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Contents

Cover Illustration: In this issue Bryan Earl continues his investigation into tin melting in the West of England. From time to time he mentions furnaces depicted in Agricola (De Re Metallica) and in Book IX (page 419 in the Hoover edition) there is a drawing showing a small furnace used by the Lusitanians (ancient Lusitania comprised Portugal and parts of Spain) for melting tin from tin-stone.

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Ancient Chinese copper smelting, sixth century BC: Recent excavations and simulation experiments

~~Edited and translated by~~ D B Wagner

Excavations at the ancient copper-mine site at Tonglüshan in Daye County, Hubei, have in recent years produced a great wealth of new material concerning ancient Chinese mining and smelting techniques. The present article describes recent work on ten copper-smelting shaft furnaces found here.

The mine site

Daye has long been an important site of iron and copper production. The Swedish geologist F.R. Tegengren visited the area in 1915 and saw "ruins of old smelters and vast heaps of slag", which he estimated at

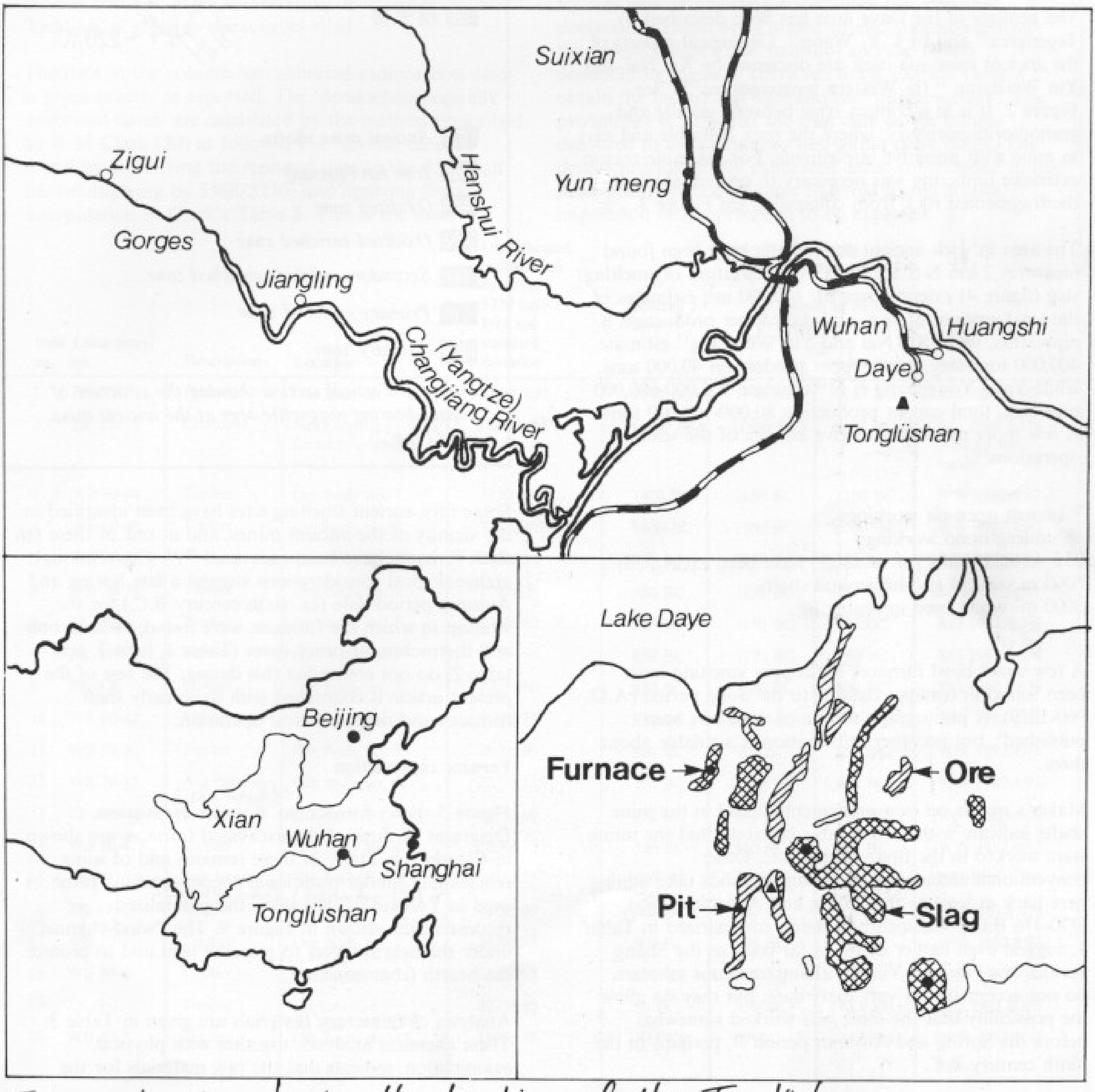


Figure 1: Map showing the location of the Tonglüshan mine site (3, p.12).

several hundred thousand tons[33]. In modern times Daye has been better known for its iron production, and Tegengren, noting that the ancient slag contains as much as 51.5% iron, concluded that the ancient smelting methods were fantastically inefficient. Modern work shows that the slag is actually from copper smelting, fluxed with iron oxides.

The location of Tonglüshan can be seen on the map, Figure 1. Modern open-pit mining operations began here in 1965. Numerous ancient mine shafts were discovered, but these seem to have been ignored until the discovery of a bronze axehead in 1973 made it clear that the shafts were much more ancient than had been thought. Excavations were undertaken by the Hubei Provincial Museum in 1974 and by the Institute of Archaeology, Chinese Academy of Social Sciences, in 1979-80.

The geology of the Daye area has been described by Tegengren[33] and by C.Y. Wang[37]. Geological aspects of the ancient mine site itself are discussed by Xia Nai and Yin Weizhang [11] (in Western languages see[1],[4]). See Figure 2. It is at a contact zone between granite and granodiorite-porphyry, where the rock is friable and easy to mine with primitive implements. For the same reason extensive timbering was necessary to prevent shafts in the fragmented rock from collapsing; see Figure 3.

The area in which ancient mine shafts have been found measures 2 km N-S x 1 km E-W. A stratum of smelting slag (figure 4) extends over ca. 140,000 m²; estimates of the total amount of slag, and the copper production it represents, vary. Xia Nai and Yin Weizhang[11] estimate 400,000 tons slag, total copper production 40,000 tons, while Yang Yongguang et al[12] estimate 500,000-600,000 tons slag, total copper production 80,000-100,000 tons. A few more numbers can give an idea of the scale of operations[12].

7 ancient open-pit workings
18 underground workings
252 vertical shafts (of which 93 have been excavated)
8000 m vertical and horizontal shafts
3000 m³ wood used in timbering

A few small bowl furnaces for copper smelting have been found in contexts datable to the Song period (A.D. 960-1279). A photograph of one of these has been published[3], but no other information is available about them.

Maker's marks on iron implements found in the mine shafts indicate with considerable certainty that the mines were worked in the first century B.C. Other conventional archaeological dating methods take mining here back at least to the Spring and Autumn period (770-476 B.C.). Radiocarbon dates, summarized in Table 1, suggest even earlier dates, as far back as the Shang period. Xia Nai and Yin Weizhang, cautious scholars, do not accept such a very early date, but they do allow the possibility that the mine was worked somewhat before the Spring and Autumn period [11], perhaps in the ninth century B.C.

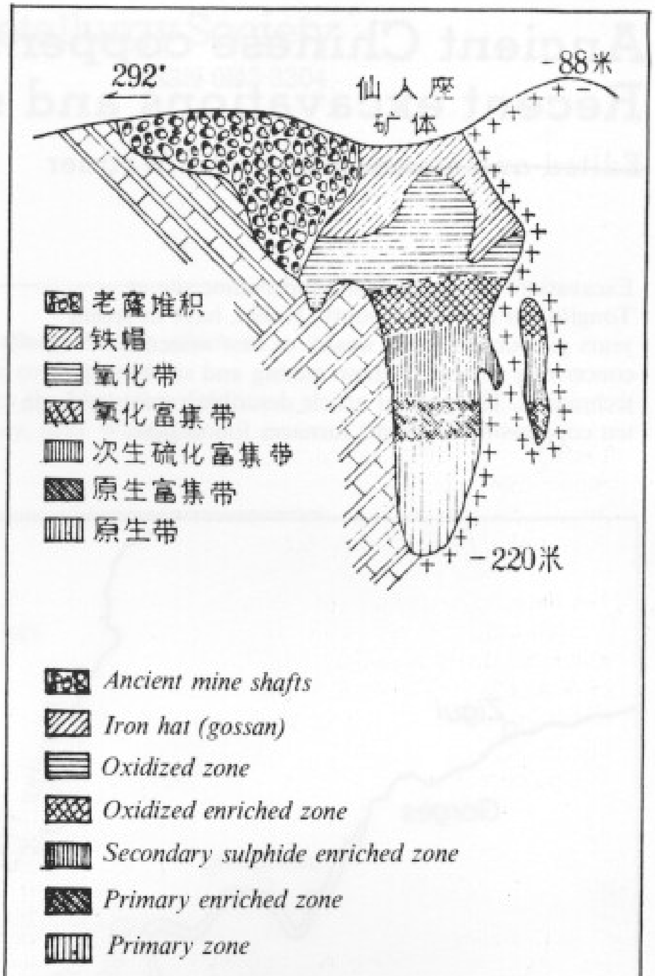


Figure 2. Vertical section showing the structure of copper-bearing magnetite ores at the ancient mine site (11, p 2).

Some fifty ancient smelting sites have been identified in the vicinity of the ancient mines, and at one of these ten shaft furnaces have been excavated [20],[11]. Conventional archaeological considerations suggest a late Spring and Autumn period date (ca. sixth century B.C.) for the stratum in which the furnaces were found; radiocarbon and thermoluminescence dates (Table 1, item 2, and table 2) do not contradict this dating. The rest of the present article is concerned with these early shaft furnaces and their technical operation.

Furnace construction

Figure 5 shows furnace no. 6 under excavation. Diagrams of three of the excavated furnaces are shown in Figures 6-8. Study of these remains and of some remarkably similar traditional copper-smelting furnaces used in Yunnan in 1958 gives the generalized reconstruction shown in Figure 9. The "wind-channel" under the hearth serves to preserve heat and to protect the hearth from moisture.

Analyses of refractory materials are given in Table 3. These chemical analyses, together with physical examination, indicate that the raw materials for the refractories were: kaolin (china clay); a local red clay whose principal constituents are kaolinite and iron oxides; pieces of iron ore; iron-ore sand (sieve tailings); quartz sand; and stones. For the different parts of the furnace different mixtures of these materials were used. For example the base was made of a mixture of red clay, stones, pieces of iron ore, and iron-ore sand, while the furnace lining was made of kaolin and quartz sand.

Furnace charge

The principal ore minerals found in the ancient workings at Tonglüshan are[22,21]:

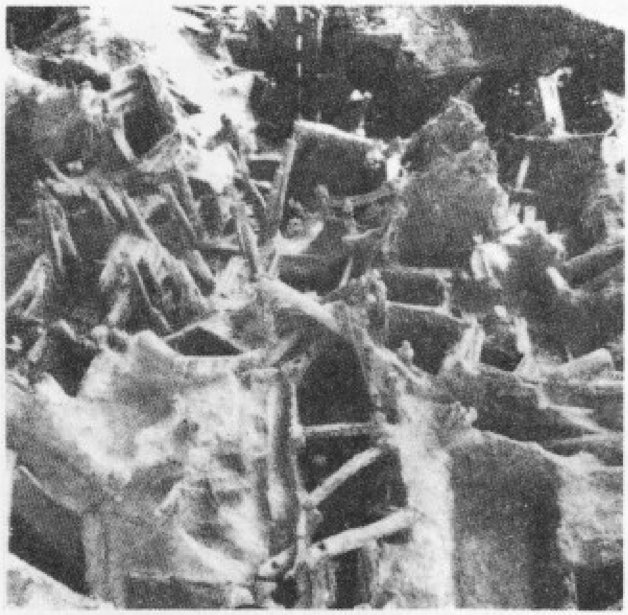
chrysocolla, $CuSiO_3.2H_2O$	andradite, $3CaO.Fe_2O_3.3SiO_2$,
malachite, $CuCO_3.Cu(OH)_2$	$Cu_3(AlSi_3O_{10})(OH)_2.nH_2O$
azurite, $2CuCO_3.Cu(OH)_2$	native copper, Cu
magnetite, Fe_3O_4	cuprite, Cu_2O
haematite, Fe_2O_3	tenorite, CuO

Table 1 Available radiocarbon dates from the ancient copper-mine site at Tonglüshan. Sources are indicated in the last column. More information on 'description' and 'location' is given in the sources cited.

The data in the column 'uncalibrated radiocarbon date' is given exactly as reported. The 'dendochonologically calibrated dates' are calculated by the method prescribed by R M Clark (30) as follows. The 'central date' is found by converting the reported date to the 5568 half-life (multiplying by 5568/5730) and applying linear interpolation in Clark's Table 8. This is the most probable date for the sample. The reported standard deviation is adjusted upward to account for other error sources besides counting error; twice this standard deviation is respectively added to and subtracted from the reported date (5568 half-life) and the results dendochronologically corrected using Clark's Table 8 to obtain the 'maximum age' and the 'minimum age'. The probability is 95% that the true date of the sample delivered to the laboratory lies within these limits. The dendochronologically calibrated dates are rounded to the nearest multiple of 50 years to avoid giving a false impression of the precision to be expected.

Item no.	Laboratory no.	Description	Location	Uncalibrated radiocarbon date (bp, 5730 half-life) and standard deviation	Dendochronologically calibrated date: central date	limits at 95% confidence level: max. age	min. age	Notes
1	**ZK-758**	**Timber**	**Ore body no. 7**	**3260±100**	1500 BC	1750 BC	1250 BC	KG 1981.4:367
2	ZK-559	Charcoal	Near smelting furnace, ore body no. 11	(3205±400)	(1450 BC)	(2500 BC)	(450 BC)	KG 1980.4:376 'Sample too small'
3	WB 80-44	Timber	Ore body no. 7	3150±80	1400 BC	1650 BC	1100 BC	WW 1982.4:92
4	WB 80-40	Timber	Ore body no. 7	3140±80	1400 BC	1600 BC	1050 BC	WW 1982.4:92
5	WB 80-39	Timber	Ore body no. 7	2810±80	950 BC	1250 BC	750 BC	WW 1982.4:92
6	WB 79-35	Timber	Ore body no. 7	2795±75	950 BC	1250 BC	750 BC	WW 1982.4:91
7	ZK-560	Timber	Ore body no. 7	2735±80	900 BC	1150 BC	550 BC	KG 1980.4:376
8	ZK-877	Timber	Ore body no. 7	2720±80	850 BC	1150 BC	550 BC	KG 1982.6:659
9	ZK-876	Timber	Ore body no. 7	2705±80	850 BC	1100 BC	500 BC	KG 1982.6:659
10	WB 80-42	Timber	Ore body no. 7	2680±75	850 BC	1000 BC	550 BC	WW 1982.4:92
11	WB 79-36	Timber	Ore body no. 7	2600±80	800 BC	950 BC	450 BC	WW 1982.4:91
12	WB 79-37	Axe handle (iron head)	Ore body no. 7	2575±135	750 BC	1000 BC	400 BC	WW 1982.4:91
13	ZK-878	Timber	Ore body no. 7	2575±80	750 BC	900 BC	450 BC	KG 1982.6:659
14	WB 80-41	Timber	Ore body no. 4	2500±75	550 BC	850 BC	400 BC	WW 1982.4:92
15	ZK-297	Axe handle (bronze head)	Ore body no. II (typo for 11?)	2485±75	500 BC	850 BC	400 BC	KG 1977.3:202-3
16	ZK-879	Timber	Ore body no. 7	2475±80	500 BC	850 BC	400 BC	KG 1982.6.659
17	WB 80-43	Timber	Ore body no. 7	2470±75	500 BC	800 BC	400 BC	WW 1982.4:92
18	WB 80-6	Timber	Ore body no. 7	2430±65	450 BC	800 BC	250 BC	WW 1982.4:92
19	ZK-561	Timber	Exploration line no. 24	2075±80	50 BC	350 BC	AD 200	KG 1981.4:367
20	WB 80-7	Timber	Ore body no. 7	1905±75	AD 200	50 BC	AD 300	WW 1982.4:92

1. 一组完整的井巷



2. 采掘面上纵横交错的古巷道

Figure 3. Ancient mine shafts under excavation (11, plate 2.1-2).

The ancient workings are all in the oxidized zone; therefore sulphide ores were not encountered. Chemical analyses of some ore samples are given in Table 4. (More analyses of iron ores are given by Tegengren[33].) A basketful of rich malachite ore was found in the mine (photograph in 3) so the especial value of these ores was apparently recognised. However broken-up chunks of leaner ore, diameter 3-4 cm, were found in pits near furnace no. 10. It is apparent that a mix of ores of different categories was charged.

Table 2 Thermoluminescence dates for refractories from furnaces (17, p. 550; cf. 18)

sample no.	location	age years	laboratory error years
TK11-1	inner wall, furnace no. 1	1830	±210
TK11-2	do.	2447	±240
TK11-3	do.	2278	±205
TK12	base, furnace no. 1	2374	±142
TK14-1	wall, furnace no. 2	1877	±153
TK14-2	do.	1769	±162
TK14-3	do.	1913	±189
TK17	wall, furnace no. 3	2856	±295
TK67	wall, furnace no. 10	3014	±320
TK68	tapping arch, furnace no. 10	2895	±305

Limestone is widely distributed in the vicinity, and in the simulation experiments (described below) a limestone flux was used. There is, however, no evidence that limestone was charged in the ancient furnaces. An analysis of the local limestone was published by C.Y. Wang in 1917[37]:

SiO_2	$Al_2O_3Fe_2O_3$	CaO	MgO	sp.gr.
3.14	1.14	52.63	0.92	2.71

(thus $CaCO_3$ 93.86%, total 99.06%).

There is no doubt that the fuel used was charcoal. No analyses have been published for the charcoal found on the site.

Furnace output

Table 5 gives analyses of two pieces of raw copper found in the ancient furnaces. These should be closely representative of the actual product of the furnaces. The copper ingot analysed in Table 6 was not found in a dateable context, but it may very well be from the same time as the furnaces. The axehead analysed in Table 6 was found in an ancient mine shaft, so it is likely to be of the same time; the relatively high iron content suggests that it may have been cast from the locally-produced copper.

Three reports of slag analyses are given in Tables 7-9. It can be seen that some rows in each table are also found in one or both of the others, but that some rows in each table are unique. A few typographical errors (none of which affects the order of magnitude) can be detected. To these may be added Tegengren's analysis of a single slag sample[13]:

Silica	23.63%	
Ferrous iron oxide	60.00% }	Metallic iron 51.5%
Ferric iron oxide	6.90% }	
Phosphoric acid	0.33%	

"These items make up a total of about 91%; the remaining 9% consist of lime, alumina, magnesia and manganese."

Some results of the phase analysis of slag samples are given in Table 10. Melting points of various samples were in the range 1334-1449° C in air and in the range 1100-1200° C in argon. Fayalite (Fe_2Si0_4) is produced by the combination of silica ($Si0_2$) and wüstite (Fe0) above 1270° C, so the slag must have been above this temperature at some point in the smelting process[21]. Copper with 3-4% iron has a melting point (liquidus) in the range 1100-1200° C, and it seems reasonable to estimate the hearth temperature at 1200-1300° C.

Furnace operation

Reduction of the various copper compunds to metallic copper should be straightforward in this furnace; the essential technical problem is to produce a free-flowing slag. The ore analyses (Table 4) show that silica and iron oxides are by far the most important components of the gangue, and the slag analyses (Tables 7-10) indicate that the strategy adopted was to use a mix of ores of different compositions such that a slag was produced whose principal component is fayalite (Fe_2Si0_4). In fayalite the weight ratio $Si0_2$/Fe is 0.54: in nearly all the slag samples this ratio is between 0.5 and 1.0, with a mean of about 0.7. In the ore analyses in Table 4 the ratio ranges between 0.23 and 7.7; thus an appropriate mix of these ores could give the required ratio in the slag.

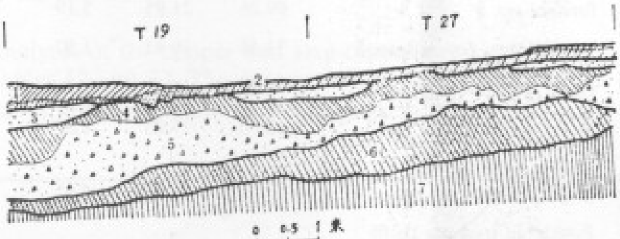


Figure 4. Section of the strata near the ancient smelting site (20, p 30). The scale shows 1 m. 1. Modern accumulation of earth mixed with iron ore, thickness 0.05-0.35 m. 2. Disturbed surface stratum of grey-brown earth mixed with a small amount of slag, thickness 0.15 m. 3. Black limy soil mixed with a small amount of slag, thickness 0.05-0.35 m. 4. Grey-brown earth mixed with a large amount of slag, thickness 0.1-0.6 m. 5. Red-brown and grey-brown earth mixed with a large amount of slag and fragments of red-fired clay, thickness 0.15-1.2 m. 6. Red clay mixed with a small amount of slag, fragments of re-fired clay, magnetite ore, malachite, and charcoal, thickness 0.25-0.9 m. 7. Natural alluvial soil.

Figure 5. Furnace no 6 under excavation (3, p 19: cf. 22, p 63). Slag accumulation in background.

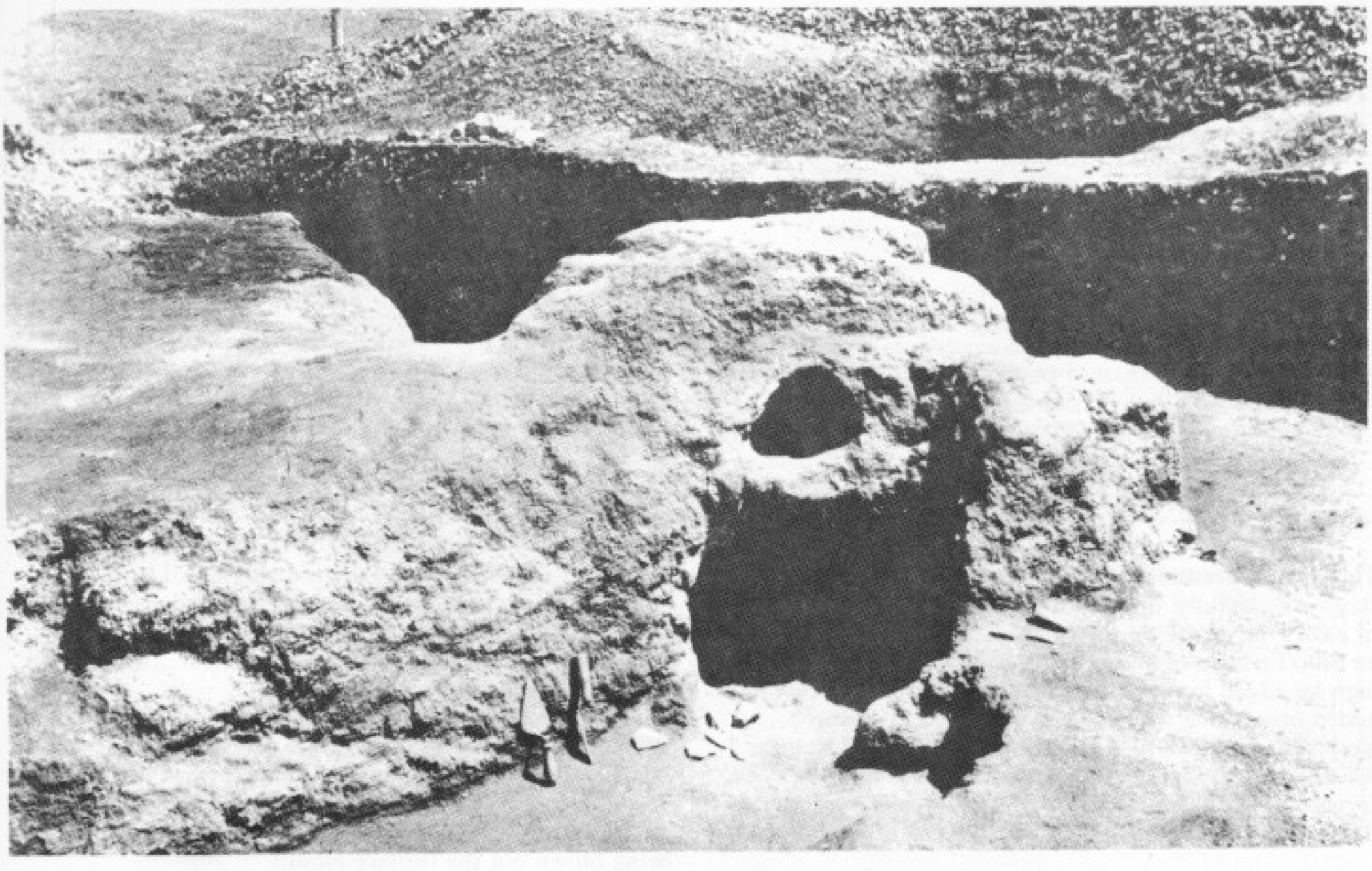


Table 3 Analyses of refractories (21, p. 159)

Sample location	principal chemical constituents %								refractoriness °C	sample no.
	SiO_2	Al_2O_3	Fe_2O_3	Cao	MgO	Na_2O	K_2O	TiO_2	°C	
Lining of upper part of tapping arch, furnace no. 4	76.67	18.35	4.04	0.16	—	0.034	0.51	0.35	1580	6
Lining of upper part of tapping arch, furnace no. 5	72.43	18.68	4.75	0.48	—	0.035	0.66	0.44	1580	8
Penultimate layer of furnace wall, furnace no. 9	69.26	21.95	5.19	0.28	—	0.043	0.70	0.56	1610	7
Inner lining, furnace no. 5	73.48	19.43	1.52	2.20	0.26					nai-16
Outer wall, furnace no. 4	38.28	15.10	21.24	3.78	1.32					nai-21
Outer wall, furnace no. 5	61.60	17.85	1.03	1.93	0.43					nai-24
Kaolin from mound beside furnace no. 4	53.68	19.43	4.45	2.27	0.86				1370	nai-22
Powdered iron ore from mound beside furnace no. 6	30.36	6.647	28.04	0.42	1.59					kuang-25

Table 4 Analyses of some ore samples (21, p. 162)

category	designation	location	principal constituents											sample
			Cu	FeO	Fe_2O_3	Fe (Fe_3O_4)	SiO_2	CaO	Al_2O_3	MgO	S	no.		
III	malachite	beside furnace no. 6	53.52	0.51	0.43			3.52	0.29	0.33				kuang-23
I	iron ore	beside furnace no. 9	0.98			7.60	62.38	25.53	1.18	2.55	0.61	0.18		18
I	copper - iron ore	beside furnace no. 6	3.28 2.059	2.71 3.33	21.35 18.85			9.68 17.60	0.47 1.22	1.63 1.37	0.82 1.51			kuang-19 kuang-17
		Tonglüshan	1.87				54.2	12.44	1.64	2.1	0.48			
II	chrysocolla	west of smelting site	.20.34			trace	6.34	48.83	0.23	10.72	0.42	0.59		20
		mine shaft of Western Zhou period	40.40			0.60	2.99	20.00	0.64	4.41	0.37	0.53		14
	iron ore with malachite inclusions	west of smelting site	31.88			1.40	17.29	15.72	1.27	2.50	0.22	0.53		19
III	malachite	mine shaft of Spring and Autumn period	51.82			trace	1.90	2.88	0.073	0.77	0.14	0.57		23
	black copper ore	mine shaft of Spring and Autumn period	22.45				21.29							IV-1

The smelter presumably watched the condition of the slag very carefully, and knew by experience the effect of each type of ore on the slag. In effect he aimed for an SiO_2/Fe ratio of about 0.7; if the ratio became too high he added iron ore, and if it became too low he added ores which were high in silica and low in iron. Very rich ores such as malachite (ca. 50% Cu, 2% Fe, 3% SiO_2) do not seem to have been necessary for furnace operation, but obviously would have been desirable for reasons of efficiency.

Figure 10 shows the area around furnace no. 6. Apparently ore was broken up with a stone on a flat stone anvil and then sieved. The richer ores were charged in larger chunks, 3-4 cm in diameter, while iron ore was charged as gravel or sand.

Presumably the use of this smaller particle size was necessary to obtain an immediate effect when the slag began to freeze up because of an excess of silica, but it no doubt caused difficulties with the fine particles being blown out the furnace mouth.

Lu Benshan and Zhang Hongli[21] note that in traditional Chinese copper-smelting furnaces used in 1958 the weight of coke charged was generally 20-30% of the weight of ore, but was sometimes as high as 50%. The iron content of the raw copper from Tonglüshan is somewhat higher than from these later furnaces, and this suggests that the charcoal ratio may have been 50%. Assuming that the blast volume was 4 m^3/min, that the ore charged was 24% copper on average, that recovery of copper was 95%, and that a limestone flux was not used, they calculate that production was ca. 353 kg per 24 hours. The details of this calculation are given in a forthcoming article[16] which I have not seen. The simulation experiments used a much leaner ore than this, and 100 kg of copper was produced in 10½ hours; this extrapolates to ca. 230 kg in 24 hours, and thus the calculation seems quite reasonable.

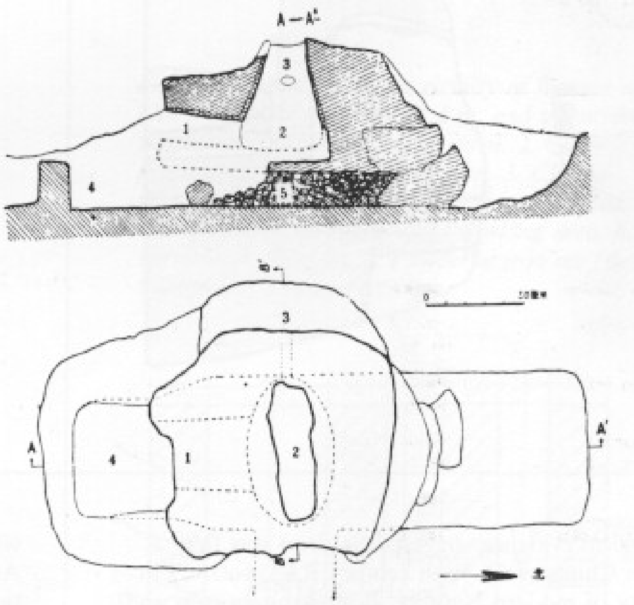
— 5.0 m^3/min at a pressure of 122-130 mm water. The total charge was:

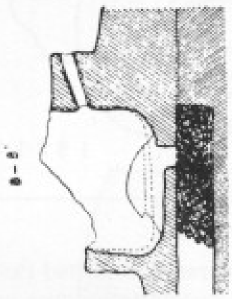
1002.5 kg lean ore (analysis in Table 11)
100 kg rich ore (no analysis given)
111 kg quartz
122.5 kg limestone
731 kg charcoal

This was charged in 109 batches, i.e. about 10 batches per hour. Slag was tapped 14 times (opening only the upper part of the taphole) and copper was tapped twice. Copper output was 70 kg tapped and 30 kg remaining in the hearth.

Analyses of the copper and slag tapped are given in Tables 12 and 13. The amount of slag produced is not stated, but calculation of the Ca0 balance between input

Figure 6. Diagram of furnace no 4 (20, p 34). The scale shows cm, and the arrow points north. 1. Tapping arch. 2. Hearth. 3. Tuyere. 4. "Wind channel". 5. Slag supporting the hearth.





Simulation experiments

In order to clarify various questions concerning the operation of the ancient furnaces two experimental reconstructions were built and tested in June 1980. The experimental results have been reported in several articles[16,19,21,22], of which [22] is the most detailed.

Experimental furnace no. 1 had only one tuyere, and the blower used for the blast was too weak. The result was this the charge did not descend. When the furnace was dismantled 2 kg of metallic copper was found in the hearth.

Experimental furnace no. 2 was much more successful. Two different diagrams of the same furnace are shown in Figures 11 and 12; construction and operation are shown in Figures 13-16. The furnace was operated continuously for 10 hours 36 minutes. The blast was 4.5

and output indicates roughly 700 kg slag. Further consideration of material balances then indicates that the total of 1102.5 kg ore charged contained 9% Cu, 23% Fe, and 10% SiO_2; these figures may be compared with the ore analyses in Table 11. The only obvious way of explaining the low calculated iron content is to assume that the samples analyzed in the table are unrepresentative with respect to iron.

Unfortunately the experimenters' temperature measurement equipment broke down in the field, and no temperature measurements could be reported.

The invention of iron-smelting

I am personally more interested in iron than in copper, and I have studied these copper-smelting furnaces because they may throw some light on the origin of iron-smelting in China. Presently-available

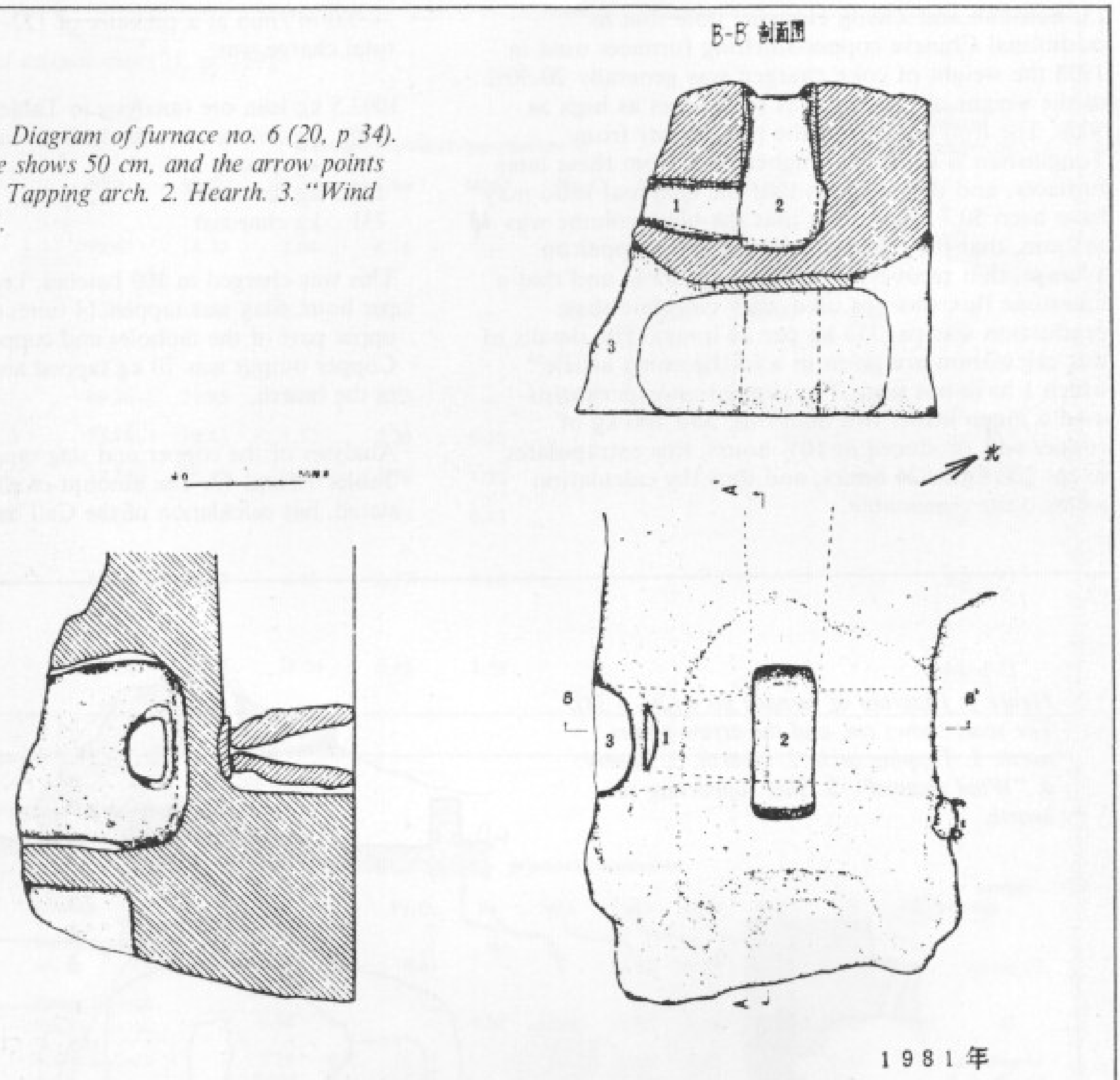


Figure 7. Diagram of furnace no. 6 (20, p 34). The scale shows 50 cm, and the arrow points north. 1. Tapping arch. 2. Hearth. 3. "Wind channel".

archaeological evidence suggests that iron was first smelted in China in the sixth century B.C., possibly in the vicinity of modern Nanjing. Both wrought-iron and cast-iron artifacts have been found. This is about the same time as the furnaces reported here, and only about 450 km to the north-east.

Under what conditions could a furnace like this be made to produce iron? It seems that all that was really necessary was a higher concentration of CO in the furnace atmosphere. Reduction of copper requires very little CO; reduction of Fe_2O_3 and Fe_3O_4 to FeO requires somewhat more, while reduction of FeO to Fe requires considerably more (see eg. [32]). Thus to produce metallic iron in this furnace, with the same ore charge and at the same operating temperature, all that was required was to increase the amount of charcoal charged, and possibly to decrease the blast.

The most likely result of initial experiments in this direction would be "bloom iron" with low carbon, left behind in the furnace unmelted. This could be worked by smiths in the usual way, or it could be charged in a cupola furnace of the type used for bronze-casting, where it would be carburized and melted (see e.g.[31]). Ancient Chinese bronze-casting techniques were by this time so highly developed that it would probably not have been especially difficult to develop the techniques necessary to cast this new metal into useful or decorative objects.

Enough is known about bloomery furnace operation (e.g. [34]) to make it clear that operating a furnace of this type as a bloomery furnace is a practical as well as a theoretical possibility. The next question is whether it could be made to function as a blast furnace which operates continuously and produces molten iron. There are two problems here. First, the iron must remain in a CO-rich atmosphere long enough raise its carbon content to ca. 4% (melting point ca. 1150° C). Second, a free-flowing slag must be produced. The second problem could be solved by using ores like those analyzed in table 11, with high iron content and fairly low silica (ca. 50% Fe, 8% SiO_2); with a loss of perhaps 10-15% of the iron in the ore a slag could be produced which resembles the copper-smelting slag. The first problem is more difficult to deal with theoretically, since it involves complex considerations of reaction kinetics.

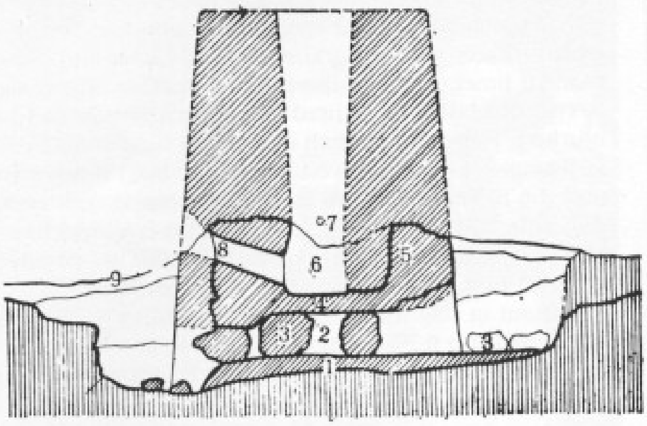


Figure 8. Diagram of furnace no 10 (11, p 9; also 15, p 19). 1. Foundation. 2. "Wind channel". 3. Supporting stones. 4. Hearth bottom. 5. Furnace wall, including part of the furnace lining. 6. Hearth. 7. Tuyere. 8. Tapping arch. 9. Working area.

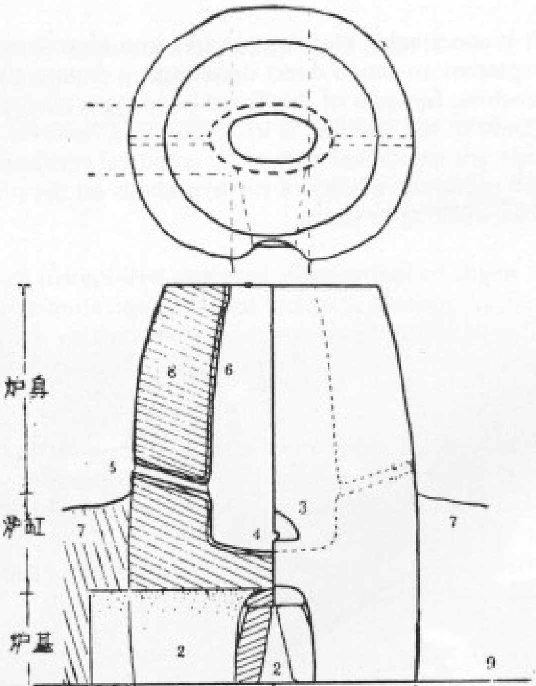


Figure 9. Generalized reconstruction of the ancient copper-smelting furnace (19, p 40). The scale shows cm. The three sections indicated on the left are, top to bottom: shaft, hearth, foundation. 1. Base. 2. "Wind channel". 3. Tapping arch. 4. Taphole. 5. Tuyere. 6. Inner lining. 7. Working area. 8. Furnace wall. 9. Ground surface.

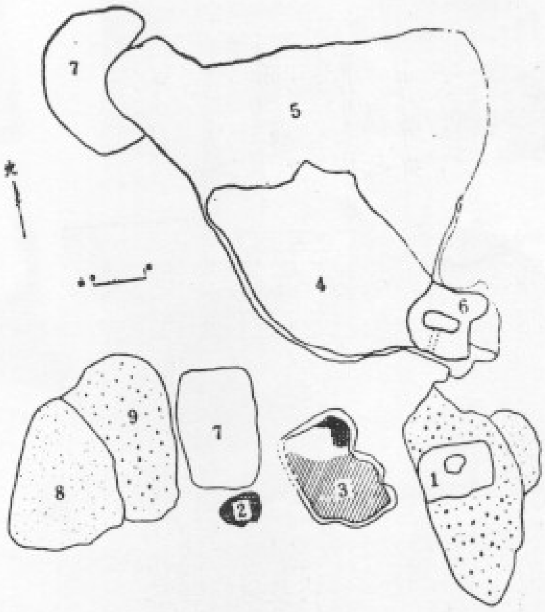


Figure 10. Features in the vicinity of furnace no 6 (20, p 36). The scale shows 1 m, and the arrow points north. 1. Ore-dressing anvil. 2. Clay-preparation pit containing kaolin. 3. Clay-preparation pit containing red clay and kaolin. 4. Working area. 5. Slope up to working area. 6. Furnace. 7. Slag pit. 8. Powdered iron ore (sieve tailings). 9. Crushed iron ore.

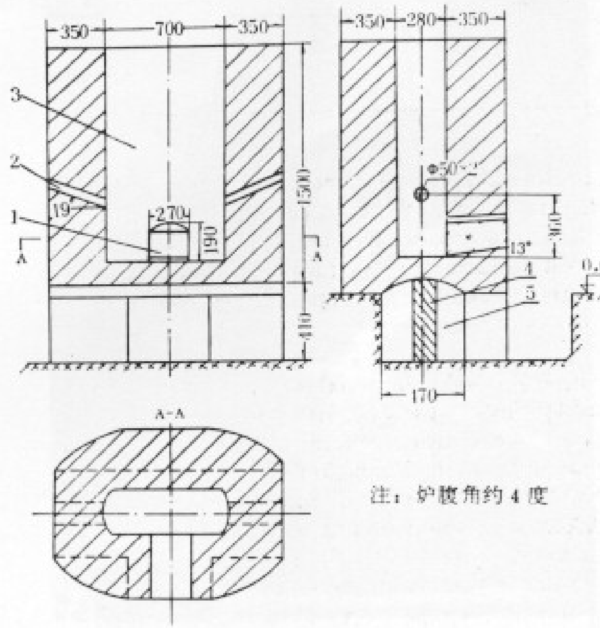


Figure 11. Diagram of experimental furnace no 2, according to (22, p 65). 1. Tapping arch, 270 x 190 mm. 2. Tuyere, ϕ50 mm. 3. Shaft, 700 x 280 x 1500 mm. 4. Stone support for hearth. 5. "Wind channel".

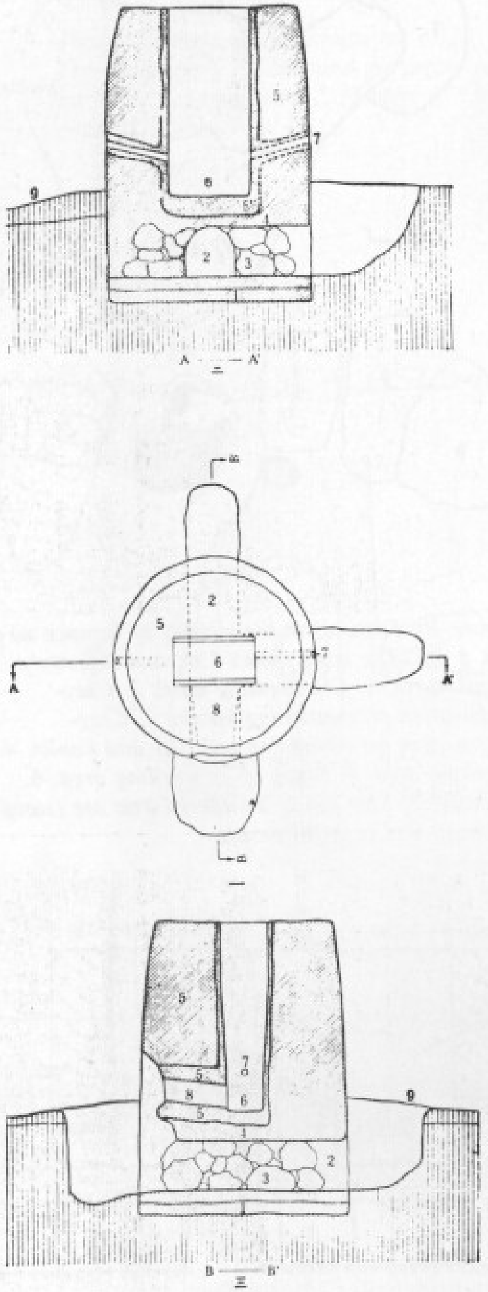


Figure 12. Diagram of experimental furnace no 2, according to (15, p 20). 1. Base. 2. "Wind channel". 3. Stones supporting the hearth. 4. Hearth bottom. 5. Furnace wall. 6. Hearth. 7. Tuyere. 8. Tapping arch. 9 Working area.

Fortunately there is empirical evidence which indicates that a furnace of this size and general construction could be used as an iron blast furnace. I have elsewhere ([36]; see also [35]) described several very small traditional "dwarf" blast furnaces used in various parts of China into modern times. Some of these are as small as 30 cm high. A type of blast furnace used in southern Henan and northern Hubei had a shaft about 2 m high and 45 cm in diameter as its narrowest point. The blast input was only 1.6 m^3/min. The ore used was ironsand with about 65% iron and 5.5% silica. About 1.5 times as much charcoal as ironsand was charged. No flux was used, but CaO from the furnace lining may have been important in slag formation. Loss of iron to the slag was very small (*Ca* 0.2%). The hearth temperature was normally in the range 1250-1300° C. Production was 700-750 kg pig iron per 24 hours.

The structure of the Tonglüshan furnaces was obviously optimized for copper smelting, and a great deal of experience would have been needed to develop an efficient furnace and operating procedures for iron smelting. Nevertheless the "dwarf" iron blast furnaces are similar enough to the Tonglüshan copper-smelting furnaces to indicate that molten iron could have been produced at some level of efficiency in these with only a small change in operating procedures.

It is conceivable that the "dwarf" iron blast furnaces represent an actual direct development from copper-smelting furnaces of the Tonglüshan type, though I doubt it; the question is irrelevant here, however, and they are mentioned only as an empirical verification of the technical viability of my hypothesis on the origin or iron-smelting in China.

It might be that metallic iron was well-known to the copper-smelters, a sign of incorrect operation of the furnace. Then the discovery of iron-smelting would simply have been the discovery that this undesirable by-product could be useful.

The technical conditions for the discovery of iron thus seem to be clarified, but economic conditions remain to be considered. Why would anyone wish to produce iron at Tonglüshan? There was no shortage of copper ores, production per day would be unlikely to be significantly higher, and charcoal consumption would be considerably higher. The wrought- or cast-iron produced initially would not have been a superior material to bronze. There is in fact no sign that iron was ever smelted at Tonglüshan in ancient times. The possibility remains, however, that the same type of furnace was used in other regions where conditions were different: for example at a small copper-ore deposit which at some point was exhausted, leaving only iron ores. In order to continue supplying metal products it would then have been necessary to shift over to iron production.

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Figure 13. Experimental furnace no 2 under construction (11, plate 1.4).

Figure 14. Experimental furnace no 2 under construction (15, plate 5.2).

Figure 15. Charging of experimental furnace no 2 (11, plate 2.3).

Figure 16. Tapping of slag, experimental furnace no 2 (15, plate 5.4).

Table 5 Analyses of raw copper samples (21, p. 166)

location	Cu	Sb	Pb	Zn	Sn	Fe	S
furnace no. 3	93.32	0.0075	0.038	0.014	0.023	3.35	
furnace no. 4	93.99			0.66		3.99	1.33

Table 6 Analyses of artifacts found in the vicinity (13, p. 21)

	Cu	Sn	Fe	Sb	Pb	Al	Zn
bronze axehead	90.27	6.25	1.05	0.18	0.15	0.02	3.01
copper ingot	91.86	0.11	5.44	0.18	0.03	0.01	2.88

Table 7 Analyses of ancient slag samples (22, p. 64)
Compare tables 8-9.

location	form	Cu	FeO	Fe_2O_3	SiO_2	CaO	MgO	S	Al_2O_3
T-36	flake	0.897	53.93	1.54	29.92	3.29	0.86	0.68	7.48
T-45	flake	0.994	53.01	0.90	29.26	2.68	0.86	0.63	6.30
T-45	flake	0.598	50.40	5.32	31.02	2.93	0.71	0.31	6.99
T-37	flake	0.765	48.97	2.29	34.32	2.98	1.12	0.75	10.11
T-33	flake	0.68	47.03	5.75	34.32	4.46	0.97	0.31	8.53
mean		0.787	50.67	3.14	31.77	3.33	0.88	0.54	7.88
inner wall, furnace no. 5		1.06	8.8	2.75	56.98	1.22	0.41	0.20	0.025
beside furnace no. 6	plate	0.995	44.73	5.61	36.74	3.17	0.91	0.39	7.807
inside furnace no. 6	coarse	0.798	36.02	1.84	22.22	1.34	1.33	0.84	4.355
beside furnace no. 6	plate (verdigris precipitant)	1.12	51.81	trace	28.60	3.90	1.62	0.57	6.41
beside furnace no. 6	plate	0.858	50.46	0.53	25.96	1.95	1.51	0.93	6.30

Bibliography

Sections 1-2 below are intended to be complete, while section 3 lists a few interesting recent publications on ancient Chinese mining and metallurgy, and section 4 lists various other publications cited in this article.

Abbreviations

CR: **China reconstructs.** Beijing: China Welfare Institute.

CSA: **Chinese sociology and anthropology.** White Plains, N.Y.: International Arts and Sciences Press.

JHKG: **Jiang Han Kaogu** (Archaeology of the Changjiang — Hanshui region). Wuchang, Hubei: Hubei Provincial Archaeological Society.

JHMS: **Journal of the Historical Metallurgy Society.**

KG: **Kaogu** (Archaeology). Beijing: Science Press.

KGXB: **Kaogu xuebao** (Acta archaeologia Sinica). Beijing: Science Press.

KSW: **Keji shi wenji** (Essays on the history of science and technology). Shanghai: Shanghai Science and Technology Press.

TAIME: **Transactions of the American Institute of Mining Engineers.**

WW: **Wenwu** (Cultural relics). Beijing; Cultural Relics Press.

YJ: **Youse jinshu** (Non-ferrous metals). Beijing: Metallurgical Industry Press.

ZKSY: **Ziran kexue shi yanjiu** (Studies in the history of natural sciences). Beijing: Science Press.

1. The Tonglüshan mine site

In Western languages:

1. **Buck, David D. (tr.), "Reconnaissance of ancient mine and smelter sites in Hupei province"**, *CSA, 1975*, **8**.1:3-18. *Tr. of KG 1974*,4:251-254, 256.

2. **Hsia Nai (=Xia Nai), "The slaves were the makers of history"**, *CR, Nov. 1975*, **24**.11:40-43.

3. **Tonglüshan (Mt. Verdigris Daye) — A pearl among ancient mines.** *Ed. by* **Huangshi Museum, Hubei; Chinese Society of Metals, Publication Committee; and Archaeometallurgy Group, Beijing University of Iron and Steel Technology. Beijing: Cultural Relics Publishing House, 1980.** Chinese and English text. Chinese title: *Tonglüshan – Zhongguo gu kuangye yizhi.* No pagination; in references here the pages have been arbitrarily numbered with the Chinese title page as p. 1.

4. **Vogel, Hans Ulrich, "Bergbauarchäologische Forschungen in der Volksrepublik China: Von Chengde bis Tonglüshan — ein Forschungsbericht", Der Anschnitt: Zeitschrift für Kunst und Kultur im Bergbau** *(Bochum: Vereinigung der Freunde von Kunst und Kultur in Bergbau). 1982*, **34**: 138-153.

5. **Xia Nai and Yin Weizhang, "Digging up an ancient copper mine"**, *CR, March 1982*, **31**, 3:38-40. Abridged and popularized tr. of[11].

6. **Barnard, Noel:** (I understand that Prof. Barnard, of the Australian National University, Canberra, is preparing a study of mining technology at the Tonglüshan site.)

In Chinese:

7. **Hu Yongyan, "Daye Tonglüshan gu kuange yizhu jinnian lai de kaogu fajue ji qi yanjiu"**, *(Recent excavations and studies on the ancient mining and smelting site at Tonglüshan, Daye County, Hubei). JHKG 1981. 1: 77-78. (Not seen; cited KG 1982. 5: 555).*

Table 8 Analyses of ancient slag samples (21, p. 163) Compare tables 7, 9.

location	Cu	FeO	Fe_2O_3	Fe	Fe_3O_4	SiO_2	CaO	MgO	S	Al_2O_3	sample no.
tail slag, furnace no. 4	1.26			49.54	10.00	6.89	0.46	0.43	0.74	5.70	11
tail slag, furnace no. 5	0.625			43.88	8.00	31.92	1.86	0.68	0.58	6.66	10
inside furnace no. 6	0.80	36.02	1.84			22.22	1.34	1.33	0.84	4.36	zha-13
beside furnace no. 6	0.955	44.73	5.61			36.74	3.17	0.91	0.39	7.81	zha-12
ditto	0.858	50.46	0.53			25.96	1.95	1.51	0.93	6.30	zha-15
furnace 3, layer 1	0.58	41.92	7.15			24.11	1.2	0.7	0.76	6.0	12-1
furnace 3, layer 2	0.67	46.70	13.71			25.08	2.0	0.9		3.6	12-2
furnace 3, layer 3	0.20	46.83	14.33			26.90	1.68	2.0	1.02	3.0	
T19-V	0.56			40.15		30.34	3.50	1.17	0.38	6.55	V-17
T36	0.90	53.93	1.54			29.92	3.29	0.86	0.68	7.48	zha-6
T37	0.77	48.97	2.29			34.32	2.98	1.12	0.75	10.11	zha-9
T45	0.60	50.40	5.23			31.02	2.93	0.71	0.31	6.99	zha-8

Table 9 Analyses of ancient slag samples (20, p. 37) Compare tables 7-8

sample no.	location	form	Cu	FeO	Fe_2O_3	SiO_2	CaO	MgO	S	Al_2O_3
12	beside furnace no. 6	plate	0.95	44.73	5.61	36.74	3.17	0.91	0.39	7.81
13	inside furnace no. 6	coarse, excrementoid	0.80	36.02	1.84	22.22	1.34	1.33	0.84	4.355
15	beside furnace no. 6	flake	0.85	50.46	0.53	25.96	1.95	1.51	0.93	6.30
mean of sample nos. 6-10			0.70	50.67	3.14	31.77	3.30	0.88	0.54	7.88

8. **Li Tianyuan, 'Kuangye Keogu zhan xinyan'** *(New work on the archaeology of mining and metallurgy), JHKG 1980. 1:* 98.

9. **Shi Wen, 'Hubei Tonglüshan Chunqiu Zhanguo gu kuangjing yizhi shi nuli chuangzao lishi de guanghui jianzheng'** *(The Spring and Autumn – Warring States mining site at Tonglüshan, Hubei is proof positive that the slaves were the makers of history), WW 1975. 2: 13-18.*

10. **Tonglüshan Excavation Team, 'Hubei Tonglüshan Chunqiu Zhanguo gu kuangjing yizhi fajue jianbao'** *(Brief report on the ancient mining site of the Spring and Autumn and Warring States periods at Tonglüshan, Hubei), WW 1975. 2: 1-12* + plates 3-5.

11. **Xia Nai & Yin Weizhang, 'Hubei Tonglüshan gu tongkuang** *(Ancient copper mines and smelting furnaces at Tonglüshan in Hubei), KGXB 1982. 1: 1-14* + plates 1-2. English summary.

12. **Yang Yongguang, Li Qingyuan & Zhao Shouzhong, 'Tonglüshan gu tongkuang kaicai fangfa yanjiu'** *(Mining methods at the ancient copper mine at Tonglüshan),* parts I-II, *YJ, 1980,* **32**.4: 84-92; **33**.1:82-86, 44. Short English summaries.

13. **Ye Jun, 'Tonglüshan gu kuangjing yizhi chutu tiezhi ji tongzhi gongju de chubu jianding'** *(Preliminary investigation of iron and bronze atifacts from the ancient mining site at Tonglüshan, Hubei), WW 1975. 2: 19-25.*

14. Yin Weizhang, 'Hubei Tonglüshan Dong Zhou tongkuang yizhi fajue' *(Excavation of the Easten Zhou period mining site at Tonglüshan, Hubei), KG 1981. 1: 19-23* + plates 4-5.

2. The Tonglüshan copper-smelting furnaces

15. **Bai Rongjin & Yin Weizhang, 'Hubei Tonglüshan gu tongkuang zaici fajue — Dong Zhou liantong lu de fajue he liantong mosi shiyan'** *(Further excavations at the ancient copper mine at Tonglüshan, Hubei – excavation of Easten Zhou period copper-smelting furnaces and experimental reconstruction of the copper-smelting technology), KG 1982. 1: 18-22* + plate 5.

16. **Jinshu shi wenji (Metallurgical history: proceedings of a conference held in 1980).** *Shanghai: Shanghai Science and Technology Press, forthcoming.* (Not seen; cited in **21**, p. 158, n. 1.) Includes Zhu Shoukang on ancient Chinese copper smelting and Lu Benshan on ancient copper-smelting at Tonglüshan.

Table 10 Phase analysis of slag samples (21, p. 164)

location	copper and copper sulphides	magnetite Fe_3O_4	fayalite Fe_2SiO_4	fine crystals and glass	limonite $2Fe_2O_3.3H_2O$	other
furnace no. 3 (sample 12-2)	Primarily metallic copper in fine grains	10%	65%	15%±		
furnace no. 6		present	present	present	cuprite	(Cu_2O)
T19-5	1%±. Coarser grains primarily chalcocite (Cu_2S); finer grains primarily chalcopyrite ($CuFeS_2$) and bornite ($FeS.2Cu_2S.CuS$).	10%	50% coarse crystals	37%±	2%± Some in veins.	quartz (SiO_2)
T20-6	0.5%±, primarily chalcocite (Cu_2S).	8% comparatively fine-grained	50% coarse crystals	40%±	2%±	

Table 11 Analyses of samples of the ore charged in experimental furnace no. 2 (22, p. 66)

sample no.	Cu	FeO	Fe_2O_3	SiO_2	CaO	MgO	S	Al_2O_3	TiO_2	calculated Fe
1	7.08	2.60	72.81	7.12	—	0.16	0.06	0.76	0.12	52.99
2	8.07	2.50	71.92	6.51	0.22	0.08	0.03	0.76	0.12	52.29
3	11.30	2.43	66.35	6.78	—	0.08	0.03	0.85	0.10	48.34
4	8.77	2.44	59.20	11.49	1.93	0.08	0.11	1.14	0.13	43.34
mean	8.81	2.49	67.57	7.98	0.54	0.10	0.06	0.88	0.12	49.24

Table 12 Analyses of raw copper from experimental furnace no. 2 (22, p. 66)

	Cu	Fe	S	Pb	Sb	Zn	Ni	Sn	Bi
first tap	94.41	3.18	0.117	0.05	0.0036	0.021	0.0078	0.0085	0.0027
second tap	97.25	2.52	0.106	0.074	0.0047	0.035	0.0065	0.014	0.0035

Table 13 Analysis of slag from experimental furnace no. 2 (22, p. 66)
Mean of analyses of each of 14 tappings.

Cu	Fe	SiO_2	CaO	SiO_2+CaO	SiO_2/Fe	(SiO_2+CaO)/Fe
0.837	36.67	32.67	10.00	42.62	0.948	1.194

17. **Institute of Archaeology, Chinese Academy of Social Sciences, 'Hubei Daye Tonglüshan gu liantong lu de reshiguang niandai'** *(Thermoluminescence dating of ancient copper-smelting furnaces at Tonglüshan, Daye County, Hubei), KG 1981. 6: 551, 550.*

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19. **Lu Benshan & Hua Jueming, 'Tonglüshan Chunqiu liantong shulu de fuyuan yanjiu'** *(Studies toward the reconstruction of the Spring and Autumn period copper-smelting shaft furnaces at Tonglüshan), WW 1981. 8: 40-45. Note the errata to this article given in (15, p. 22, n. 2).*

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