enigmatic slag structure among the slag heaps of Beer Ora. It is not a 'symbolic church' but a mosque built by the seventh century A.D. Islamic metallurgists of the Arabah. This, of course, also explains why the 'apse', i.e. the *mihrab*, was orientated south, towards Mecca.

The age-old tradition of erecting places of worship in the centre of mining and smelting regions, still adhered to in modern times, and well documented by our Arabah expeditions from the fifth millennium B.C. beginnings of metallurgy to the fourteenth–twelfth centuries B.C. Egyptian mining temple of Timna,[8] can now be followed through to the seventh century A.D. at Beer Ora – a total of about 6000 years of mining and metallurgy and metal-related worship.

Beno Rothenberg

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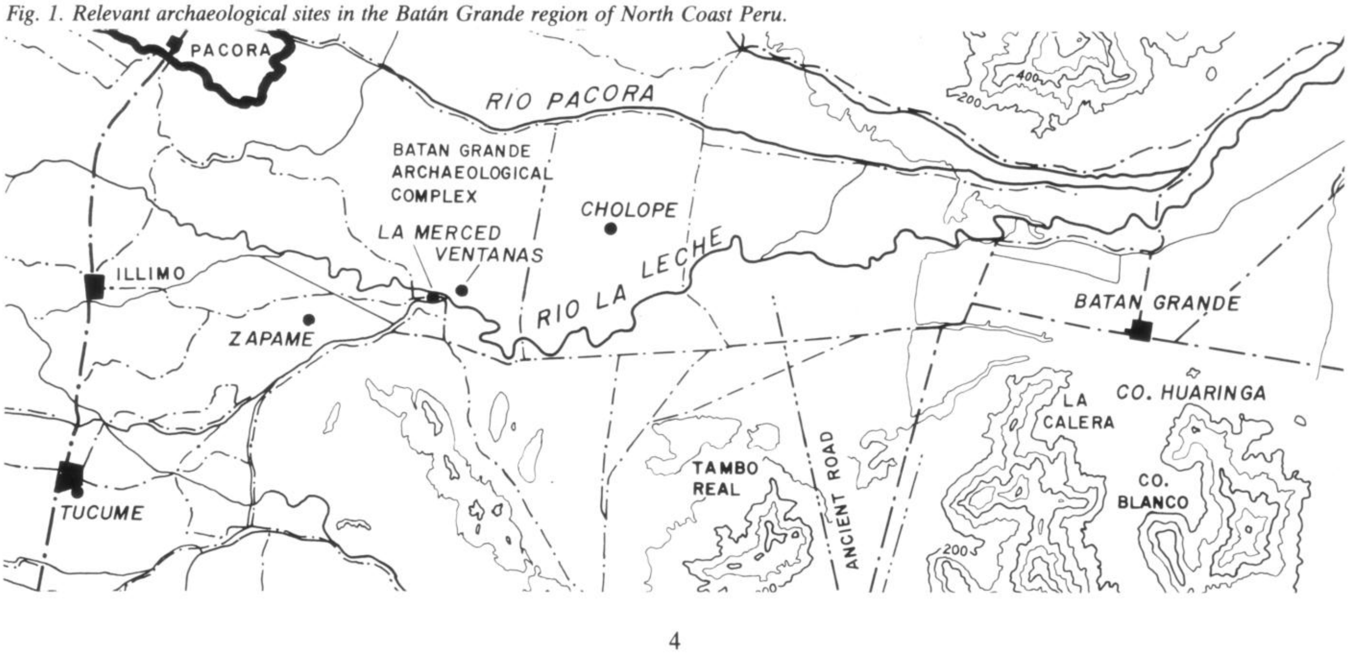
Arsenical Copper Smelting at Batán Grande, Peru

The Sicán Archaeological Project, under the direction of Professor Izumi Shimada (Harvad University), is a long-term interdisciplinary study carried out to date over nine seasons (1978–86). A primary research aim is an understanding of both cultural and technological aspects of Sicán copper production. John Merkel, who recently took a doctoral degree in archaeo-metallurgy on an IAMS Fellowship at London University, is collaborating with Dr. Stuart Fleming (MASCA, University of Pennsylvania) on the analytical programme of the Sicán Archaeological Project. Dr. Merkel (currently at Harvard, but shortly to join the staff of the Institute of Archaeology, University College London) is on the Scientific Committee of IAMS. The project is supported by grants from the National Geographic Society, the National Science Foundation and Harvard University.

Starting with the Middle Sicán Period, A.D. 900–1100, copper-arsenic alloys definitely replace unalloyed copper to become the mainstay of the North Peruvian metallurgical tradition. At the sites around Batán Grande (Fig. 1), indigenous copper production ended with the Spanish conquest at A.D. 1532–5. This brief report will discuss new evidence from technical investigations of the ores, slag, speiss, copper and furnaces, including copper smelting experiments conducted on site.

Based on work to date, it appears that Batán Grande represents part of an extensive, regional network of copper production sites. Six prehistoric mines and three smelting sites have been identified and, in part excavated in the Batán Grande area. The earliest remains of copper smelting furnaces date from *c.* A.D. 900–1000. At the site of Huaca del Pueblo, Batán Grande, five rows of small bowl-shaped furnaces have been excavated (Fig. 2). More than fifty examples of such furnaces have been examined altogether in the three

Fig. 1. Relevant archaeological sites in the Batán Grande region of North Coast Peru.



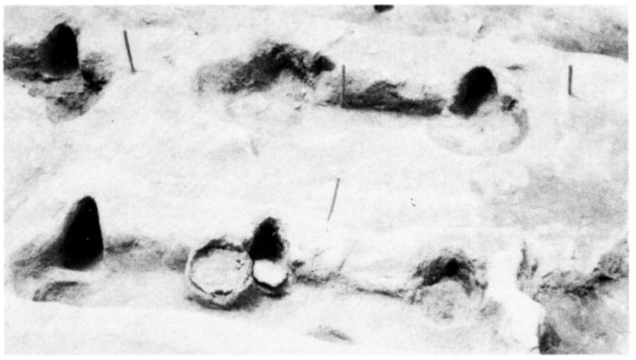


Fig. 2. Huaca del Pueblo, Batán Grande, stratified furnace sets approximately four metres below the present surface.

known smelting sites. Based upon furnace volumes and slag density estimates, each furnace could have held 5 to 10kg. of molten slag and copper (Fig. 3). Tuyères, also abundant at the smelting sites, were presumably positioned pointing into the open front of the furnace directed toward the bottom. The ceramic tuyères (Fig. 4) were connected to blow pipes. No remains of bellows have ever been found and ethno-historical documents clearly note their absence in Pre-hispanic South America. Copper production was based upon a 'prill extraction' technique; furnace slag containing entrapped metallic copper prills was crushed on large stable anvils, called 'batanes', with a heavy rocking stone in order to separate the copper prills for subsequent collection by hand. Small copper ingots, weighing 300–600g., were produced by remelting copper prills.

There has been much speculation concerning the ancient production of copper-arsenic alloys. Based upon laboratory analyses of finished objects, some scholars have argued that the alloy may have been produced from smelting deliberately mixed ores. At Batán Grande, there is new archaeo-metallurgical evidence which supports this theory.

Proton induced X-ray emissions (PIXE) analyses of ore specimens recovered from excavation of smelting sites indicate that the dominant copper mineral was malachite. It is significant that of over 40 samples of

Fig. 3. Well-preserved furnace at Cerro Huaringa (near the modern village of Batán Grande) shown during excavation.

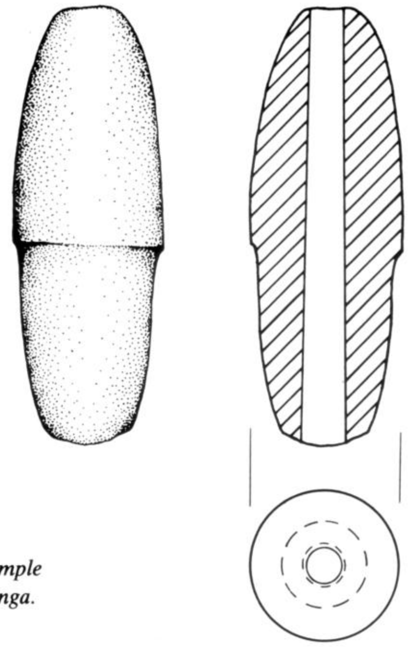


Fig. 4. Tuyère example from Cerro Huaringa.

copper ores from the smelting site of Huaca del Pueblo, only four had concentrations of arsenic over 0.05%. Two specimens had about 0.2% arsenic, but there were also two with high concentrations of 6% and 11% arsenic. These two specimens were also different in colour than the 'best' grade copper ore specimens from the site. This suggests that arsenic-rich ores were recognized as being different from the usually smelted ores at Huaca del Pueblo. Available fluxes, also collected at the smelting site, included hematite and limonite. Six samples of iron ore flux were analyzed, only one had 4% arsenic, the others were below 0.05% arsenic.

Copper ore collected for the smelting experiments from nearby surface deposits at Cerro Blanco did not have arsenic concentrations above 0.05%. However, iron ore used as flux in the experiments also collected at Cerro Blanco contained up to 0.5% arsenic. In the mining survey of the immediate area, at a large, shallow ancient mine, called Cerro Meilliso, arsenopyrite (FeAsS) and scorodite ($FeAsO_4 \cdot 2H_20$) were identified. (Scorodite is a common weathering product of arsenopyrite.) PIXE results for one of the specimens were 38% Fe, 49% As and 12% S. Results were confirmed by electron probe microanalysis (EPMA) and the phases identified by X-ray diffraction (XRD) and petrographic techniques. The absolute date when this local mine was utilized for its arsenic-rich ores is still somewhat uncertain. Outside the mine are Pre-hispanic ceramics and wall foundations with standardized room dimensions. The mine was cut with stone tools. It most probably predates Spanish contact. Thus, surface deposits of arsenic-rich mineralization are present in the Batán Grande area.

Slag specimens and crushed slag samples collected from around the smelting furnaces at Huaca del Pueblo, would be termed 'furnace-type, spinel-type', following Professor H-G. Bachmann's 1980 classification. Typical ranges for slag-forming constituents are 35–60% FeO, 10–35% SiO_2, 2–10% Al_2O_3, 5–20% CaO, and 2–10% Cu. The slag is characteristically heterogeneous. Such slag compositions have estimated free running temperatures often well above 1150°C. Copper prills of varying sizes are entrapped throughout practically every slag sample. 'Droplets' of matte (CuFeS) have also been identified in the slag. Copper losses were considerable, despite crushing and hand sorting of the prills from the furnace slag.

Another discovery among the excavated material collected from around the furnaces is the presence of speiss. These specimens have weathered surfaces of iron oxides. Average composition for the speiss is about 56% Fe, 41% As and 4% Cu.

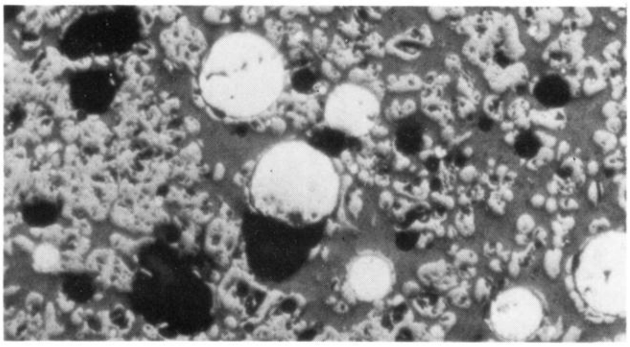


Fig. 5. Photomicrograph (×80) copper prills entrapped in slag from Cerro Huaringa.

The compositions of copper prills entrapped in the slag (Fig. 5) provide essential data for reconstructing the smelting process at Batán Grande. Using EPMA, our average concentration of arsenic in the copper prills is about 6%. Arsenic has been found to range typically from 1–20% in the entrapped copper prills in the slag at Huaca del Pueblo. Values above the solid solubility of about 7% arsenic are common. Some compositions of inclusions and two phase regions in prills were measured with up to 40% arsenic. These high-arsenic copper prills entrapped in the smelting slag, along with the presence of speiss at the smelting site, indicate some necessary additional input of arsenic in the furnace charge in excess of that from the available copper ore and flux. The ore compositions from the smelting sites, along with the identification of distinct mine locations for arsenic-rich ores, suggest that three separate ore components were recognized and mixed in the smelting charges at Huaca del Pueblo. Based upon mass balance estimates, the low levels of arsenic in the majority of copper ore and iron ore samples would not account satisfactory for the observed products. A few 'erratic' ore specimens included accidentially in a smelting charge could produce occasional copper-arsenic alloys. However, accidental inclusions would not sustain a tradition or 'industry' based upon predominant use of copper-arsenic alloys.

We believe that the Batán Grande evidence best supports a model for alloy production using deliberate additions of local (perhaps supplemented by some imported) arsenic-rich ores in smelting charges. Considerable variability in arsenic concentrations and the speiss products suggest rather poor control over ore sorting and charge preparation. It is possible that mixing or 'blending' of complex prills from high-arsenic smelting runs was undertaken, to counteract refining losses, in a further attempt to control final alloys for finished objects. At Batán Grande there is no evidence at present to recommend an alternative theory for deliberate secondary alloying in a separate step after smelting.

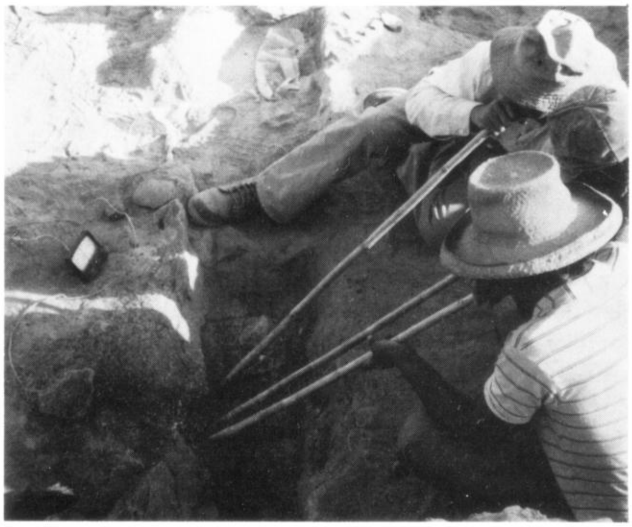


Fig. 6. Reconstruction copper smelting experiment at Cerro Huaringa using a 500-year-old furnace. Three local workmen shown using cane pipes and ceramic tuyères.

Experimental smelting reconstructions were conducted at Batán Grande to test several aspects of furnace operation and product compositions. In the final experiment, an ancient furnace was re-used after some 500 years of abandonment (Fig. 6). It was determined in the preliminary experiments that these furnaces incurred very little damage with each smelting run because the charcoal bed protected the furnace walls from slagging. Based upon our observations, these small furnaces were not filled with molten slag at any given time during smelting. Using blow tubes, maximum temperatures over 1200°C were frequently measured during the experiments, but only in a relatively small zone directly in front of each tuyère. With three or four tuyères (the maximum number that could practically fit into the open furnace front) and the use of ceramic sherds covering the front of the furnace to contain heat (evidence for which is also abundant at the Batán Grande smelting sites), we could not get the entire furnace charge to melt at any one time. We were rotating blowers and trying to operate at maximum airflows and burning rates. Under these restraints, one possible way which was tested to operate the furnace was to start with small charges (under 100g. of mixed ore and flux) placed slowly on top of the burning charcoal in the back of the preheated furnace. With continued blowing, temperatures of small charges would quickly reach 1100 to 1200°C. However, with each subsequent small charge, the temperature measurements would quickly fall below 1100°C. It does not seem possible to achieve a thermal balance between charcoal and small ore charges based upon observation alone. As continued small charges first melted and then cooled and solidified, a solid mass was slowly accumulated, building toward the front until the furnace was filled. Operating volumes were less than expected due to slag-coated unburned charcoal remaining in the furnace. Clearly, variable low burning rates at only about 2kg. charcoal per hour, relative to heat losses, were limiting factors. Nevertheless, the smelting products were comparable in many respects (expect for arsenic) to the Sicán products.

In the experiment with the 500-year-old furnace, from 775g. furnace slag only about 30g. of copper prills were collected after crushing (Fig. 7). The slag was 44% FeO, 34% SiO_2, 3% Al_2O_3, 8% CaO and 6% Cu. The concentrations of arsenic in the prills were especially interesting. The copper ore (31% Cu) had less than 0.05% As, but the iron ore selected for the experiments had up to 0.5% As, as noted above for Cerro Blanco. From smelting a 1 : 1 ratio of ore to flux, the copper prills resulted with about 1% arsenic. Such levels of arsenic in the flux clearly represent accidental inputs in the smelting charges. These figures give some further indication as to the partitioning of arsenic into the copper product in smelting under 'primitive' conditions, such as documented previously in other simulation smelting experiments.

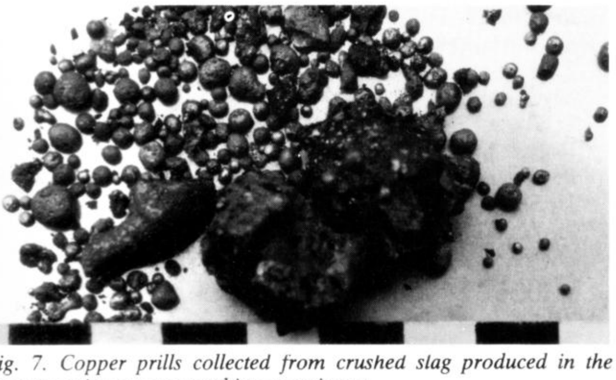


Fig. 7. Copper prills collected from crushed slag produced in the reconstruction copper smelting experiment.

In conclusion, since the concentrations of arsenic in the majority of ore and flux samples collected from the Huaca del Pueblo smelting site were at least an order of magnitude lower (below 0.05% As), the results of these experimental smelting reconstructions underscore the necessity of seeking an additional, separate arsenic input to the smelting charge. 'Accidental' inclusions of arsenic-rich ore or flux cannot account for the production scale utilizing high-arsenic prills and alloys that characterize the period from A.D. 900 to the Spanish conquest. Full documentation of the analytical results and broader cultural interpretation of Sicán metallurgy will be published in a forthcoming volume of *Sicán Archaeo-Metallurgy*.

John Merkel and Izumi Shimada

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Peter Wincierz

4 May 1930 – 22 April 1988

It is with a deep sense of sorrow that we have to announce the sudden death of Prof. Dr.-Ing. Peter Wincierz, Frankfurt/M.

From the very beginnings of IAMS, in the early '70s, Peter was one of the central members of our archaeo-metallurgical research group and he also took part in our fieldwork in the Arabah and Sinai. His major contribution to our research projects was in the field of theoretical as well as applied extractive metallurgy.

In the last few years, in spite of his heavy responsibilities as Director of the Metal-Laboratory of Metallgesellschaft AG Frankfurt/M, Peter spent many of his rare off-duty hours working together with his IAMS colleagues on the very exacting development of new experimental and theoretical models of copper smelting.

Shortly, before his untimely death, Peter completed his part of the final version of 'Mathematical Modeling of Late Bronze Age/Iron Age Smelting of Oxide Copper Ore', published, posthumously, in the May issue of *Metall, Internationale Zeitschrift fur Technik und Wirtschaft*, Berlin/Heidelberg.

It is with great sadness, but also with a deep sense of gratitude, that we turn the pages of the voluminous manuscript *Ancient Smelting of Oxide Copper Ores*, written by Peter Wincierz and M. Bamberger for the forthcoming second volume of *Researches in the Arabah*, which reached us almost together with the Job's message of Peter's death.

Peter has left his mark not only on the development of new archaeo-metallurgical research methods but also, and in many ways, on his research partners and colleagues who will greatly miss his unique expertise, his unbending professional integrity and, most of all, his unfailing loyal friendship.

B.R.