. Mark Pollard. Chichester, UK: John Wiley & Sons.

Wohlfarth, Barbara, Charles Higham, Kweku A. Yamoah, Akkaneewut Chabangborn, Sakonvan Chawchai, and Rienk H. Smittenberg
2016 Human adaptation to mid- to late-Holocene climate change in Northeast Thailand. *The Holocene* 26(11):1875–1886, DOI: https://doi.org/10.1177/0959683616645947.

Workman, David R.
1977 *Geology of Laos, Cambodia, South Vietnam and the Eastern Part of Thailand*. Overseas Geological and Mineral Resources 50. London: Institute of Geological Sciences.

Yankowski, Andrea, Puangtip Kerdsap, and Nigel Chang
2015 "Please pass the salt": An ethnoarchaeological study of salt and salt fermented fish production, use and trade in northeast Thailand. *Journal of Indo-Pacific Archaeology* 37:4–13, DOI: https://doi.org/10.7152/jipa.v37i0.14711.

Zaw, Khin, Sebastien Meffre, Chun-Kit Lai, Clive Burrett, M. Santosh, Ian Graham, Takayuki Manaka, Abhisit Salam, Teera Kamvong, and Paul Cromie
2014 Tectonics and metallogeny of mainland Southeast Asia: A review and contribution. *Gondwana Research* 26(1):5–30, DOI: https://doi.org/10.1016/j.gr.2013.10.010.

Zaw, Khin, M. Santosh, and Ian T. Graham
2014 Tectonics and metallogeny of mainland Southeast Asia: Preface. *Gondwana Research* 26(1):1–4, DOI: https://doi.org/10.1016/j.gr.2014.01.005.