Journal of World Prehistory
https://doi.org/10.1007/s10963-024-09186-w

Reassessing Bronze Age Metallurgy in Upland Southwest China on the Basis of Excavations at Longbohe, Yunnan

Fu Jie[1] · Li Yingfu[1] · Hu Changcheng[3] · Wan Yang[3] · Yang Fan[3] · Zhu Yunsheng[4] · Vincent C. Pigott[5] · Charles Higham[6] · Li Yuniu[2]

Accepted: 26 June 2024

Abstract
Longbohe is a newly discovered copper mining, smelting and production site located strategically beside the Red River on the China–Vietnam border in Southeast Yunnan, China. Recent excavations have dated it from the second half of the second millennium to the end of the first millennium BC, making it the earliest copper mining and processing site in Upland Southwest China and Southeast Asia. The metallurgical production tradition in Upland Southwest China and Southeast Asia is recognized and detailed with reference to the *chaîne opératoire* revealed at the Longbohe site. The location of Longbohe provides evidence for a route along which metallurgy was introduced from Southwest China into Southeast Asia. Current evidence further suggests that metallurgy probably arrived on the Yunnan–Guizhou Plateau along the eastern Qinghai–Tibet Plateau corridors, and then entered Southeast Asia along south-flowing rivers. The Longbohe site is thus a most significant find in the southward dissemination of metallurgical technological systems into Southwest China and Southeast Asia in the later second millennium BC.

Keywords Archaeometallurgy · Longbohe · Copper smelting · Southeast Asia · Upland Southwest China · Bronze Age

✉ Li Yuniu
southwestuplandfox@163.com

1 School of Archaeology and Museology, Sichuan University, Chengdu, China

2 Center for Archaeological Science, Sichuan University, Chengdu, Sichuan, China

3 Yunnan Provincial Institute of Cultural Relics and Archaeology, Kunming, Yunnan, China

4 Honghe Hani and Yi Autonomous Prefecture Cultural Relics Institute, Mengzi, China

5 Asian Section, University of Pennsylvania Museum, Philadelphia, USA

6 Department of Anthropology, University of Otago, Dunedin, New Zealand

Published online: 28 August 2024

Introduction

Upland Southwest China (USC) comprises the Western Sichuan Plateau, the Yunnan–Guizhou Plateau and Western Lingnan. Yunnan Province, located in southwest USC, borders Vietnam, Laos and Myanmar in Mainland Southeast Asia (MSEA). It is a transition zone between the high-altitude eastern Qinghai–Tibet Plateau and MSEA. The excavation of Longbohe (LBH) in 2017–2019 by Sichuan University and the Yunnan Provincial Institute of Cultural Relics and Archaeology led to the discovery and dating of a key new copper mining, smelting and production complex that illuminates the penetration of metallurgical knowledge into Southwest China and beyond into Southeast Asia.

Longbohe lies on the right bank of the Red River, a highly strategic location that links two regions where the adoption of copper-base metallurgy is now well documented. To the north lies the Yunnan upland where several sites, such as Jicha, Haimenkou and Hebosuo now document the establishment of copper/bronze casting by 1600–1300 BC (Fu et al., 2024; Yao et al., 2020). Downstream one enters the broad expanse of the delta and the sites of the Đồng Đậu and Gò Mun Bronze Age in 1300–700 BC (Pryce, 2022). Later, the Dian chiefdom developed in Yunnan and the Đông Sơn culture in Vietnam entered the Iron Age around 400–200 BC (Yao, 2016). This location is not only a choke point for the exchange of goods and ideas, but also commands rich veins of copper ore. It plays a role in bridging USC and MSEA (Fig. 1).

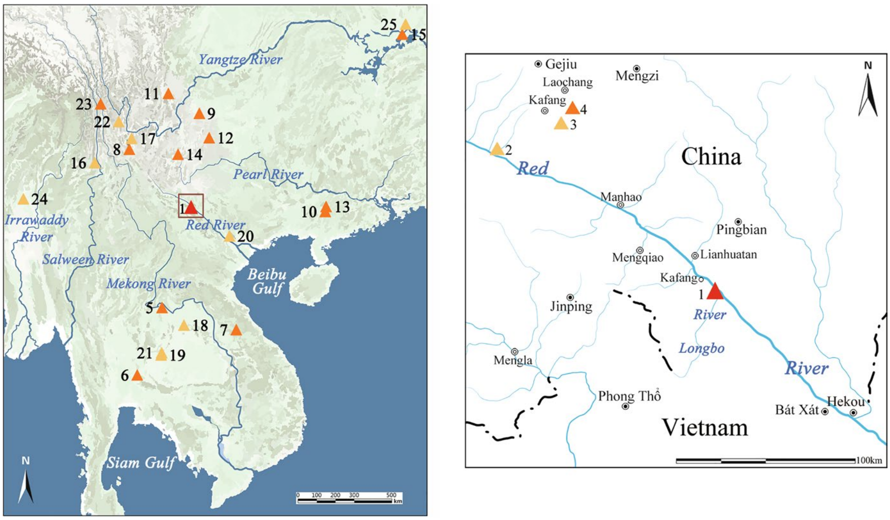

Fig. 1 Maps showing the location of LBH and other sites mentioned in the text: (1) LBH; (2) Mayutian cemetery; (3) heimajin cemetery; (4) Chongzipipo; (5) Phu Lon; (6) Khao wong Prachan valley, including Non Pa Wai and Nil Kham Haeng; (7) Vilabouly; (8) Hejiashan; (9) Dashan; (10) Tongshiling; (11) Dongping; (12) Tonggushan; (13) Liuchen and Luoxiu; (14) Jiangedi and Hebosuo; (15) Tonglushan; (16) Xiaolongjingpo; (17) Fengqingdao cemetery; (18) Ban Chiang; (19) Ban Lum Khao; (20) Phùng Nguyên, Đõng Đâu and Gò Mun; (21) Ban Non Wat; (22) Haimenkou; (23) Jicha; (24) Nyaung'gan, Oakaie and Halin; (25) Panlongcheng

Chinese scholars have hitherto focused mainly on the construction of regional cultural types and the chronological framework (Peng, 2008; Yang, 2011). Yao introduced some of the materials from the perspective of the empire frontier (Yao, 2016). In terms of the research on metallurgical technology, excavated metal artifacts have been the primary focus (Li & Han, 2011; Yuan & Li, 2018), with little attention paid to mining and processing sites. Recent research into the Bronze Age of MSEA has concentrated, for the most part, on issues of chronology and transmission routes that involve two incompatible models (Pryce, 2014, 2018) (Fig. 23). Charles Higham and colleagues have proposed the 'short chronology' (Ciarla, 2007a; C. Higham et al., 2015; C. Higham & T. Higham, 2009; C. Higham, T. Higham, Ciarla et al. 2011a; C. Higham, T. Higham, & Kijngam 2011b; T. Higham et al., 2020; Pigott & Ciarla, 2007; Pryce, 2011). This model is based on radiocarbon determinations on charcoal, rice, human bone, shell and millet from multiple sites, which support the argument that the Steppe technology, using bivalve moulds with suspended cores to cast hollow-socketed tools and weapons, was transmitted south into MSEA through the highly sophisticated shang culture from the central plains and subsequently via the Lingnan area in the late second millennium BC. In contrast, Joyce White and Elizabeth Hamilton put forward the 'long chronology' on the basis of radiocarbon determinations on organic ceramic temper from Ban Chiang and other supporting data (White, 2008; White & Hamilton, 2009, 2018, 2019). They argue that the metallurgy in MSEA was immediately derived from the Seima-Turbino metalworking traditions on the eastern Eurasian Steppe, by practitioners moving through the eastern piedmont of the Qinghai–Tibet Plateau and into Yunnan and then to the site of Ban Chiang in Thailand by c. 2000–1800 BC.

There are 10 well-defined Bronze and early Iron Age sites related to metallurgical production in USC (Fig. 1).

- The newly excavated **Jicha** site, strategically located on the bank of the upper Mekong River, was a settlement site with specialized metallurgical area, where in-ground furnaces, *tuyères*, and moulds were found dated to at least 700–300 BC (Fu et al., 2024).
- **Dashan** (400–100 BC) and **Tongshiling** (100 BC–AD 100) were copper-smelting sites that employed in-ground furnaces (Li et al., 2007; Qin, 1985; Sun et al., 1986; Yin, 1993).
- **Dongping** (50 BC– AD 200) was a government-controlled copper-smelting and coin-casting site that utilized shaft furnaces in the Xinmang Period and the Eastern Han Dynasty (AD 8–220) (Xichang, 1977; Liu & Zhang, 1990; Lin & Zhang, 1994; Ren & Hu, 2006).
- **Tonggushan** (400–1 BC) was a copper-casting site that might belong to the Yelang culture (Cheng, 1993; Liu & Xiong, 1993).
- **Liuchen** (300 BC–AD 400) and **Luoxiu** (200 BC–AD 800) were two sites where in-ground furnaces were employed to produce bloomery iron (Zheng, 1990; Huang & Li, 2008; Meng, 2015; Zhang et al., 2020; Zou et al., 2022).
- **Chongzipipo** (AD 1–200) was a probable tin and copper smelting site that used in-ground furnaces (Dai & Zhang, 1998).

- **Hejiashan** (400–300 BC) yielded a smith's burial where bronzes, moulds and animal-head-shaped *tuyères* were buried (Zhang, 2000).
- **Jiangedi** (100–1 BC) was a metallurgical hoard that might belong to the Dian chiefdom, where bronze, iron and bimetallic bronze-iron artifacts and metal raw material were uncovered (Hu, 2016).

However, these related sites did not offer much evidence on certain questions. These sites are nearly all dated to the late first millennium BC or early first millennium AD, which is somewhat late for discussing technical traditions and their origin. Due to the limitations of current fieldwork and the excavated sites themselves, the technical information they provided was quite fragmented, making it hard to draw conclusions.

In the context of the Bronze Age, the region neighbouring USC followed a radically different track. To the west, the dispersed 'Copper Hoard culture' communities were active in drainage of the Brahmaputra River and the Ganges River (Yule, 1997). Hitherto, the technical influence of the Copper Hoard culture has not been observed in USC and MSEA (Pryce, 2014; Pryce et al., 2022), although some copper flat axes have emerged in southwestern USC (Fu et al. in prep.). Turning to the Central Plains, the highly prosperous Shang and Zhou dynasties forged a sophisticated sacrificial bronze vessel tradition; meanwhile, bronze production was subject to strict governmental control (Chang, 1980; Falkenhausen, 2006). Tonglushan, where deep mine shafts, galleries, furnaces and tools have been excavated (Huangshi, 1999), is a representative Shang and Zhou dynasty metallurgical site beginning in 1200 BC and located in the middle reaches of the Yangtze River (Liu et al., 2019).

Only three early copper-production sites are known in MSEA. A complete complex from mines through smelting to casting has been identified in the Khao Wong Prachan Valley of Central Thailand. A new dating initiative on the smelting and casting sites of Non Pa Wai and Nil Kham Haeng has shown that this activity began in the later second millennium BC (Ciarla, 2007b, 2008; T. Higham et al., 2020; Pigott, 2019; Pryce et al., 2011; Rispoli et al., 2013). Phu Lon is a mining complex with smelting evidence dating to the first millennium BC beside the Mekong River in Northeast Thailand (Natapintu, 1988; Pigott & Weisgerber, 1998; Pigott, 1988a, 1988b, 2019). The Vilabouly Complex is an upland location at Sepon in Laos (Cadet et al., 2019, 2021; Tucci et al., 2014). Ore processing at all three took place in the vicinity of the mines, with refractory technological systems that involved crucibles with lagging. Copper and binary tin-bronze alloying, lost-wax and bivalve-mould casting were employed. It appears that production was organized in small decentralized units and their output incorporated ingots, axes, spears, fishhooks, arrowheads, bangles, anklets and bells.

These production centres were integrated with consumer sites located in lowland areas suited to rice production. Limited excavations at sites such as Ban Chiang, Non Nok Tha and Ban Na Di uncovered burials in which the dead were interred with few mortuary offerings (C. Higham, 1996; White & Hamilton, 2009). Recent re-dating of Non Nok Tha and Ban Chiang has placed the transition from the Neolithic into the initial Bronze Age at c. 1100–1000 BC (C. Higham et al., 2015). In the central plain of Myanmar, this transition has been dated to c. 1000 BC at Oakaie

(Pradier, 2019), while other key early sites are Nyaung'gan and Halin (Pryce et al., 2018).

The extensive excavation of Ban Non Wat, however, has revealed a six-phase Bronze Age sequence involving an early and exclusive enclave of remarkably wealthy 'aggrandizer' burials, with quantities of exotic shell, marble and copper-base mortuary offerings. This outstanding wealth was ephemeral, lasting for about six to eight generations between 1050 and 850 BC (C. Higham, 2022; C. Higham & Cawte, 2021; C. Higham & Kijngam, 2012).

Through his analyses of lead isotope signatures, T. O. Pryce (e.g., Pryce & Pigott, 2022) has been able to link the copper from some of these sites to their ore sources. By c. 1000 BC, copper was moved over considerable distances, from Vilabouly to Ban Chiang and Myanmar, from the Khao Wong Prachan Valley mines to Ban Non Wat, and from Yunnan into Myanmar. It is clearly of the utmost importance to incorporate the copper from Longbohe into this network.

The Excavation of Longbohe (LBH)

With finds of 28 in situ in-ground furnaces, LBH fills an important gap in our knowledge of prehistoric copper production in USC and MSEA. These were mainly bowl furnaces—with a unique, sandy clay lining applied to the base, and include one dated to c. 1400 BC. In addition, a considerable number of tools for mining, ore processing and metal casting, as well as production waste including slag and fragments of burnt clay, were unearthed. These have helped us to reconstruct the metallurgical technology.

LBH offers a point of reference for reviewing regional excavated metallurgical sites, and on this basis, we can present our interpretation of the 'upland mode' of production involving their location, layout and technology, which in turn provides valuable information for further fieldwork. LBH also affords hints on the emergence and transmission of copper-base metallurgy in USC and MSEA, which, it will be argued, tend to support the upland route of the 'long chronology' but the younger date of the 'short chronology'.

In an area of about 6 km^2, 14 locations and several copper mines have been identified. Locations are scattered across the gentle and open terrain on a ridge, with areas varying from approximately 2000–10,000 m^2 (Fig. 2). Locations A and B were discovered in 2004. The former lies in a gully at the foot of the LBH mine on the west bank of the Red River, named Laohuchong (Tiger Gully). Six copper artifacts were collected there, including a curved-bladed sword, a heart-shaped hoe, a buckle, a chisel, a boot-shaped axe and a shouldered axe (Yang, 2006).

In 2019, 11 trenches were excavated at Locations 1, 2 and 3, covering an area of 518 m^2, the deposit in Location 3 being the most informative (Fig. 3). The stratum of Location 3 comprises five layers. Layers 1 and 2 are modern. Layer 3 is a compact brown clay, containing a small quantity of burnt clay and charcoal fragments, potsherds, stoneware, slag and shaped burnt clay. Layer 4 is a loose black sandy clay, containing burnt clay and charcoal, potsherds, stoneware, slag and shaped burnt clay. Layer 5, covering only a small area, is a slightly compact brown clay,

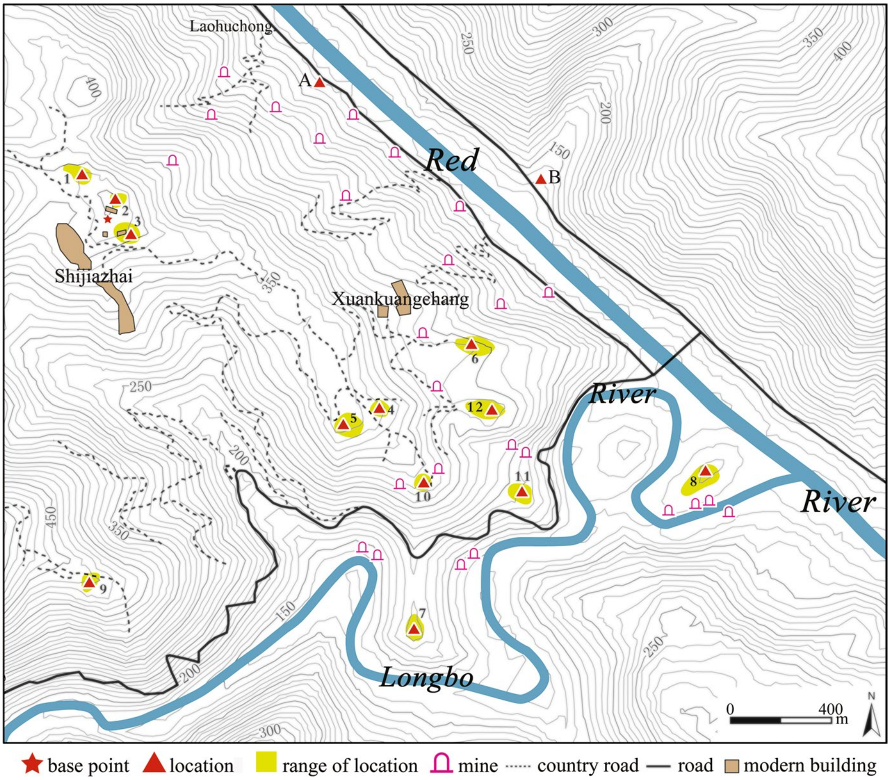

Fig. 2 Map showing locations within LBH

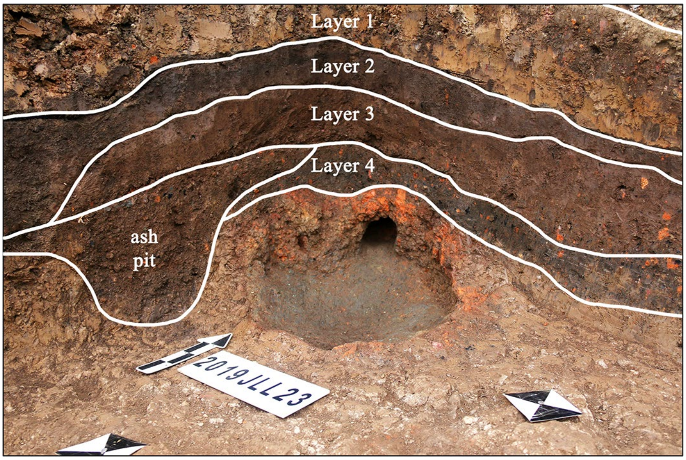

Fig. 3 View of the northwest corner of Unit TS7E7, showing Layers1–4 (Layer 5 is absent) and a furnace sealed by Layer 4

containing burnt clay nodules, potsherds, slag and shaped burnt clay. Smelting activity was observed on the surface of Layer 5 and virgin soil.

Evidence for metallurgical activities was concentrated at Location 3 and included pits, furnaces and postholes cut through the natural substrate. Ceramic and stone moulds were encountered in pits.

Twenty-eight in-ground furnaces—the best-defined and richest collection of early in-ground furnaces yet encountered in China and SEA—were identified on the gentle slope near the hilltop. These differ from the shaft furnaces of the Central Plains during the spring and autumn period (Huangshi, 1999). Most furnaces were well preserved, and their scorched clay structures are clearly visible, including blowing grooves, hearths, lining (also lagging) and discharging gaps. Some have ancillary facilities, like charging pits, ingot-casting pits, operating platforms and surrounding postholes.

Nearly 300 ceramic, stone and copper artifacts were found in the 2019 excavation. Ceramic remains include vessels, spindle whorls, standers and moulds. The pottery was hand-made, using sandy clay, and was fired at a relatively low temperature (Wan, 2018). About half of the vessels were decorated with cord-marking, *appliqué*, incised patterns or a combination of these. The stone implements include pitted hammerstones, trapezoidal hammers, grinding stones and moulds. The pitted hammerstones are the most common. A small broken tube was the only copper-base artifact recovered.

A number of vertical and horizontal mineshafts were discovered, mostly interspersed with the smelting locations (Fig. 4). Pitted hammerstones and fire-setting remains were encountered in some of the mineshafts.

Ore Mining, Processing and Fuel Preparation

More than 50 pitted hammerstones were unearthed or collected, accounting for the vast majority of stone artefacts (Fig. 5). These are oblate stone tools with a concave surface, mostly made of river cobbles with an appropriate shape. A typical specimen has an oval cross section, with a pit on both the broad surfaces symmetrically. They are shaped as half-ovals, rounds and rounded rectangles, with dense pecking marks visible on the narrow edges of most examples, indicating that this type of stone tool was mainly used for ore crushing by hand against some sort of stone anvil. They were encountered in both mineshafts and smelting locations, and are clearly related to mineral mining and processing.

There are also differences in the shape of the pits on the broad surface, which can be divided into three types: Type A, the pits formed by pecking; Type B, the large shallow pits formed by grinding; and Type C, the smaller but deeper pits formed by pecking and grinding (Fig. 5). The second type can be used cooperatively with the stone balls or grinders to grind ore. Those pitted hammerstones were adapted for ore preparation from mining to grinding. Two large sandstone hammers with a trapezoidal section were also unearthed (Fig. 6). This type has a narrow subface with slight

Fig. 4 Mines in LBH site: (1) below Location 3; (2) below Location 11 and Location 12; (3) below Location 8, across the Longbo River in Vietnam; (4) modern, below Location 3 but upon the Laohuchong

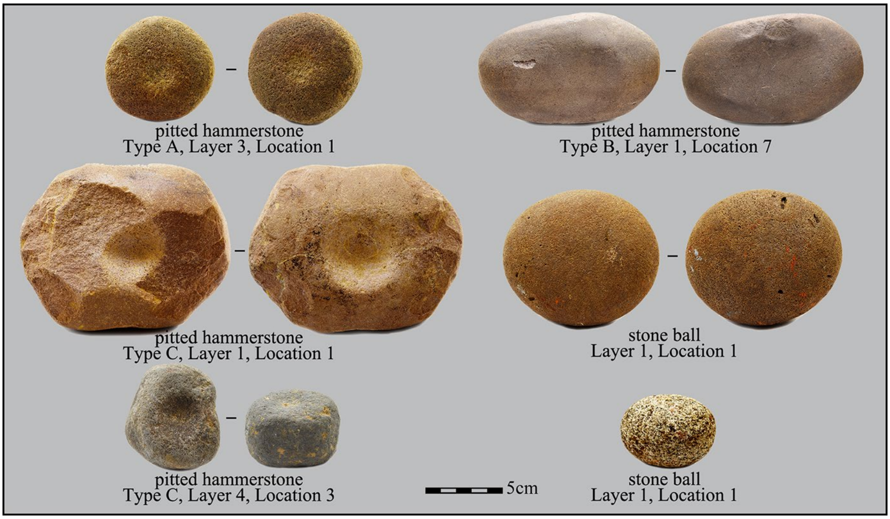

Fig. 5 Stone tools for mining and processing unearthed at LBH

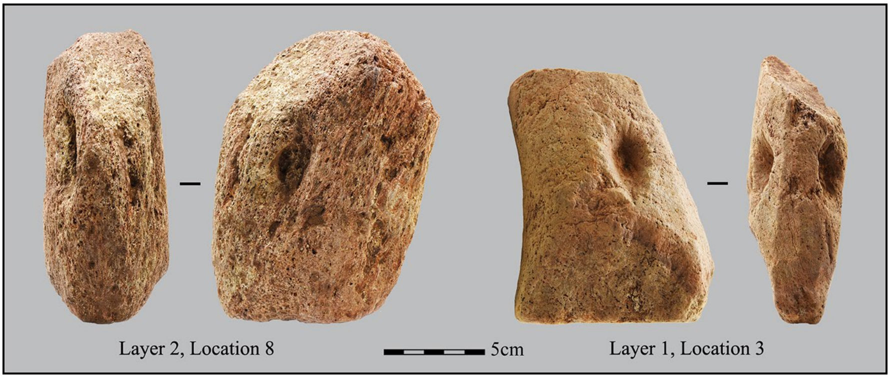

Fig. 6 Trapezoidal sandstone hammers unearthed at LBH

impact marks and there are symmetrical pits near the slanted edge of each broad surface.

Furnace L27 and charging pit K1 were encountered at Location 3, which revealed the smelting fuel used at LBH (Fig. 7). The K1 pit has a long diameter of 74 cm, a short diameter of 50 cm and a depth of 20 cm. Lumps of principally *Castanopsis* charcoal were stacked in the pit, with a regular length of 1–3 cm.

Furnaces

The LBH furnaces are mainly of the in-ground type, dug on the slopes near the hill-top, then walled with fine clay and sintered. There are three types (Table 1).

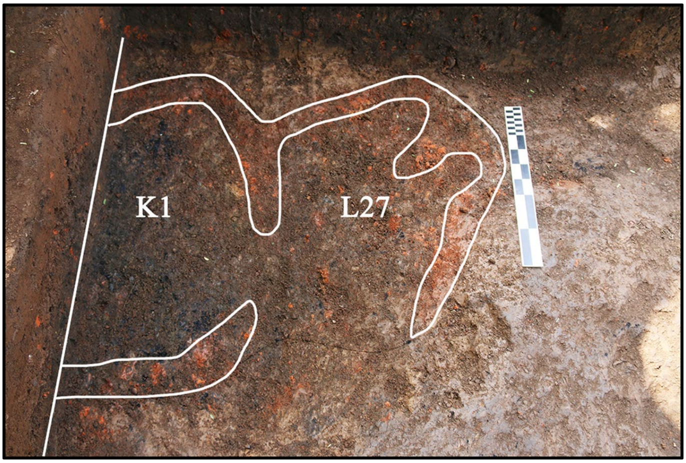

Fig. 7 View of the charcoal pit (K1) and furnace (L27) before cleaning. The circled regions are the burnt clay walls

Table 1 LBH furnaces mentioned in the text

Field No	Layer, Location	Slope (°)	Superstructure (length, width, depth) (cm)	Hearth (diameter/ length, width, depth) (cm)
2019L1	Surface, 1	15	Single groove 12.1, 11.3, 11	63, 28.1
2019L6	5, 3	19	Double grooves Left: 20.9, 15.3, 17.2 Right: 27.6, 13.6, 12.4	54.3, 58.3, 23.2
2019L21	Virgin, 3	11	No groove	50, 19.3
2019L24	Virgin, 3	12	Blowing room 22.2, 32.1, 22.4	44.7, 52.3, 27.2
2019L28	Virgin, 3	21	Double tunnels Left: 48.2, 9–35.6, 40 Right: 33.5, 9.3–34.5, 39.3	59.2, 44.5, 34.4

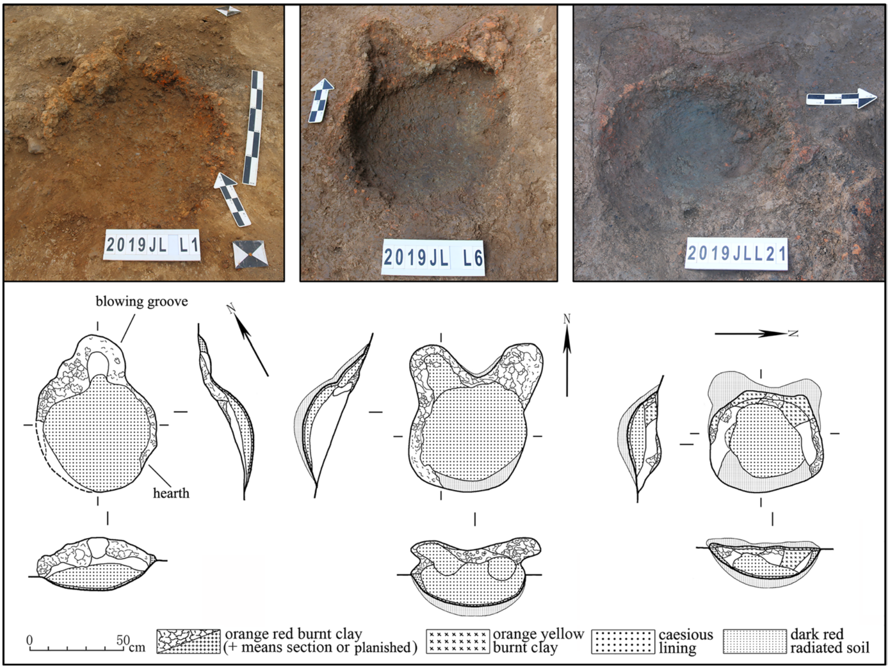

Fig. 8 Photos and drawings showing the furnace of Type A, Type Ba and Type C. The evolution of furnace shape is visible from left to right

Only two Type A bowl furnaces were discovered (Fig. 8, left). A single exterior blowing groove was constructed on the upper part, the lower part comprising a bowl-shaped hearth. The lower side of the hearth is generally open for slag tapping or removing the furnace contents. A layer of green–grey, sandy clay lining was applied on the bottom of the furnace.

Twenty-one Type B furnaces with double blowing grooves were discovered (Fig. 8, middle). Only one Type C furnace, with no visible blowing groove, was found (Fig. 8, right). The differences in blowing grooves indicate a technical innovation.

Some of the Type B furnaces were discovered with pits in which a blower was half-buried, which were classified as Type Bb and Type Bc.

Four Type Bb furnaces were discovered (Fig. 9). The upper part is a blowing pit with a rounded rectangular section and an inverted trapezoidal profile. The lower part is a hearth shaped like a dustpan, with an open lower side. Two underground symmetrical holes connected the two spaces. A lining was applied on the bottom of the hearth, sometimes extended to the holes.

Only one Type Bc furnace was discovered (Fig. 10). The upper part comprises two underground, inclined blowing pits, connecting with the hearth. The shape of the hearth is the same as Type Bb, and also lined.

Furnaces were constructed in groups during the late period at LBH. Two furnace groups were uncovered in this excavation. A furnace group is generally comprised of two levels of furnaces; the blowing grooves of the upper furnace are normal, but they are shorter or have disappeared when it comes to the lower rank of the furnace group (Fig. 11).

Type Bb and Type Bc furnaces were usually distributed independently, but in some instances there were ancillary facilities around them. For example, there are more than 10 postholes on the left, right and upper sides of Type Bb furnace L4, which is roughly rectangular with L4 as the centre. These postholes seem to have provided a simple shelter over the furnace. There is also an operating platform on the lower side. As another example, the lower side of Type Bc furnace L28 has a similar operating platform, and there are two round shallow pits on the lower left side, which are presumed to be ground moulds for casting pie-shaped ingots (Fig. 10).

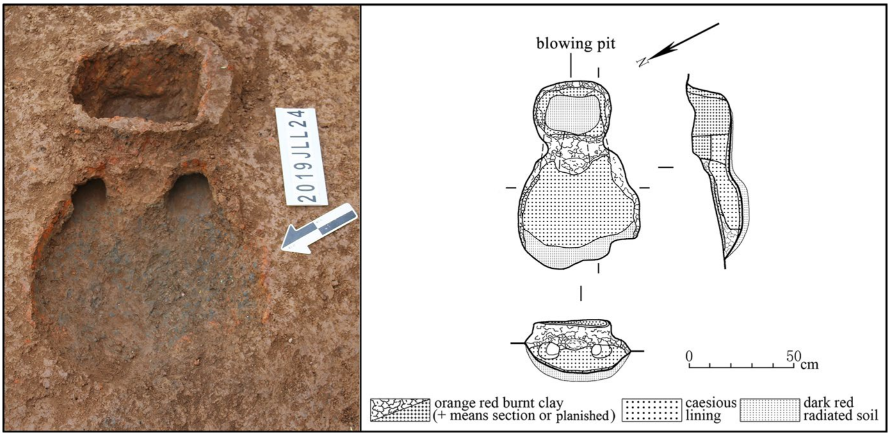

Fig. 9 Photo and drawing showing the furnace of Type Bb

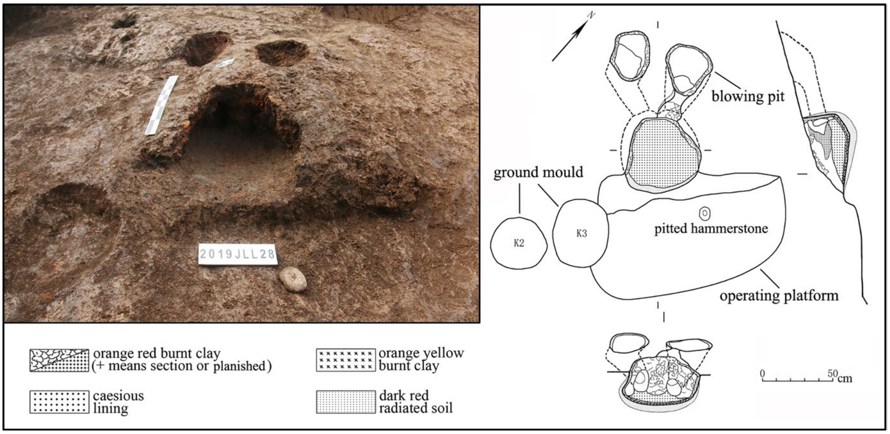

Fig. 10 Photo and drawing showing the furnace of Type Bc

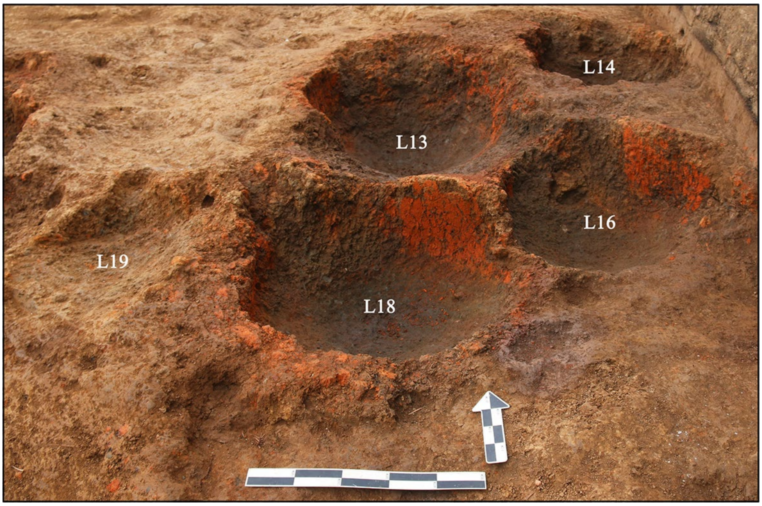

Fig. 11 One of the furnace groups at Location 3. L13, 14, 16, 18 are sealed by Layer 3; L19 is a remnent bottom, sealed by Layer 5, cut by L18

Lining

The base of all furnaces was coated with a caesious, clayey material that hardened up after heating (Fig. 12). Compared with the furnace wall that was not covered with this material, the wall with lining always appears to be a less-heated orange–yellow rather than orange–red, showing that this material had a heat-resistance function. It may have increased the endurance of the furnace, or reduced heat dissipation from the hearth.

Fig. 12 The double-layer caesious linings of furnace L27

For further analysis, some of this material was collected and ground into powder. Samples were examined by X-ray diffraction (Philips X' Pert Pro MPD DY129) at the Analytical and Testing Centre of Sichuan University. According to the XRD results, quartz is the main component of the material (Table 2), indicating knowledge of the physical properties of quartz. The quartz might come from copper-quartz-associated ore or river sand.

Tuyères and Bellows

No *tuyères* or bellows have been unearthed. Given the lack of *tuyères* and bellows at the site and the location of furnaces packed on to the slope, the possibility of utilizing natural wind to drive the smelting should not be ruled out. However, the blowing grooves of Type A and the connective holes of Type B, could to some extent be regarded as fixed *tuyères*. Considering these structures, the bellows used should be similar to the cylindrical pistons used in Thailand and Laos (Evrard et al., 2016; Pryce et al., 2010). Similar bellows have been identified in USC. Song (2003) has described cylindrical piston bellows used in the iron-smelting activities of the Naxi nationality in northwest Yunnan. Qing Dynasty (AD 1844) sources have also recorded that this kind of bellows was recently used in south Yunnan (Wu & Ma, 2017).

The information mentioned above allowed the blowing method to be roughly reconstructed. The Type A and Type Ba furnaces might have involved tubes (probably of wood or bamboo), fixed in the grooves with clay, to guide the blast from bellows to the hearth. As for Type Bb and Type Bc furnaces, the bellows might have been partially buried in the blowing pits or tunnels (Fig. 13).

Table 2 Ingredients of lining samples collected from furnace and cultural layer

Excavation No	Compound Name	Chemical Formula	Semiquant [%]
2019JLL15	quartz, aluminium silicon oxide, rutile, magnesium silicate	SiO_2, $Al_{4.54}Si_{1.46}O_{9.73}$, TiO_2, Mg_2SiO_4	80, 12, 1, 7
2019JLL27	quartz, rutile, illite	SiO_2, TiO_2, $K(Al_4Si_2O_9(OH)_3)$	40, 1, 59
2019JLTS5E3③:8	quartz, aluminium silicon oxide, magnesium silicate, iron titanate, rutile	SiO_2, $Al_{4.59}Si_{1.41}O_{9.7}$, Mg_2SiO_4, $FeTiO_3$, TiO_2	69, 12, 16, 2, 1

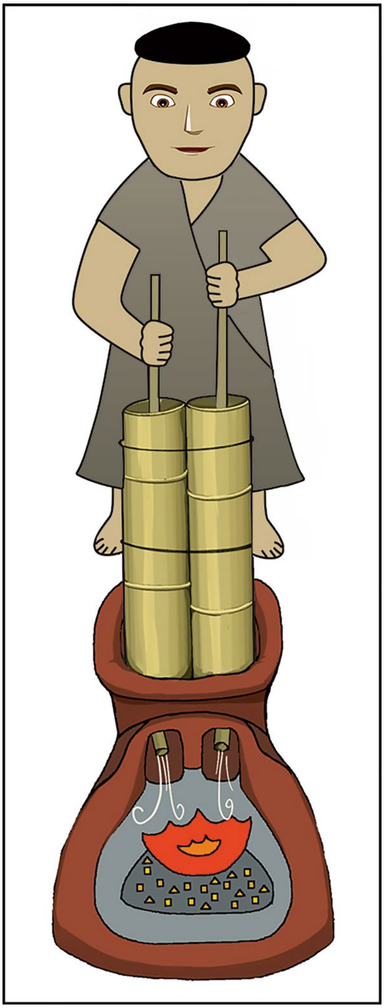

Fig. 13 Reconstruction of the blowing method for the Type Bb furnace

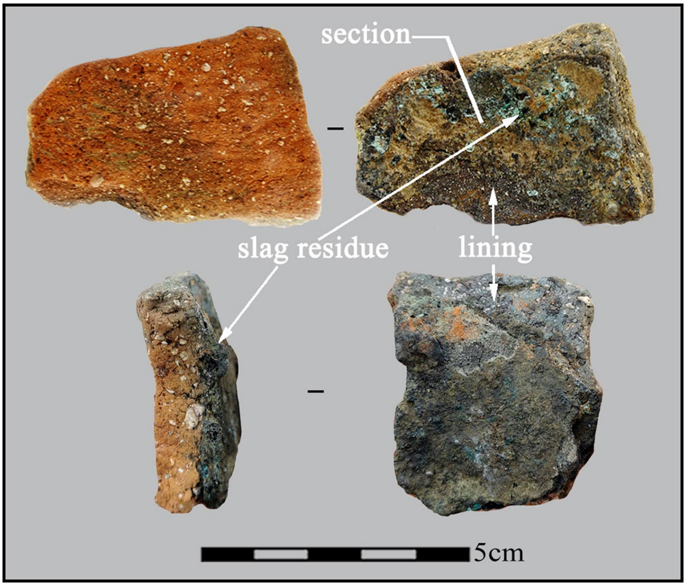

Fig. 14 Crucible fragments unearthed from Layer 4, Location 3

Crucibles and Moulds

No complete crucibles have been found, but several fragments with slag residue attached on the inner wall were recovered from Layer 4, Location 3 (Fig. 14). They are quartz-sand potteries, decorated with cord marks, around 1 cm thick. Unlike ordinary pottery, a thin caesious lining was applied on the inner wall. Given its thickness and quality, this kind of crucible may only be capable of holding or transferring the melt.

A thin section (Fig. 14) was prepared to check the lining. It was mounted in epoxy resin, ground and polished. The lining layer is roughly visible via the optical microscope (Leica CM6000M), but there seems to be no obvious boundary between the lining and pottery, indicating that this lining might have been prepared before sintering rather than applied later (Fig. 15).

Twelve moulds were recovered (Fig. 16). All are cambered-back bivalve moulds. Four are ceramic, made of a sandy clay, the back or pouring surface of some being decorated with patterns. There are eight sandstone moulds. Two broken stone moulds were recycled into a pitted hammerstone and a grinding stone.

One of the ceramic moulds appears to have been utilized for casting a waisted vessel, possibly for a bronze drum. One stone mould cast a curved-bladed spear or sword and another one was for a bell. The others are ambiguous, but many of the moulds have shallow, sharp casting cavities that seem to be for the blades of tools or weapons.

Two intriguing techniques were observed on those moulds (Fig. 18). One is the ‘closing technique’. Some of the moulds have pits on the back or top—the

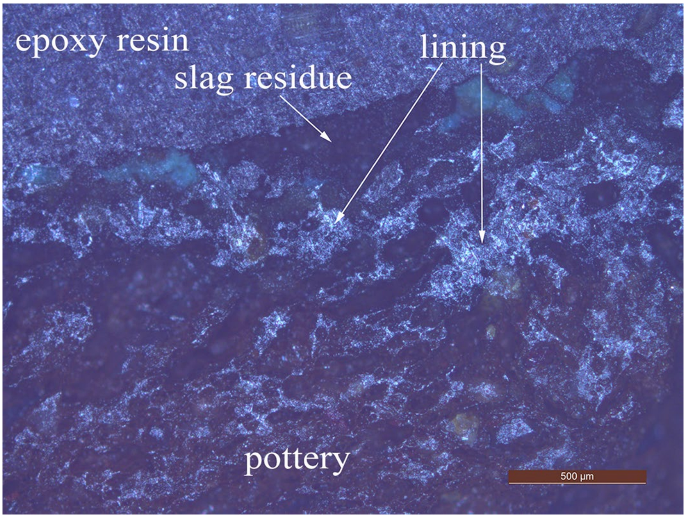

Fig. 15 Photo showing the section of crucible fragment

so-called 'mould buckle' (Fig. 16). There are black smoke marks on the back of all the moulds, and some are quite regular. There is no smoke mark between the buckles and the mould-closing lines, which signifies the use of the mould buckles. One possible scenario is that the buckles would have been filled with clay when it was used to fix the moulds before preheating. During the baking,

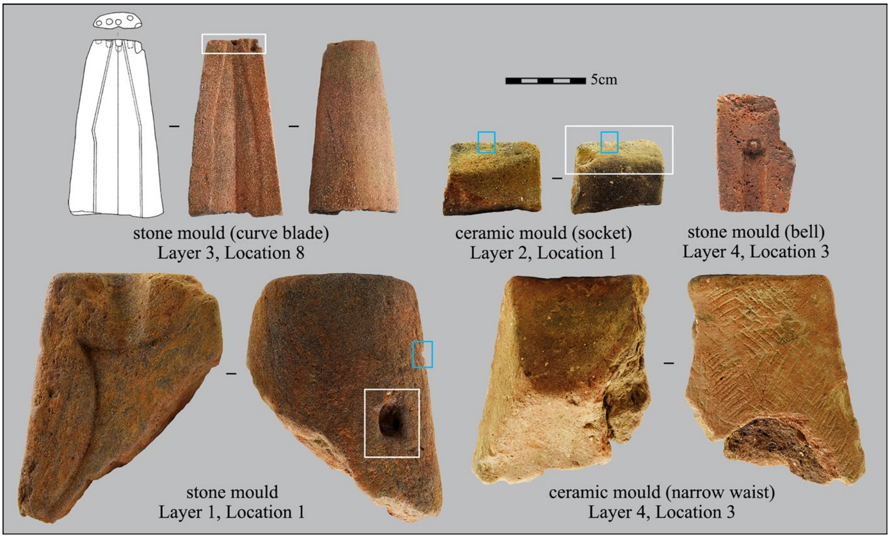

Fig. 16 Moulds unearthed at LBH. The white frames mark the mould buckles and the blue frames mark the calibrating line; the relationship between the burnt mark and mould buckle can be observed on the back of the second mould

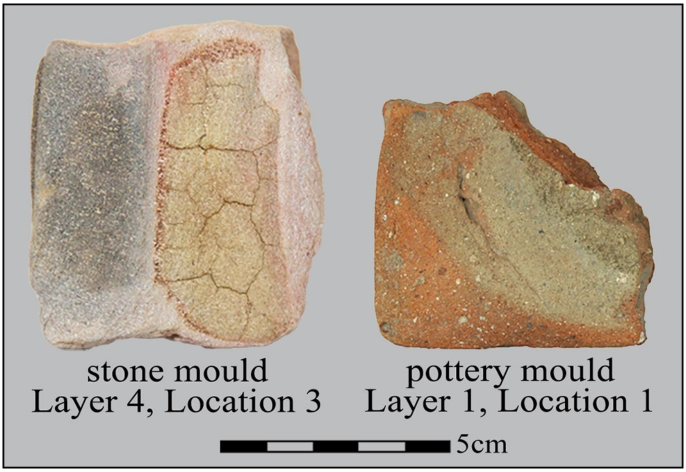

Fig. 17 Moulds unearthed at LBH. A yellow sandy lining was applied to the surface of the casting cavity

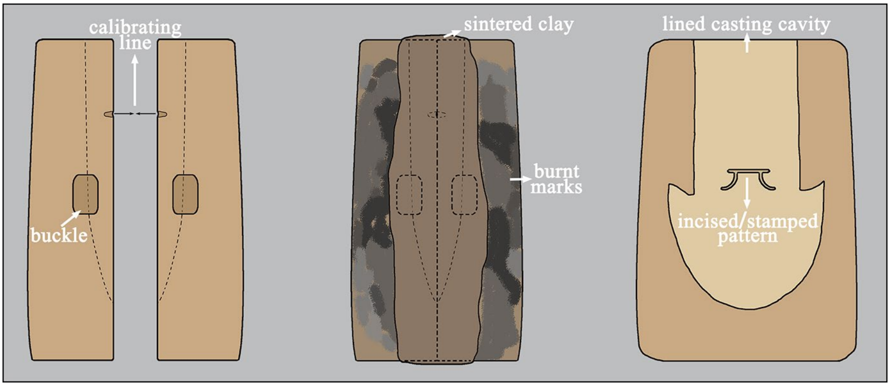

Fig. 18 Drawings showing the function of calibrating line, mould buckles and mould lining

the filling clay would have sintered, then the bivalves would have been fastened. In addition, a groove perpendicular to the closing line is sometimes observed in the upper part of the ‘buckle’. That is the ‘calibrating line’ to accurately clamp together the bivalves (Figs. 16, 18).

Another example is the ‘lining technique’. An artificial, yellow sandy lining layer was recognized on the surface of the casting cavity of two moulds (Fig. 17). The difficulty of accurately controlling the shape of the casting cavity is one of the defects of the stone moulds. This kind of lining layer seems to reduce this to some extent, and also allows more technical possibilities for the forthcoming cultural flourishing of the Bronze Age. Such possibilities include the casting of intricately patterned vessels by stamping and incising (Fig. 18), and the casting of vessels of the same shape but with different patterns.

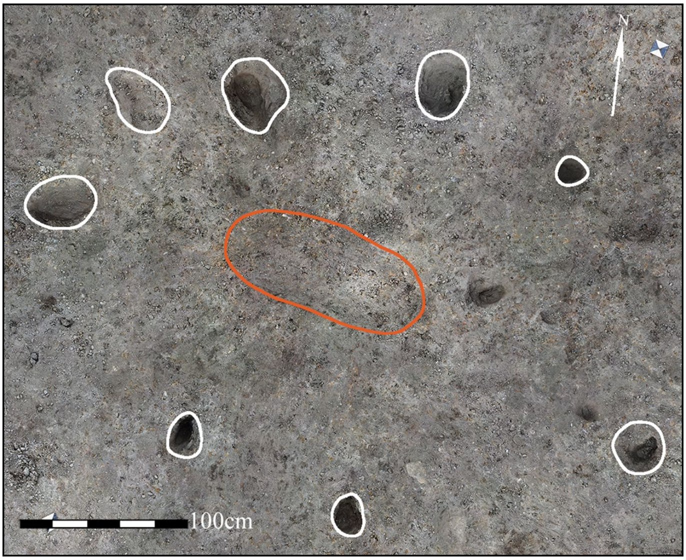

Fig. 19 Photo showing the structures found at Location 1. White circle for pile holes, orange for fire pit

The Layout of Processing and Production Units

An oval structure was revealed in the central part of Location 1 (F1) (Fig. 19). F1 is located in the middle of the hill, ringed by several posts, with a diameter of c. 4 m. There is an oval fire pit in the centre of the structure, which contains charcoal and burnt clay nodules, slag and animal bones. Similar vestiges were also found in Location 3.

On the basis of these discoveries, the hill can be regarded as a production locale: the central flat area on top was a simple and temporary residence; the slight downward slope is strewn with furnaces; and the dumping area of the smelting waste lies further below. Mine shafts were often encountered on the side near the valley bottom. Thus, the layout of smelting units is vertical, and is quite intensive rather than decentralized (Fig. 20).

The Chronology of Longbohe (LBH)

Few Bronze Age sites are known in the middle reaches of the Red River valley. Pottery similar to that from LBH was detected in the Mayutian cemetery in Gejiu, about 70 km upstream (Xiao & Wan, 2013) (Fig. 1). A curved-bladed spear that matches the mould unearthed at LBH was encountered. The human bones from the Mayutian cemetery have been dated to 2470 ± 35 BP, 2565 ± 25 BP and 2530 ± 40 BP (calibrated to 767–421 BC, 805–572 BC and 799–541 BC, 95.4% probability).

Sixteen samples from LBH were collected for AMS dating. Data calibration and Bayesian analysis were conducted with OxCal v. 4.4.2 and IntCal 20 (Ramsey, 2009;

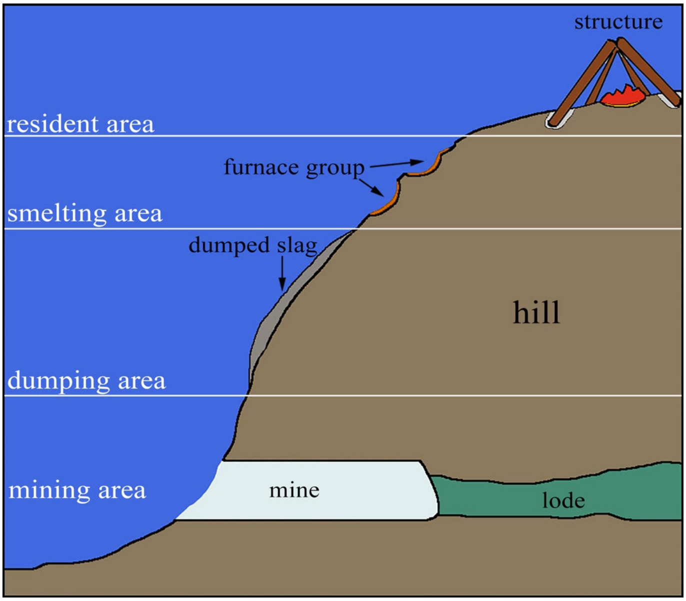

Fig. 20 Drawing showing the vertical layout of a processing and production unit

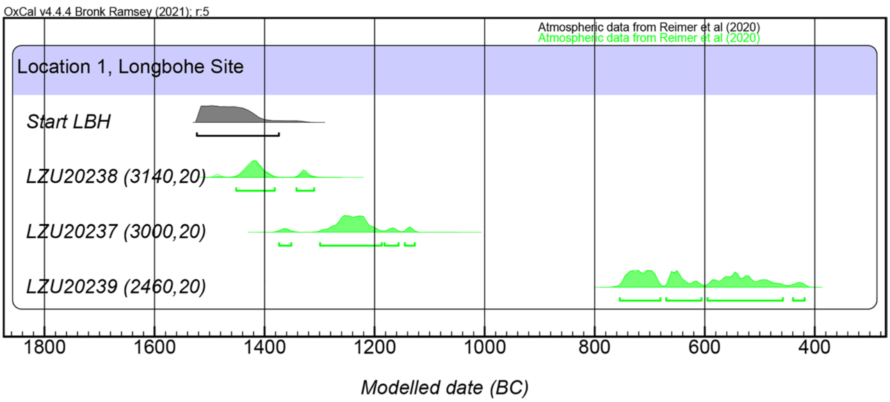

Fig. 21 Calibrated age for Location 1, Longbohe

Reimer, 2020). In addition to the chronological logic of dates' relationship to the observed stratigraphy, attention was paid to the chronological difference between the charcoal samples taken from the surface of the lining and the sample from furnace fill. The former is supposed to be residue from the last smelting activity and the latter is more likely to represent the age when the furnace was eventually abandoned and covered.

Three charcoal samples collected from Location 1 were tested (Fig. 21). One was acquired from the fill of furnace L1, dated within the radiocarbon Hallstatt

Plateau at 2460 ± 20 BP (755–420 cal BC) (LZU20239). The second was enclosed in a piece of slag found in furnace L1, dated 3140 ± 20 BP (1456–1384 cal BC) (LZU20238). The third was picked from Layer 3 (different from Location 3), dated 3000 ± 20 BP (1300–1189 cal BC) (LZU20237). From the perspective of stratigraphy, the furnace L1 was exposed on the surface and cut through the virgin soil capped by Layer 3. Thus, the dates of furnace L1 and Layer 3 are presumed to be contemporary and corroborate each other. The shape of furnace and the stone artefacts such as the bark cloth beater (most of which belong to a late Neolithic or early Bronze Age context in the neighbourhood: eg. Sichuan et al., 2016) found at Location 1 suggest that its age is earlier than that of Location 3,

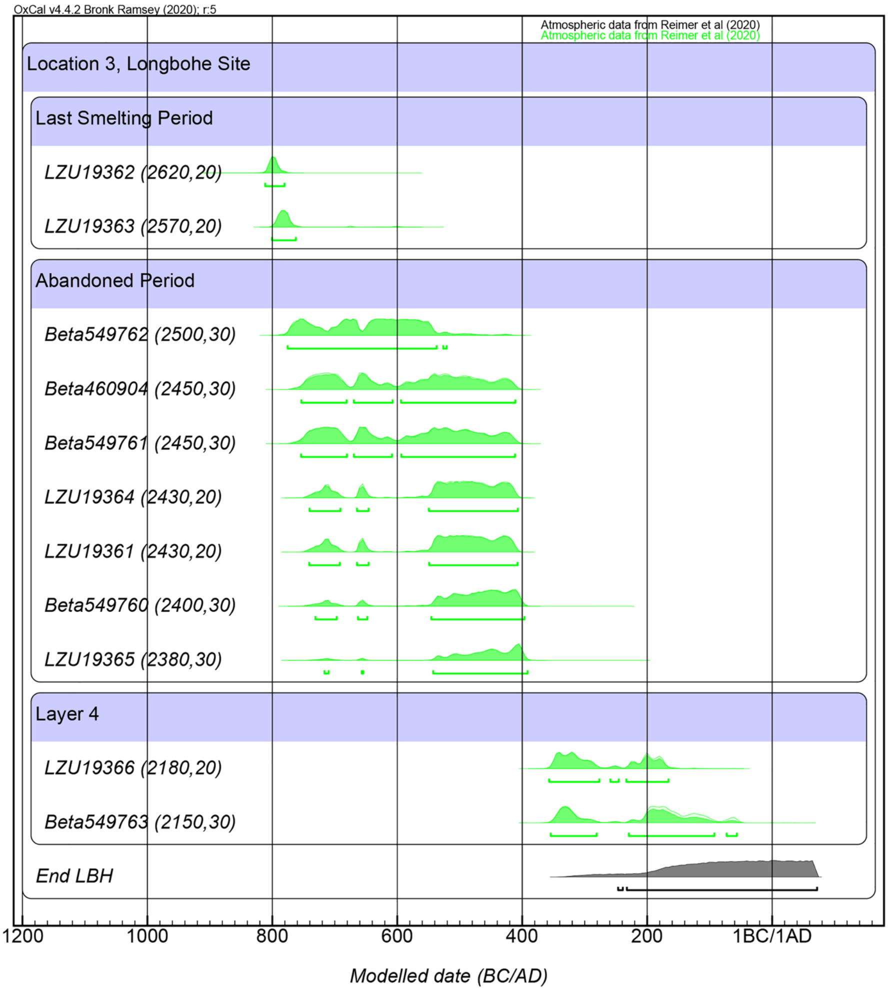

Fig. 22 Bayesian age model for Location 3, Longbohe

which is verified by the dates. Therefore, though the samples seem to be somewhat deficient, we consider them data.

Twelve charcoal samples collected from Location 3 were dated, including two from Layer 4, three from the surface of the lining (last smelting period) and seven from furnace filling (abandoned period). Bayesian modelling was carried out to demonstrate these samples' dating (Fig. 22). One sample collected from the surface of the lining, dated 3260 ± 20 BP (1609–1453 cal BC) (LZU19360), was excluded as it was regarded as old wood. It is unfortunate that no sample was obtained from the small-scale Layer 5, which represented a period when double-grooved bowl furnaces were sporadically used. It is therefore quite difficult to pin down the start boundary of Location 3, although the end is clear. A final sample was collected in the filling of a vestige at Location 9, dated 2450 ± 30 BP (754–412 cal BC) (Beta—460,903).

On the basis of these data, we can say that metallurgical activities began c. 1400 BC at LBH, and reached a peak c. 800–400 BC. The date ceiling of LBH is slightly later than the earliest bronze implements found on the Western Sichuan Plateau thus far (c. 1500 BC) (Tang & Miyamoto, 2013), and is contemporary with the earliest bronze or metallurgical implements on the Yunnan–Guizhou Plateau (c. 1400 BC) (Zhou, 2016), and just earlier than the upper limit of the Bronze Age in SEA (c. 1200 BC) (C. Higham & Cawte, 2021; C. Higham et al., 2015; C. Higham, T. Higham, Ciarla et al. 2011a; C. Higham, T. Higham & Kijngam 2011b; T. Higham et al., 2020). Therefore, a north-to-south diminishing chronological slope is evident (Lu, 2019).

The Patterns Revealed by the Longbohe (LBH) Site: The Upland Tradition

LBH provides us with new evidence for the progressive southward expansion of copper-base technologies from Southwest China into Southeast Asia (White, 1988). We suggest that some patterns of this production system can be described as an 'upland tradition' of Bronze Age metallurgical production in both regions.

The first metal specialists usually identified copper ores in upland locations. In addition to LBH, these include Tongshiling in Lingnan, Phu Lon in northeast Thailand and Vilabouly in Laos. Inselbergs in the Khao Wong Prachan Valley were being exploited by c. 1200 BC. These mines were linked to a smelting locale. The layout of smelting locales is vertical, as also seen at Liuchen and Luoxiu in the early Iron Age. Structures are located on hilltops. Smelting areas ringed by in-ground furnaces are found on the gentle slope near the top of the hill. Further downslope one encounters dumped smelting waste. Mines are found at the bottom of the hills, where lodes have been exposed by frequent running water and rain, making it easier to discover and exploit them.

Using in-ground furnaces to smelt is another significant feature of the 'upland tradition'. Sub-surface hearths with a lining and bowl shape were built on the sloping land. The lining is the foremost technical characteristic of these in-ground furnaces. In addition to those at Tongshiling, Liuchen and Luoxiu in Lingnan, such furnaces have been encountered at Dashan in Guizhou and Chongzipipo in Yunnan

(Dai & Zhang, 1998; Huang & Li, 2008; Meng, 2015; Yin, 1993; Zheng, 1990), and recently at Jicha in Yunnan (Fu et al., 2024). Before the discovery of LBH, these furnaces were often thought to be remnants of the base of shaft furnaces, but this now seems not to be the case. Such in-ground furnaces obviously played a crucial role in the Bronze Age of both USC and SEA.

Unique refractory technology is one of the technological cores of the 'upland tradition'. Refractory material, a mixture of quartz sand with clay, was applied to the inner side of the hearths and crucibles to improve the heat resistance and preservation. In addition to those at LBH, lined furnaces have also been found at Tongshiling, Guangxi (Qin, 1985). Lined crucibles were first identified at Phu Lon by Vernon and subsequently he identified the lining at Ban Chiang and other sites in northeast Thailand (Vernon, 1996, 2019). At Ban Na Di in the same region, crucibles were found in direct association with hearths for melting bronze prior to casting (Cawte, 2012). In addition, a piece of crucible fragment with sandy lining was found at Jicha, northwest Yunnan (Fu et al., 2024). Though we cannot say for sure whether this technology was a local innovation or an exotic introduction, the refractory material found in USC and MSEA seems to have a common technological source.

The use of stone tools is also a feature of the 'upland tradition', especially when compared to the Shang and later metallurgical sites of the 'Central Plains tradition', as characterized by directed management and the separation of smelting and casting, with shaft-furnace smelting and ceramic- and piece-mould casting. The metallurgical sites of the 'Central Plains tradition' approximately in the same period as LBH are represented by Tonglushan (mainly 1200–400 BC) in Hubei, where mining tools are mainly made of bronze or even iron (Huangshi, 1999). However, stone mining tools are more common in metallurgical sites of the 'upland tradition', such as LBH, as well as at the Jicha site in northwest Yunnan, Tonggushan site in Guizhou and Phu Lon in northeast Thailand (Fu et al., 2024; Pigott & Weisgerber, 1998; Xi & Zhu, 1987). Preference for stone tools in the Metal Age is unusual and might be related to the particular way in which production and distribution were organized in upland society.

The casting technology of the 'upland tradition' includes two characteristics: the use of ceramic or stone bivalve moulds and ceramic crucibles. Charles Higham and colleagues (C. Higham, T. Higham, Ciarla et al. 2011a) have reviewed the stone moulds found in USC. Ceramic moulds may be more common in MSEA, and the early ceramic moulds in the USC can only be found at Jicha and Xiaolongjingpo, the Hejiashan burial, the Fengqingdao cemetery and the LBH site in Yunnan (Dali, 2013; Wang, 1998; Yunnan, 2017). Both ceramic and stone moulds have been encountered in these five sites. Large ceramic crucibles were encountered at Tonggushan in Guizhou (Cheng, 1993; Liu & Xiong, 1993), at Vilabouly in Laos (Cadet et al., 2019, 2021; Tucci et al., 2014) and in the Khao Wong Prachan Valley in Central Thailand (Pigott, 2019); all have no lining and are of a contrasting shape. Many moulds were found in residential rather than metallurgical sites, indicating that the mastery of smelting and casting technique might have had a different penetration in upland society.

In the light of the materials detailed above, areas including the Western Sichuan Plateau, the Yunnan–Guizhou Plateau, Western Lingnan and MSEA should be ascribable to the 'upland tradition'. But these technological patterns do not rule out regional distinctions. Like the crucibles described above, the *tuyères* also display differences. Those unearthed in northwest Yunnan and southwest Sichuan are curved and decorated to resemble horse heads (Fu et al., 2024; Zhang, 2000), while the *tuyères* uncovered in Western Lingnan are no longer decorated like animals, although they retained the curved head (Qin, 1985; Sun et al., 1986). Interestingly, no *tuyères* are currently known from sites in MSEA.

The Route Along Which Metallurgy was Introduced: Longbohe as a Key Site

In the 1980s, Enzheng Tong suggested that in prehistory, northeast China and southwest China, on the rim of the Central Plains, had certain cultural elements in common, including microliths, stone tombs and stone constructions, which he characterized as typical of his 'crescent-shaped cultural-communication belt' (Hein, 2014; C. Higham., 2002 Tong, 1986) (Fig. 23). Tong surmised that a similar natural environment and contrasting ethnic identity facilitated the formation of this interaction belt (Tong, 1986). In the context of the Bronze Age, Tong pointed out that stone moulds and lost-wax casting, designs with animal themes and utilization of curved-bladed weapons were observed both in northeast and southwest China (Tong, 1986). These

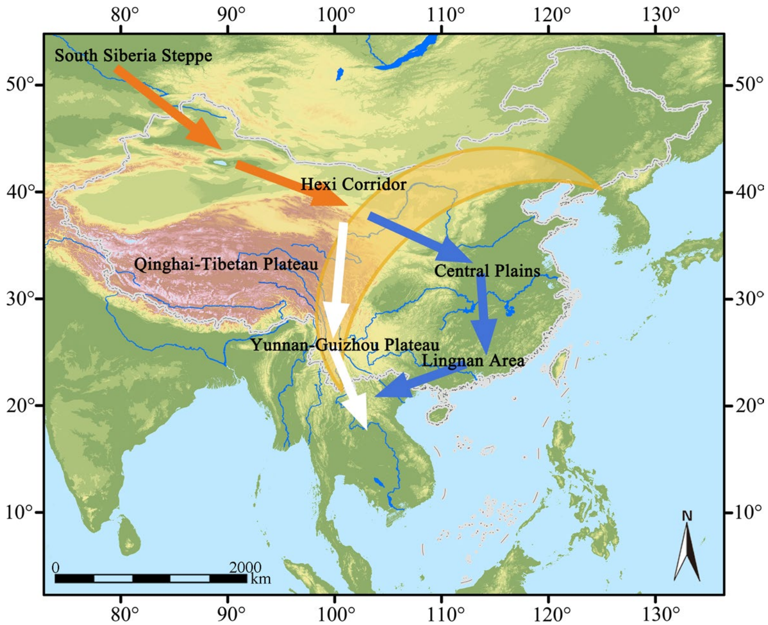

Fig. 23 Map showing Tong's Crescent Belt (yellow area); the probable route of the transmission of copper-base technology from the Steppe into northwest China (orange arrows); the hypothesized route of the 'long chronology' (white arrows) and the 'short chronology' (blue arrows)

similarities actually indicated the eastward and southward spread of metallurgy after it had entered northwest China. Tong was one of the first scholars to propose the possibility of a southward metallurgical spread via USC.

White and Hamilton also recognized this southward route (2009) (Fig. 23). They hypothesized that metalworkers—or the metalworking tradition—of the Seima-Turbino horizon, arrived via the Qijia culture, located in Gansu Province, northwest China, and might have infiltrated Sichuan along the south-flowing rivers, arriving in northwest Yunnan through the Western Sichuan Plateau. Then the immigrants, or the technology, diffused downstream along the rivers flowing through northwest Yunnan, finally reaching Ban Chiang in northeast Thailand by 2000–1800 BC. However, in the light of the new radiocarbon determinations from multiple sites in China, including Longbohe and Jicha, we place the early copper-base technology in the middle and late second millennium BC.

This later diffusion route involving Sichuan and Yunnan is supported by the horsehead-shaped *tuyères* unearthed at Dajing in Inner Mongolia, northeast China (a metallurgical site of the Xiajiadian culture, c. 1050–800 BC), and also at Hejiashan in Yunnan, southwest China (Wu, 1983; Zhang, 2000), which suggests that they may have shared a common technological origin, probably in northwest China. The information provided by LBH is also supportive of the 'upland route'. In terms of furnaces, those found at LBH are more similar in shape and structure to furnaces in the Bronze Age of the Eurasian Steppe (Koryakova & Epimakhov, 2014), although there is a large geographical gap, especially considering the contrasting above-ground shaft furnaces popular in the middle reaches of the Yangtze River during the Bronze Age (Lu & Hua, 1981). In-ground furnaces with a terraced layout similar to

Fig. 24 Map showing metallurgical similarities and their connections with the rivers

those at LBH were also found at Dajing (Wu, 1983). Pitted hammerstones—similar to those discovered at LBH—were mentioned in Tong's vision of the 'crescent-shaped cultural-communication belt', and also appeared at Dajing (Tong, 1986), perhaps representing the mining and processing tools in the same technological system as the in-ground furnace and the horsehead-shaped *tuyère*.

So by what route was metallurgy transmitted into MSEA? Longbohe provides relevant new data, sharing as it does some cultural elements with Bronze Age sites in northeast Thailand (Fig. 24). For example, oval stone hammers similar to those found at LBH were encountered at the metallurgical site of Jicha on the upper Mekong River (Fu et al., 2024) and the prehistoric copper-mining site of Phu Lon on the middle Mekong River (Pigott & Weisgerber, 1998). The lagged crucibles from LBH are virtually identical with those from Ban Non Wat, Phu Lon and Ban Chiang (Cawte, 2012; Vernon, 1996, 2019). How did these long-distance similarities emerge? A common source may be a relatively plausible explanation. Along with many major rivers that originate in or flow through Yunnan, the junction of the Red River and the Mekong River is located in northwest Yunnan (Pigott & Ciarla, 2007, Fig. 7). It is there that one encounters the arrival of copper technology at Haimenkou and related sites (Yao et al., 2020). The Shweli River links nodal Yunnan with the Irrawaddy catchment and the dry zone of central Myanmar. Also, the mining complex at Jicha on the bank of the upper Mekong River, one of the newest metallurgical sites excavated by the authors, corroborates the aforesaid hypothesis (Fu et al., 2024). The inexorable spread of this new technology finds its logical expression in the opening of the Longbohe copper mines from c. 1400 BC.

Conclusions

Longbohe is a Bronze Age copper production site that involved mining, smelting and casting. It dates between c. 1400 BC and 100 BC, yet metallurgical activities ceased around 400 BC. Its technological system includes: the mining and ore-processing technique composed of pitted hammerstones and ore-grinding stones; in-ground furnace construction; the refractory technique applied to the interior of furnaces and crucibles; the processing and production unit layout adjusted to hilly conditions; the continuously improved blowing technique using wooden/bamboo piston bellows to drive the smelt; and casting with lined crucibles and ceramic or stone moulds.

LBH provides an important case study for understanding the related metallurgical technology systems in USC and Southeast Asia. The southward expansion of metallurgy naturally began by prospecting for promising copper ore sources, which are always found in upland terrain. Mining and processing involved stone mauls and in-ground furnaces (mainly bowl furnaces) for smelting. Furnaces and crucibles were lined for increased refractoriness. Longbohe thus presents the same mining and smelting practices as have been identified at Vilabouly in Laos, Phu Lon and the Khao Wong Prachan Valley in Thailand, sites located 700–900 km to the south.

The location and chronology of LBH support the model of a transmission of metallurgical expertise from Yunnan into the Red River delta region, and beyond into wider Southeast Asia. The employment of in-ground furnaces and pitted hammerstones argue for an 'upland route' along which metallurgy arrived in USC from the eastern Eurasian Steppe via Northwest China and along the eastern Qinghai–Tibet Plateau. On the other hand, the similarities between LBH in the Red River Basin and Bronze Age sites in the Mekong River Basin also focus the technology source upstream along the rivers, that is in northwest Yunnan. In terms of chronology, the Yunnan–Guizhou Plateau, including LBH, had entered the Bronze Age of the region in 1600–1400 BC, while the sites at the end of the transmission route, such as Phùng Nguyên, Non Pa Wai, Ban Chiang and Ban Non Wat in the lower reaches of Red River or Mekong River, were later (C. Higham & Cawte, 2021; C. Higham et al., 2015; T. Higham et al., 2020; Pigott, 2019). While Longbohe supports the Red River as a major transmission route, it does not rule out other lines of communication followed by skilled metalworkers, including those from Central Yangtze to Lingnan and the Pearl River to Vietnam by following the coast.

Acknowledgements We are grateful to two anonymous reviewers for their constructive comments. We also thank the professional and excellent work of editors Prof. Timothy Taylor and Sarah Wright. We also appreciate Wang Hui from the Analytical & Testing Center of Sichuan University for her help with some of the analyses.

Funding This work was funded by the Ministry of Science and Technology of the People's Republic of China (2022FY101505), National Social Science Fund of China (15ZDB056), the National Natural Science Fund of China (T2350410495), Sichuan University (SKSYL2023-05 & 2035xd-02).

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

References

Cadet, M., Sayavongkhamdy, T., Souksavatdy, V., Luangkhoth, T., Dillmann, P., Cloquet, C., Vernet, J., Piccardo, P., Chang, N., Edgar, J., Foy, E., & Pryce, T. O. (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.

Cadet, M., Tereygeol, F., Sayavongkhamdy, T., Souksavatdy, V., Luangkhoth, T., Chang, N., Dillmann, P., & Pryce, T. O. (2021). Late prehistoric copper smelting in the Lao PDR: Experimental reconstruction based on the Vilabouly Complex evidence. *Journal of Archaeological Science: Reports, 37*, 102932.

Cawte, H. (2012). The crucibles and moulds. In C. F. W. Higham & A. Kijngam (Eds.), *The origins of the civilization of Angkor: Vol. 5. The Bronze Age* (pp. 458–485). Bangkok: Fine Arts Department.

Chang, K. (1980). *Early civilization in China: Shang civilization*. Yale University Press.

Cheng, X. (1993). The first trial excavation at Tonggushan site, Pu'an [普安铜鼓山遗址首次试掘]. In S. Xiong & X. Song (Eds.), *Forty years of field archaeology in Guizhou: 1953–1993 [贵州田野考古四十年]* (pp. 61–64). Guizhou Minzu Press. (In Chinese.).
Ciarla, R. (2007a). Rethinking Yuanlongpo: The case for technological links between the Lingnan (PRC) and central Thailand in the Bronze Age. *East and West, 57*(1), 305–328.
Ciarla, R. (2007b). 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.
Ciarla, R. (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.
Ciarla, R. (2013). Interazioni culturali e tecnologiche tra Cina meridionale e Sudest asiatico continentale tra la fine del II millennio a.C. e l'inizio del I millennio a.C.: La dispersione meridionale della tecnologia del rame/bronzo. PhD dissertation, Universita Ca'Foscari Venezia.
Dai, Z., & Zhang, Z. (1998). A brief excavation report of Chongzipipo smelting site, Gejiu [个旧冲子皮坡冶炼遗址发掘简报]. *Yunnan Cultural Relics, 1*, 8–11. (In Chinese.).
Dali, M. (2013). *Historical relic collection at Dali Bai Nationality Autonomous Prefecture Museum [大理白族自治州博物馆馆藏文物精粹]*. Yunnan People's Publishing House. (In Chinese.).
Evrard, O., Pryce, T. O., Sprenger, G., & Chiemsisouraj, C. (2016). Of myths and metallurgy: Archaeological and ethnological approaches to upland iron production in 9th century AD northwest Laos. *Journal of Southeast Asian Studies, 47*(1), 109–140.
Falkenhausen, L. (2006). Chinese society in the age of Confucius (1000–250 BC): The archaeological evidence. *Cotsen Institute of Archaeology Press*. https://doi.org/10.2307/j.ctvdmwwt6
Fu, J., Li, Y., Hu, C., Pan, G., Yang, X., He, Q., Higham, C., & Li, Y. (2024). Southbound transmission of metallurgy: New excavations at Jicha in the Hengduan Mountains Yunnan. *Antiquity*. https://doi.org/10.15184/aqy.2024.70
Hein, A. (2014). The 'crescent-shaped cultural-communication belt': Tong Enzheng's model in retrospect: An examination of methodological, theoretical and material concerns of long-distance interactions in East Asia. *British Archaeological Reports*. https://doi.org/10.30861/9781407313238
Higham, C. (1996). *The Bronze Age of Southeast Asia*. Cambridge University Press.
Higham, C. (2002). *Early cultures of mainland Southeast Asia*. River Books.
Higham, C. (2022). Stasis or stimulus? Exotic materials and social display in Southeast Asia: Response to Pfaffenberger. *Advances in Archaeomaterials, 3*(1), 34–43.
Higham, C., & Cawte, H. (2021). Bronze metallurgy in Southeast Asia with particular reference to northeast Thailand. *Journal of World Prehistory, 34*, 1–46.
Higham, C., Douka, K., & Higham, T. (2015). A new chronology for the Bronze Age of northeastern Thailand and its implications for Southeast Asian prehistory. *PLoS ONE, 10*(9), e0137542.
Higham, C., & Higham, T. (2009). A new chronological framework for prehistoric Southeast Asia, based on a Bayesian model from Ban Non Wat. *Antiquity, 83*(319), 125–144.
Higham, C., Higham, T., Ciarla, R., Douka, K., Kijngam, A., & Rispoli, F. (2011a). The origins of the Bronze Age of Southeast Asia. *Journal of World Prehistory, 24*(4), 227–274.
Higham, C., Higham, T., & Kijngam, A. (2011b). Cutting a Gordian Knot: The Bronze Age of Southeast Asia: Origins, timing and impact. *Antiquity, 85*(328), 583–598.
Higham, C., & Kijngam, A. (2012). *The origins of the civilization of Angkor: Vol. 5. The excavation of Ban Non Wat: The Bronze Age*. Bangkok: Fine Arts Department of Thailand.
Higham, T., Weiss, A. D., Higham, C., Ramsey, C. B., d'Alpoim Guedes, J., Hanson, S., Weber, S., Rispoli, F., Ciarla, R., Pryce, T. O., & Pigott, V. C. (2020). A prehistoric copper-production centre in central Thailand: Its dating and wider implications. *Antiquity, 94*(376), 948–965.
Hu, S., (2016). Dian Kingdom smelting and casting site at Jiangedi, Ma'e village, Chenggong [呈贡麻莪村尖阁地滇国冶铸遗址]. In Yunnan Cultural Relics and Archaeology Institute (Eds.), *Anthology of archaeological excavation reports on Shizhaishan Culture* [石寨山文化考古发掘报告集] (pp. 720–725). Beijing: Science Press. (In Chinese.)
Huang, Q., & Li, Y. (2008). Investigation on ancient iron smelting sites in Guigang County of Guangxi [广西贵港地区早期冶铁遗址初步考察]. *Nonferrous Metals Engineering, 1*, 137–142. (In Chinese with English abstract.).
Huangshi, M. (1999). *Ancient mining and smelting site at Tonglushan [铜绿山古矿冶遗址]*. Cultural Relics Press. (In Chinese with English abstract.).
Koryakova, L., & Epimakhov, A. V., (2014). *The Urals and western Siberia in the Bronze and Iron Ages*. (pp. 29–54). Cambridge University Press. Chinese Translation.

Li, X., & Han, R. (2011). *Research on metal technology of ancient Dian kingdom [古滇国金属技术研究]*. Science Press. (In Chinese.).

Li, Y., Huang, Q., & Wan, F. (2007). Preliminary investigation on ancient copper smelting sites in Beiliu county and Rongxian county of Guangxi [广西北流铜石岭容县西山冶铜遗址初步考察]. *Nonferrous Metals Engineering, 4*, 175–179. (In Chinese with English abstract.).

Lin, X., & Zhang, Z. (1994). Excavation of Han dynasty smelting and casting site in Dongping, Xichang, Sichuan [四川西昌东坪汉代冶铸遗址的发掘]. *Cultural Relics, 9*, 29–40. (In Chinese.).

Liu, E., & Xiong, S. (1993). Excavation report on Tonggushan site, Pu'an [普安铜鼓山遗址发掘报告]. In S. Xiong & X. Song (Eds.), *Forty years of field archaeology in Guizhou: 1953–1993 [贵州田野考古四十年]* (pp. 65–87). Guizhou Minzu Press. (In Chinese.).

Liu, R., Pollard, M., Rawson, J., Tang, X., Bray, P., & Zhang, C. (2019). Panlongcheng, Zhengzhou and the movement of metal in early Bronze Age China. *Journal of World Prehistory, 32*, 393–428.

Liu, S., & Zhang, Z. (1990). Investigation of Han dynasty copper smelting site in Dongping, Xichang, Sichuan [四川西昌市东坪村汉代炼铜遗址的调查]. *Archaeology, 12*, 1069–1075. (In Chinese.).

Lu, B., & Hua, J. (1981). Reconstructive research on the spring and autumn period copper-smelting shaft furnace at Tonglushan site [铜绿山春秋炼铜竖炉的复原研究]. *Cultural Relics, 8*, 40–45. (In Chinese.).

Lu, H. (2019). Mountain corridor or costal route? Rethinking transmission of early bronze technology to Southeast Asia. Presentation at the meeting on 'Origin and diffusion of metallurgy in Southwest China and Southeast Asia', Qionglai, Sichuan.

Meng, Z. (2015). Iron smelting site from Han Dynasty to Six Dynasties in Liuzhuoling, Pingnan, Guangxi autonomous region [广西壮族自治区平南六浊岭汉至六朝冶铁遗址]. In CAS (Eds.), *Yearbook of archaeology in China (2014)* [中国考古学年鉴 (2014)] (pp. 278). China Social Science Press. (In Chinese.)

Natapintu, S. (1988). Current research on ancient copper-base metallurgy in Thailand. In P. Charoenwongsa & B. Bronson (Eds.), *Prehistoric studies: The Stone and Metal Ages in Thailand* (pp. 107–124). Thai Antiquity Working Group.

Peng, C. (2008). *Bronze Age of the Yunnan-Guizhou Plateau [云贵高原的青铜时代]*. Guangxi Science & Technology Publishing House. (In Chinese with English abstract.).

Pigott, V. C. (1988a). Prehistoric copper mining in the context of emerging community craft specialization in Northeast Thailand. In A. B. Knapp, V. C. Pigott, & W. H. Eugenia (Eds.), *Social approaches to an industrial past: The archaeology and anthropology of mining* (pp. 205–225). Routledge.

Pigott, V. C. (1988b). The Thailand archaeometallurgy project. *Journal of Metals, 40*(1), 36–37.

Pigott, V. C. (2019). Prehistoric copper mining and smelting in Southeast Asia: Evidence from Thailand and Laos. In J. C. White & E. G. Hamilton (Eds.), *Ban Chiang Northeast Thailand: Vol. 2C* (pp. 5–56). University of Pennsylvania Press.

Pigott, V. C., & Ciarla, R. (2007). On the origins of metallurgy in prehistoric Southeast Asia: The view from Thailand. In S. L. Niece, D. Hook, & P. Craddock (Eds.), *Metals and mines: Studies in archaeometallurgy* (pp. 76–88). British Museum.

Pigott, V. C., & Weisgerber, G. (1998). Mining archaeology in geological context: The prehistoric copper mining complex at Phu Lon, Nong Khai province, northeast Thailand. In T. Rehren, A. Hauptmann, & J. D. Muhly (Eds.), *Metallurgica antiqua: In honour of Hans-Gert Bachmann and Robert Maddin* (pp. 135–162). Deutsches Bergbau-Museum.

Pradier, P., Kyaw, A., Win, T., Willis, A., Favereau, A., Valentin, F., & Pryce, T. (2019). Pratiques funéraires et dynamique spatiale à Oakaie 1: Une nécropole à la transition du Néolithique à l'Âge du Bronze au Myanmar (Birmanie). *Bulletin de l'École française d'Extrême-Orient, 116*, 539–560.

Pryce, T. O. (2014). Metallurgy in southeast Asia. *Encyclopaedia of the History of Science, Technology, and Medicine in Non-Western Cultures*. https://doi.org/10.1007/978-94-007-3934-5_10178-1

Pryce, T. O. (2018). Initiating discourse on the (multi?) directionality of the Mainland Southeast Asian Bronze Age transition. In J.-Y. Choi & J.-S. Park (Eds.), *Proceedings of the Ninth International Conference on the Beginnings of the Use of Metals and Alloys BUMA-IX: Messages from the History of Metals to the Future Metal Age* (pp. 160–175). Busan, South Korea.

Pryce, T. O., Bevan, A. H., Ciarla, R., Rispoli, F., Castillo, C., Hassett, B., & Malakie, J. L. (2011). Intensive archaeological survey in Southeast Asia: Methodological and metallurgical insights from Khao Sai On, central Thailand. *Asian Perspectives, 50*, 1–2.

Pryce, T. O., Cadet, M., Allard, F., Kim, N. C., Hiep, T. H., Lam, T. M. D., Lam, W., & Foy, E. (2022). Copper-base metal supply during the northern Vietnamese Bronze and Iron Ages: Metallographic, elemental, and lead isotope data from Dai Trach, Thành Dên, Gò Mun, and Xuân Lâp. *Archaeological and Anthropological Sciences, 14*(1), 16.

Pryce, T. O., Kyaw, A. A., Kyaw, M. M., Win, T. T., Win, T. T., Win, K. H., Mon, M. M., Aye, M. M., Htay, S. H., Mar, A. A., Bellina, B., Bentley, R. A., Champion, L., Colonna, C., Cook, A. J., Favereau, A., Fuller, D. Q., Georjon, C., Higham, C., & Zazzo, A. (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*, 690–708.

Pryce, T. O., & Pigott, V. (2022). Prehistoric copper production and exchange in Southeast Asia. In C. F. W. Higham & N. Kim (Eds.), *The Oxford handbook of early Southeast Asia* (pp. 431–447). Oxford University Press.

Pryce, T. O., Pigott, V. C., Martinón-Torres, M., & Rehren, T. (2010). Prehistoric copper production and technological reproduction in the Khao Wong Prachan valley of Central Thailand. *Archaeological and Anthropological Sciences, 2*(4), 237–264.

Qin, C. (1985). Trial excavation on Han Dynasty copper-smelting Tongshiling site, Beiliu, Guangxi [广西北流铜石岭汉代冶铜遗址的试掘]. *Archaeology, 5*, 403–410. (In Chinese with English abstract.).

Ramsey, B. C. (2009). Bayesian analysis of radiocarbon dates. *Radiocarbon, 51*(1), 337–360.

Reimer, P., Austin, W., Bard, E., Bayliss, A., Blackwell, P., Bronk Ramsey, C., Butzin, M., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Hajdas, I., Heaton, T. J., Hogg, A. G., Hughen, K. A., Kromer, B., Manning, S. W., Muscheler, R., & Talamo, S. (2020). The IntCal20 northern hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon, 62*(4), 725–757.

Ren, J., & Hu, C. (2006). Brief report of the second excavation on Dongping site, Xichang, Sichuan [凉山州西昌市东坪遗址第二次发掘简报]. *Sichuan Cultural Relics, 1*, 21–26. (In Chinese with English abstract.).

Rispoli, F., Ciarla, R., & Pigott, V. C. (2013). Establishing the prehistoric cultural sequence for the Lopburi region, central Thailand. *Journal of World Prehistory, 26*(2), 101–171.

Sichuan, P. I. C. R. A., Shaanxi, P. I. A., & Vietnam, N. M. H. (2016). *Nghia Lap of Vietnam: Report on the excavation of remains of Phung Nguyen culture*. Culture Relics Press (In Chinese and English.).

Song, Z. (2003). *Dacun, E'ya: A huge living fossil of society [*俄亚大村*:* 一块巨大的社会活化石*]*. Sichuan People's Publishing House. (In Chinese.).

Sun, S., Liu, Y., & Tang, S. (1986). Investigation and research on copper-smelting Tongshiling site, Beiliu, Guangxi [广西北流县铜石岭冶铜遗址的调查研究]. *Studies in the History of Natural Sciences, 3*, 266–273. (In Chinese with English abstract.).

Tang, F., & Miyamoto, K. (2013). A brief excavation report of the stone-constructed tombs at Yan'erlong, Luhuo, Sichuan [四川炉霍县宴尔龙石棺葬墓地发掘简报]. *Sichuan Cultural Relics, 3*, 3–14. (In Chinese with English abstract.).

Tong, E. (1986). Discussion on the 'crescent-shaped cultural-communication belt' on the border from Northeast China to Southeast China [试论我国从东北至西南的边地半月形文化传播带]. In *Treatises on archaeology and cultural* [文物与考古论集] (pp. 17–43). Beijing: Cultural Relics Press. (In Chinese with English abstract.)

Tucci, A., Sayavongkhamdy, T., Chang, N., & Souksavatdy, V. (2014). Ancient copper mining in Laos: Heterarchies, incipient states or post-state anarchists. *Journal of Anthropology and Archaeology, 2*(2), 1–15.

Vernon, W. W. (1996). The crucible in copper/bronze production at prehistoric Phu Lon, Northeast Thailand: Analyses and interpretation. In F. D. Bulbeck & N. Barnard (Eds.), *Ancient Chinese and Southeast Asian Bronze Age cultures* (Vol. 2, pp. 809–820). SMC Publishing.

Vernon, W. W., White, J. C., & Hamilton, E. G. (2019). Metal product manufacturing evidence: Crucibles, molds, and slag. In J. C. White & E. G. Hamilton (Eds.), *Ban Chiang, Northeast Thailand* (Vol. 2B, pp. 103–124). University of Pennsylvania Press.

Wan, Y. (2018). Metal on the borderline: Mining and smelting site at Longbohe, Jinping county [边境之金——金平龙脖河矿冶遗址]. *Popular Archaeology, 7*, 54–61. (In Chinese.).

Wang, D. (1998). A tentative discussion of the casting mold and casting technology of Bronze Age in Yunnan [云南出土青铜时代铸范及其铸造技术初论]. In Yunnan Cultural Relics and Archaeology Institute (Ed.), *Collected works on Yunnan cultural relics and archaeology* [云南考古文集] (pp. 114–128). Kunming: Yunnan Ethnic Publishing House. (In Chinese.)

White, J. C. (1988). Early East Asian metallurgy: The southern tradition. In R. Maddin (Ed.), *The beginning of the use of metals and alloys: Papers from the Second International Conference on the Beginning of the Use of Metals and Alloys* (pp. 175–181). MIT Press.
White, J. C. (2008). Dating early bronze at Ban Chiang, Thailand. In J.-P. Pautreau, A. S. Coupey, V. Zeitoun, & E. Rambault (Eds.), *From Homo erectus to the living traditions: Choice of papers from the 11th International Conference of the European Association of Southeast Asian Archaeologists* (pp. 91–104). Bougon.
White, J. C., & Hamilton, E. G. (2009). The transmission of early bronze technology to Thailand: New perspectives. *Journal of World Prehistory, 22*(4), 357–397.
White, J. C., & Hamilton, E. G. (2018). *Ban Chiang, Northeast Thailand: Vol. 2A. Background to the study of the metal remains*. University of Pennsylvania Press.
White, J. C., & Hamilton, E. G. (2019). *Ban Chiang, Northeast Thailand: Vol. 2C. The metal remains in regional context*. University of Pennsylvania Press.
Wu, J. (1983). Excavation report on ancient copper mine site at Dajing, Lingxi, Liaoning in 1976 [辽宁林西县大井古铜矿1976年试掘简报]. *Cultural Relics Resource Series, 7*, 138–146. (In Chinese.).
Wu, Q., & Ma, X. (2017). *Mine pictures in South Yunnan [滇南矿厂图略]*. Southwest Jiaotong University Press. (In Chinese.).
Xi, K., & Zhu, S. (1987). Brief excavation report on Wayao site, Bijie, Guizhou [贵州毕节瓦窑遗址发掘简报]. *Archaeology, 4*, 303–310. (In Chinese.).
Xiao, M., & Wan, Y. (2013). Excavation on the bronze age burials at Mayutian, Gejiu, Yunnan [云南个旧市麻玉田青铜时代墓葬的发掘]. *Archaeology, 3*, 15–25. (In Chinese with English abstract.).
Xichang, M. (1977). 'Huoquan' coin moulds and ingots found in Xichang, Sichuan [四川西昌发现货泉钱范和铜锭]. *Archaeology, 4*, 284–285. (In Chinese.).
Yang, F. (2006). Archaeological excavation report of the Xinjie–Hekou highway construction area [新街–河口公路遗址考古发掘报告]. In Yunnan Cultural Relics and Archaeology Institute (Ed.), *Anthology of archaeological reports on Yunnan* [云南考古报告集 (之二)] (Vol. 2, pp. 142–152). Kunming: Yunnan Science and Technology Press. (In Chinese.).
Yang, Y. (2011). *A study on archaeological cultures in the Yunnan-Guizhou Plateau from the Warring States Period to Han Dynasties [战国秦汉时期云贵高原考古学文化研究]*. Science Press. (In Chinese with English abstract.).
Yao, A. (2016). The ancient highlands of southwest China: From the Bronze Age to the Han Empire. *Oxford University Press*. https://doi.org/10.1093/acprof:oso/9780199367344.001.0001
Yao, A., Darre, V., Jiang, Z., Lam, W., & Yang, W. (2020). Bridging the time gap in the Bronze Age of Southeast Asia and Southwest China. *Archaeological Research in Asia*, 22, Article 100189.
Yin, Q. (1993). Ancient copper smelting site in Dashan [大山古代冶铜遗址]. In S. F. Xiong & X. S. Song (Eds.), *Forty years of field archaeology in Guizhou*: 1953–1993 [贵州田野考古四十年] (pp. 186). Guiyang: Guizhou Minzu Press. (In Chinese.)
Yuan, Y., & Li, X. (2018). *Technical study of Bronze Age metal objects from the Erhai region in Yunnan [云南洱海地区出土青铜时代金属器的技术研究]*. China Social Sciences Press. (In Chinese with English abstract.).
Yule, P. (1997). The copper hoards of Northern India. *Expedition, 39*(1), 22–32.
Yunnan, C. R. A. I. (2017). *Archaeological investigation reports on western border of Yunnan* [云南西部边境地区考古调查报告]. Shanghai Classics Publishing House. (In Chinese.).
Zhang, M., Li, Y., Xiong, Z., Li, S., & Li, Y. (2020). Iron production and trading in Lingnan during the Qin and Han Dynasties. *Antiquity*. https://doi.org/10.15184/aqy.2020.1
Zhang, Z. (2000). Stone, ceramic moulds and copperware unearthed at Hejiashan, Midu, Yunnan [云南弥渡合家山出土古代石、陶范和青铜器]. *Cultural Relics, 10*, 39–49. (In Chinese.).
Zheng, C. (1990). Iron smelting site in Han Dynasty at Liuchen, Pingnan [平南六陈汉代冶铁遗址]. In China Archaeology Society (Ed.), *Yearbook of archaeology in China (1989)* [中国考古学年鉴 (1989)] (pp. 236–237). Beijing: Cultural Relics Press. (In Chinese.)
Zhou, Z. (2016). A rustic opinion on the Bronze Age of southwest China [中国西南早期青铜时代刍议]. *Chengdu Archaeological Researches, 3*, 127–145. (In Chinese.).
Zou, G., Meng, Z., Li, Y., Huang, Q., & Cui, C. (2022). From bowl furnaces to small shaft furnaces: New evidence from ancient bloomery iron smelting site at Liuzhuoling in Guangxi, Southern China, ca. 400 to 700 AD. *Archaeological and Anthropological Sciences, 14*(3), 54.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.