THE SANCTUARY OF POSEIDON AT ISTHMIA: TECHNIQUES OF METAL MANUFACTURE

(PLATES 102–108)

THIS STUDY deals with metal fragments found at the Isthmian Sanctuary of Poseidon.[1] In addition to a great marble water basin, some well-preserved bronzes, coins, architectural fragments, terracotta figurines, and small vases, and many fragments of bronze and iron, together with much broken pottery, were recovered in several dumped deposits near the Temple of Poseidon.[2] Upon an initial inspection the small pieces of armor and weapons, handles and rims of vases, fragments of bronze castings, crumpled bronze sheet, and quantities of disintegrated sheet do not appear very interesting. Yet, in spite of their fragmentary condition, these bits of metal are valuable sources of information about metal manufacturing techniques and the tools used in the process. Another group of fragments do not come from finished objects but rather are the bits and pieces of debris, such as drips and spills, risers and gates, that would be found where casting of bronzes had taken place. From their presence so near the temple we infer the existence of foundry working in or near the temenos.[3]

The investigation of metalworking at Isthmia began in 1978 as part of an interdisciplinary project whose aim was to examine objects of the period before 146 B.C., with a view to determining the raw materials used in their manufacture, the source of these materials, the methods used to produce the objects, and, if possible, the place of manufacture. Included in the project were all stone, terracotta, and metal objects that have been recovered between 1952 and 1966 during excavations directed by Professor Oscar Broneer. The team was composed of Professors W. Rostoker (metallurgist, 1978 and 1979 seasons), W. Baur (geologist, 1978 season), D. Levinson (metallurgist, 1979 season) and E. Gebhard (archaeologist, 1978 and 1979 seasons), from the University of Illinois at Chicago Circle.[4] The first season was devoted to an inspection of the objects

[1] The temple and other architectural remains of the Sanctuary of Poseidon exclusive of the theater have been published by O. Broneer: *Isthmia*, Excavations by the University of Chicago under the Auspices of the American School of Classical Studies at Athens, I, *Temple of Poseidon*, Princeton 1971; II, *Topography and Architecture*, Princeton 1973.

[2] Selected objects and a description of their recovery appear in Broneer's preliminary reports: *Hesperia* 22, 1953, pp. 183–195; 24, 1955, pp. 110–141; 27, 1958, pp. 1–37; 28, 1959, pp. 298–343; 31, 1962, pp. 1–25. The arms and armor are being prepared for publication by Dr. Alastar Jackson; Professor Isabelle Raubitschek will publish the other metal objects.

[3] By "temenos" is meant the Temple of Poseidon and the area immediately surrounding it; see Plate 102 taken from *Isthmia* II, plan III. Cf. *ibid.*, p. 3, note 10.

[4] The project was supported by a grant from the National Endowment for the Humanities matched by gifts from private donors. Permission for our work at Isthmia was kindly given by the Greek Archaeological Services through the then Ephor of Antiquities for the Argolid-Corinthia, Mrs. K. Krystalli-Votsi. The interest and encouragement of Dr. N. Yalouris, Inspector General of Antiquities, contributed much to

and visits to Olympia, Delphi and Nemea in order to compare the Isthmian material with that from the other Panhellenic athletic sanctuaries. Because of their specialized training and long experience a metallurgist and a geologist were thought well qualified to identify the raw materials and to reconstruct both the manufacturing techniques and the technology used in the production of the stone, clay, and metal objects. Following their inspection of the artifacts, Professors Rostoker and Baur designed research projects directed toward the main problems of the project. The following study of metalworking is the third in a series of reports on materials and their use at Isthmia. The first two, analyses of the iron and bronze slag, will be published separately. Other reports will follow.

We realize that the survey of technology presented herein is in a sense random and not a complete account of Greek metalworking since it is based only on the material that has survived at Isthmia, which was a sanctuary and not a city. Nonetheless it is significant that such a wide range of sophisticated techniques for working metal is represented. The international character of the shrine and the fame of the festival celebrated there would in part be responsible for the richness of the offerings. The other factor would be its proximity to Corinth. That city was a center of trade and enjoyed great prosperity during most of this period, and it was famous for the production of fine bronzes.[5]

The question of where the metal objects found at Isthmia were actually made cannot be answered. The bronzes seem to be alloys of copper with 3–5% tin,[6] which is a common proportion for the period. Chemical analyses of the bronzes and comparison with samples whose place of manufacture is fairly certain were outside the scope of this project, and the team did not deem them likely to be profitable.[7] What can be noted here is that there is a remarkable similarity between the metal objects found at Isthmia and those at Olympia, Delphi and Nemea.[8] This similarity includes not only the type and style of votive figurines, armor, weapons, and vessels, but also the presence of broken castings and other debris that appear to have come from a foundry at or near

its completion. We would like to express our thanks also to Professor H. R. Immerwahr, Director of the American School of Classical Studies at Athens, Professor H. A. Thompson, Institute for Advanced Study, Princeton, to Dr. H. Blythe, and to Dr. K. J. Weintraub, Dean of Humanities, University of Chicago, for their many kindnesses and support during many stages of the project; and to C. K. Williams, II, Director of the Corinth Excavations, for reading and commenting on the manuscript. The photographs were taken by Wendy Rostoker; a catalogue of uninventoried metals at Isthmia was undertaken by P. R. Gebhard and D. Ed-wards.

[5] Cf. Pliny, *N.H.* XXXIV.3.6–8 and elsewhere. See Plate 103 for a map of the area between Corinth and Isthmia.

[6] Two figurines from the Geometric period may have a slightly different alloy, but no tests were made on them because of their fine state of preservation and artistic value.

[7] A study of origins on the basis of style will be included in Professor Raubitschek's work.

[8] We wish to thank Professor Claude Rolley for his kindness in showing us the metal objects and the tiles in the storeroom at Delphi, Professor A. Mallwitz for his tour of the collection of bronzes at Olympia, and Professors Stephen and Stella Miller for their cooperation in showing us the metal objects from Nemea.

the site.[9] Taken in their entirety the assemblages of metal objects from all four of the Panhellenic athletic sanctuaries have much in common.

Location of Deposits

The temenos of Poseidon occupies a flat shelf of rock with a deep gully at the northwest side and a depression along its eastern edge (Pl. 102). The ground rises gradually to the west and to the south it slopes up to a nearby ridge called the Rachi.[10] The earliest temple to Poseidon was built on the rocky plateau shortly after 700 and was destroyed by fire about 480–470 B.C.[11] Before the middle of the century it was replaced by a new shrine on the same site, which in turn suffered severe damage by fire in 390 B.C. After each conflagration much of the debris from damaged portions of the temple, blocks and roof tiles, and objects housed in or near the temple were removed from the temenos and dumped into the depressions to the northwest and to the east of it.[12] Some of the material from the Archaic temple remained within it, covered by the floor of the Classical building. The area in front of the temple was also strewn with refuse, presumably covered over in later times. In addition to the numerous roof tiles and wall blocks from the Archaic temple, but many pieces of bronze, lead, iron, pottery and a few fragments of marble sculpture were also present. The debris in the North Temenos Dump, covering an Archaic road that led to the sanctuary, reached a depth of nearly seven meters at the north side. The East Temenos Dump was formed over the Archaic sacrificial area in front of the early temple, and the debris varied in depth from 0.50 m. at the west side to over two meters at the east edge of the area. A third place that served as a convenient depository for refuse was a large circular pit located 43 meters south of the west end of the temple (Pl. 102). It appears to have been dug as a great well or reservoir, but when it did not work as planned, it was filled up between 450 and 425 B.C. The pit is 5 m. in diameter and 19.75 m. deep. In addition to quantities of large stones, the shaft contained a great deal of pottery, some small pieces of stone sculpture, many metal fragments and much slag. For the purposes of the following study the metal objects from the three dumps are considered together, with the addition of a few pieces from other places connected to the sanctuary (e.g. the Rachi and the West Foundation; see Table), which belong to the 4th and 3rd centuries B.C.

Five metals are represented among the artifacts at Isthmia:

Bronze: mostly containing about 5% Sn (tin) as judged by color and hardness. It is noteworthy that unalloyed copper was not represented in any of the objects where metal remained. Most thin, sheet-metal objects and fragments were corroded to a

[9] See below, The Case for a Foundry at Isthmia.

[10] *Isthmia* II, pp. 1–3, plan II.

[11] *Isthmia* I, pp. 1–3, and notes 2–7 with references to earlier publications.

[12] For a description of the East Temenos Dump, see Broneer, *Hesperia* 28, 1959, pp. 303–304, pl. 60:a; for the North Temenos Dump, Broneer, *Hesperia* 27, 1958, pp. 2–3, pl. 1. See also *Isthmia* II, pp. 9–10, 65, 76, pls. 4:b,c, 31:b,c.

point where shape and approximate dimensions remained, but the metal itself had been completely converted to corrosion products.

Iron: very low in carbon content judging by hardness and the absence of sparking during grinding. This signifies fabricated "bloom" iron, the ancient ferrous metal. Since all of these objects were heavily rusted, the original surfaces were all mineralized and detection of carburization as an existent process was not possible.

Gold: mostly in the form of leaf (foil), but there are also three Persian coins and two tiny but very detailed castings on display in the Museum at the site. From the color the gold appears to be unalloyed or close to 24 carat.

Silver: in the form of coins or rings which are very fragile. Fresh fractures of the ring fragments disclose an inter-crystalline mode that identifies a poor quality of metal and the presence of an embrittling impurity.

Lead: with the exception of a small kouros, lead was apparently used mainly for constructional purposes not all of which are obvious. There are large numbers of short rods (80–120 mm.), rectangular in cross section and tapered at one or both ends (Pl. 104:a). They are obviously individually shaped by hammering as if for a custom fit, but their use is not known. There were a few composite artifacts: iron clamps embedded in cast lead and an iron spear butt encased in ornamental bronze.

A crude hardness test was provided by spring-loaded punches whose indentation diameters had been calibrated both for bronze and iron against the Vickers Hardness Test system. A set of analyzed, cast-bronze specimens, sectioned and polished, provided a color calibration that was useful in assigning approximate tin contents of artifacts whose metallic color could be revealed.

The Case for a Foundry at Isthmia

There are features of certain cast fragments and other metal objects that strongly suggest that castings were made at the site of the Sanctuary.

The essential features of a foundry operation are

(a) a supply of metal in pieces suitable to fit in a crucible or for rapid melting in a shaft furnace. Bronze can be remelted without significant deterioration or change of composition. For this reason bronze founders use a high proportion of scrap since it is usually available and cheaper than imported virgin metals. Note that a high proportion of any raw casting is redundant metal which must be removed and can be remelted.

(b) a melting system which can be either a kiln-style furnace handling pre-loaded crucibles or a shaft furnace which charges fuel and metal at the top and taps liquid metal out of the bottom.

(c) a pouring system which is either the means for handling hot crucibles filled with metal or channels which conduct the tapped liquid from a shaft furnace to the molds by gravity flow.

(d) a mold system comprising the mold cavity, gates, risers and runners which enforce filling, venting and controlled solidification.

(e) a finishing facility whereby gates, risers, and runners are cut off, surface defects obliterated and surfaces ground and polished.

Transporting liquid metal is an untidy process resulting in spills and dripping. Molds do leak. These events leave solidified drippings in the form of globules and droplet shapes. Spills on the ground spread out into pancake-like pieces with rounded edges.

Many accidents occur in casting. The mold pieces or the cores shift while the heavy liquid is being poured, resulting in leaks and misshapen castings. If the metal is poured too cold, it will not completely fill the mold before all liquid motion stops. Such casting misruns are rejected and can be re-used as scrap.

A foundry only ships out castings which are of good quality and completely finished. Misrun castings are broken up into small pieces convenient for melting. Cast bronze fractures reasonably easily, i.e., without much deformation, but large hammer forces are required. A fractured fragment of a casting can only have occurred by very deliberate and forceful action.

Because of the great value of scrap for remelting, gates, risers, runners, spills, drippings and misruns never leave the foundry. They are recirculated into the melting system. Purchasing scrap from the neighborhood is a common practice even today.

Some of the bronze fragments recovered from excavations at Isthmia can be interpreted either as appropriate for use in a foundry or inappropriate to anywhere else but a foundry. The objects listed below and in the table on pp. 362–363 are simply representative of the type, and other examples in each group are found among the inventoried and uninventoried bronzes from the temenos:

(a) numerous pieces of bronze which are spills or drippings (Pl. 104:b).
(b) a riser with two runners, and a gate, typically removed from a raw casting at the foundry (Pl. 104:c,d).
(c) a large variety of thick bronze fragments of a similar size that are castings deliberately broken up. Their fracture surfaces indicate forceful impact as by a sledgehammer type of tool (Pl. 104:e).
(d) quantities of bronze sheet which has been cut up and folded over on itself several times to form pieces about the same size and volume as (c) (Pl. 105:a,b).
(e) fragments of small castings which have not been finished (Pl. 104:f).
(f) fragment of a thick-walled tube which represents a misrun (Pl. 105:c,d).

A search of bronze objects in the storerooms of the museums at Delphi, Olympia and Nemea reveal in each place the same spills, drippings, risers, gates, runners, misrun castings and broken heavy fragments, all in sizes appropriate for a remelting operation.[13]

At Isthmia the fragments described were recovered from the North and East Temenos Dumps, from within the temple, and from the area east of it, with one riser coming from the Circular Pit. In some places it was not possible to separate the deposits

[13] Cf. drips and spills found in the "Mudbrick Foundry" southwest of the Hephaisteion in Athens (C. Mattusch, "Bronze and Ironworking in the Area of the Athenian Agora," *Hesperia* 46, 1977, pp. 359–362).

belonging to the Archaic temple from those put down after the fire in the Classical temple in 390 B.C. As a result of either conflagration many of the bronze objects in and near the temple would have been damaged and could have been consigned to the metalworkers for scrap. The larger castings would have been broken up to the appropriate size for remelting. It may also have been the practice at Isthmia and elsewhere simply to "recycle" old dedications which lacked historic or artistic reputation.[14]

On the basis of the evidence described above, we conclude that there were foundry operations in the vicinity of the temple sometime during the 5th and early 4th centuries B.C.[15] What have been recovered are simply the few pieces and fragments of bronze that eluded the scrap handlers. It also seems likely that the temporary establishment of a foundry to produce castings as needed was common to other temple sites.

CASTING TECHNOLOGY

There is great versatility evidenced in the variety of small bronze castings that have been recovered. Larger castings appear to have been systematically broken up, and only a few small pieces have survived. In general, castings are distinguishable from wrought products by their range of permissible shapes. Whereas today many shapes can be made interchangeably by casting or closed-die forging, die steels, die sets and deep die cavities were not possible until relatively recent times. Forging in the open-die manner with simple tools places great limitations on shapes, symmetries and sizes, especially for products of base metals.

A case in point is the decorative bronze handle IM 1793 (Pl. 105:e). This piece can be made either by casting or by closed-die forging. Forging, however, would require

[14] A concentration of patches and small fragments from bronze sculptures was found in the area of the Central Shops at Corinth, perhaps collected for remelting in the Roman period (C. Mattusch, "Corinthian Metalworking: The Forum Area," *Hesperia* 46, 1977, p. 386).

The debris in the North and East Temenos Dumps and the Circular Pit contained the same variety of damaged and undamaged metal and non-metal objects as was found within and east of the temple itself, beneath the levels of the later floors, which, however, are not preserved. The objects include the refuse from bronzeworking (described above) as well as metals not necessarily foundry debris (e.g., the objects in Plates 107:b–e, 108:a,c, and many lumps of partially melted bronze, some with pieces of iron and charcoal embedded in them, perhaps from the temple fire), and non-metal objects that had been damaged in the fire. It would appear that at the time the temenos was finally cleared of debris, a foundry had been in operation somewhere in the vicinity. The relatively small amount of damaged and undamaged bronze recovered from the area suggests that much of the scrap had already been re-used.

[15] The actual site of a foundry has not been recovered at Isthmia, but the ephemeral nature of the workshop and furnaces makes this not surprising. In the area of the Athenian Agora the furnaces have disappeared, leaving only the casting pits to mark the work site (Mattusch, *op. cit.* [footnote 13 above], p. 378). A workshop for bronze casting belonging to the second half of the 5th century B.C. has been found at Nemea, some 70 meters from the Temple of Zeus and located in the back part of an earlier building that had been destroyed. The shop included a small furnace and debris composed of bronze drippings, fragments of terracotta molds and a variety of tools (S. Miller, "Excavations at Nemea, 1976," *Hesperia* 46, 1977, pp. 19–20, fig. 5, pls. 12, 13:a). For bronze foundries at Olympia, see A. Mallwitz, "Die baugeschichtlichen Ergebnisse der Ausgrabungen 1954–1958," *OlForsch* V, Berlin 1964, pp. 42–46, pl. 24; R. Hampe and U. Jantzen, "Bericht über die Ausgrabungen in Olympia. Die Grabung in Frühjahr 1937," *JdI* 52, 1937, pp. 28–41; and W.-D. Heilmeyer, "Giessereibetriebe in Olympia," *JdI* 84, 1969, pp. 1–28.

large die blocks of considerable hardness, which are well aligned. Even a carburized, sunk die would not serve. It is inescapable that this item is a casting.

The use of patterns and mold materials can only be inferred. There are no distinctive evidences on the castings. The use of molding sands as most commonly practiced today is unlikely because the sands of Greece are predominantly limestone granules rather than silica. Limestone would be thermally unstable in contact with molten bronze. On the other hand, clays are plentiful, so that dried or baked clay molds were most likely used.[16]

The pattern system is even more speculative. Shapes and recesses can be carved into wet and sun-baked clay. Replicas of the cast shape (or portions) called patterns can be sculpted in wood or lead and used to impress a soft clay block. A casting is then poured into a cavity which is an assembly of two or more partial cavities. This system has the advantage that a large number of nearly identical castings can be made from one pattern.

The fragment of the cast bronze bowl IM 2333 (b; Pl. 106:a) illustrates what is probably the product of a solid pattern system. The exterior rim detail is part of the casting replication. The surface features suggest a mold grain rather than engraving tool marks. The quality of the pattern repetition suggests that it was indented into the soft clay mold by a block or roll as a finishing operation.

The use of cores in molding was understood.[17] The thick-walled bronze tube IM 2808 (Pl. 105:c,d), of unknown function, is a case in point. A cylindrical clay mold forms the outer surface. To form the inner hollow, a solid core of clay with a diameter equal to the inside diameter of the tube must be positioned centrally in the cylindrical cavity. Molten bronze fills the space between the mold and the core. Plate 105:c, however, shows a highly variable tube-wall thickness which signifies that the core had shifted so that its center line no longer coincided with that of the cylindrical cavity. This is one of a number of what must be construed as rejected castings whose presence at a sanctuary invites explanation. While the core shift was not an inadmissable defect at the point shown, it would have been one a few inches away, where the core was probably resting on the mold.

Thin-walled, hollow castings of asymmetrical shapes were made by the lost-wax procedure.[18] The lead-filled figurine IM 2235 (Pl. 106:b) represents a complicated series of process steps:

[16] Many fragments of clay molds have been found in the metalworking establishments in and near the Athenian Agora (Mattusch, *op. cit.* [footnote 13 above], pp. 344–346, 350–352, pls. 79–81) and at Corinth (Mattusch, *op. cit.* [footnote 14 above], pp. 387–389). Others are well described and illustrated in the chapter "Bronze and Pewter" by D. Brown in *Roman Crafts*, edd. D. Strong and D. Brown, London 1976, pp. 27–32. They are also found in the foundries listed in footnote 15 above.

[17] A clear diagram of the procedure is found in Brown, *op. cit.*, p. 37, fig. 38. See also H. Hodges, *Artifacts*, London 1964, pp. 71–72.

[18] The lost-wax process was widely used throughout antiquity with no appreciable change. Drawings illustrating the procedure are given in Hodges, *op. cit.*, pp. 72–73, figs. 10, 11. A glossary for the non-specialist is supplied by Mattusch, *op. cit.* (footnote 13 above), p. 342, note 8. She illustrates the process as performed in a modern studio, pp. 377–378 and pl. 97. See also Brown, *op. cit.* (footnote 16 above), p. 27 and fig. 21.

(a) crude clay model;
(b) wax overlay with precise surface detail;
(c) investment in clay while maintaining a channel connection by means of a stub of clay between the inner clay core and the outer clay shell;
(d) stabilization of the relative position of the core and shell by metal pins (chaplets);
(e) wax melted out and clay baked; metal poured and solidified;
(f) stripping of the clay shell and extraction of the clay core via the channel connection (now a hole);
(g) filling of the hollow bronze with molten lead via the hole.

The arrowheads illustrated in Plate 106:e,f deserve some special comment. They would have been made in large numbers, and that requires a simplified procedure for mass production. The two-barbed arrowhead (Pl. 106:f) allows this because of the design in a simple, two-fold plane of symmetry. The production technique would involve multiple indentation of the half-shape in soft blocks of clay. Two baked blocks assembled properly would allow a number of arrowheads to be cast in a single mold.[19] There is such a multiple-arrowhead casting in the inventory at Delphi.

On the other hand, the three-barbed arrowhead (Pl. 106:e) has a three-fold symmetry which is less easily duplicated and not amenable to mass production. More likely, this shape required a wax-replica process, i.e., the investment of the wax shape by clay and then the melting out of the wax. Both of these arrowheads have very thin walled, tubular sockets that require a small core which must be very carefully positioned in the mold. The wall thickness of the socket is only about 0.33 mm. thick, which is quite a casting accomplishment necessitating probably both preheated clay molds and superheated metal. It is also possible that a reaming tool was used to thin and size the socket.

Plate 106:c shows a full-scale cast bronze thumb (IM 225) which has clearly been broken off a larger casting, probably a life-size statue. The thumb is solid and appears to be unfinished. If the latter is true, then the full casting was not finished and would have been broken up for scrap at the casting site.

Sheet-Metal Processing

A great many of the metal fragments recovered at Isthmia were pieces of bronze sheet metal of about 1 mm. thickness. While retaining their original shape, most of these fragments are completely converted to corrosion products. Curiously, a few pieces survive with little or no corrosion and with the original surface finish intact.

The quantity of sheet fragments makes it clear that formed sheet objects were quite common. Probably much of this was body armor, but there were bowls and other containers and utensils with thick rims for stiffness.

Making sheet as for body armor must have been a tedious job, for there was no simple equivalent of the modern rolling mill which produces wide and long sheets from

[19] A bivalve terracotta mold for a spearhead was found at Corinth in a context belonging to the 6th century B.C. (Mattusch, *op. cit.* [footnote 14 above], p. 381 and note 6). Bivalve molds to make a series of rings were in use at Corinth in the 12th century after Christ (*ibid.*, pp. 387–388, pl. 103:c).

which smaller pieces can be cut for forming operations. In modern processing the large area and the small thickness are established by rolling, and the final shape by stretching, forming, and bending. These latter processes represent curve forming but result in relatively little change in area or thickness.

Without the rolling mill, area generation, thickness reduction, and curvature evolution can be combined. A sensible approach would be to cast flat or curved slabs, as thin as possible, representing a little more than the ultimate finished volume. The cast shape would then be subjected to incremental deformation by a system of hammers and anvils. The anvils would represent evolutions to the ultimate shape. The incremental aspect applies not only to the steps in thickness change but also to the relatively small zones of the workpiece (i.e., piece of metal being worked) at any moment between the hammer and the anvil.

The workpiece would be preheated before hammering (i.e., hot worked) as long as it was thick enough to retain temperature for a reasonable period of time. Hot working is always preferred because the workpiece metal is much softer under these conditions and does not acquire higher hardness as working progresses. Hot working becomes unfeasible, however, when the part dimensions become awkward to manipulate in and out of the heating system, and when the reduced thickness allows for very rapid cooling.

Thereafter, further sheet-metal working must involve cold deformation followed by annealing to reduce the acquired hardening and to restore a soft and ductile condition. Multistage working and annealing are for many reasons a preferred approach to fabrication. Cold-work, anneal processing uses the same tools, but the time urgency is removed. Cold working permits greater uniformity in thickness, flatness, and smoother surfaces, i.e., more free of peen marks (made by a ball-headed hammer). Furthermore, the finished product may be left in the unannealed or partially annealed condition, so that it has higher strength and hardness.

There is evidence of quite sophisticated sheet-metal working. The funnel IM 2768 a shown in Plate 106:d illustrates the difficult art of dimpling. While the remainder of the bowl shape was restrained, a circular zone was stretched to conform to a conical bulge. The formed bulge was then pierced and the hole edge flared. This sort of sheet forming taxes the ductility of the metal, particularly by stretching the hole edge, and necessitates frequent and judicious annealing. The finished product, however, was left in the cold-worked condition as, in due course, cracking (stress-corrosion cracking) occurred. The delayed cracking, perhaps years later, is the result of the residual stresses in the product. It is possible to relieve these residuals without much loss in hardness by careful control of annealing temperature, but this is a modern technique made possible by temperature measuring and control instrumentation.

Concept of the Cast Preform

Since flat rolling was not practiced, there is no need to confine our thinking to the casting of flat slabs of uniform thickness. The sensible fabricator would relate the cast shape to the finished product. He would also design the cast volume to be not much more than the finished volume because the virtue of metalworking is its capability of generating shape and dimensions without metal removal.

Consider the fabrication of a bowl (IM 3274), a fragment of which is illustrated in Plate 107:a. The rim is about 10 mm. thick, tapering quickly to the bowl wall which is about 1 mm. thick. A cast preform would have a shallow dish shape, an outer peripheral circumference at or near that of the bowl rim and a generally thick wall. A single anvil having the curvature of the final bowl is used. As deformation thins the body of the rim, the dish bulges. The fabricator begins the thinning by hammering at the center, and works in a spiral pattern to the periphery. A number of spiral-pattern passes are necessary to achieve the final wall thinness. Between the passes the metal would be annealed.

The unique design of the Corinthian helmet represents a very sophisticated example of a bowl-shaped object with variable thickness. The Corinthian helmet has a thick nose guard (*ca.* 5 mm.) integral with the skull, a neck cover which is much thinner (*ca.* 1 mm.), and a rim around the neck and cheek which is of intermediate thickness.

It would be almost impossible for an ancient craftsman to cut out a pattern from a bronze plate having the thickness of the nose guard. It would be much easier to cast a curved plate of equal or variable thickness, replicating closely the nose guard so that little forging would be necessary, and incorporating sufficient volume of metal in the curved plate (dish shaped) so that the skull cover could be formed like a bowl by the thinning action of the hammer and anvil.[20]

Some of the nose guards on helmets at Isthmia, and at both Delphi and Olympia, which are in a very good state of preservation, have added features which make the cast preform more credible. These nose guards show very thin, pin-like projections closely spaced all along the edge. Where these projections are preserved on the inside of the nose guard they would have served to affix a leather lining.[21] On the outside they are cut off and only the stubs are visible.

In principle one might produce these pin projections by drilling dozens of tiny holes through the thick bronze nose guard. This would be a task of formidable proportions even with modern tools and equipment. It is hard to believe that so many holes were drilled in thousands of such helmets.

On the other hand, producing the pins as inserts in the casting preform would be simple and actually be functional to the casting process. In preparing a mold around a

[20] A. Snodgrass assumes that the entire helmet was beaten out, but he does not mention the nosepiece specifically (*Arms and Armour of the Greeks*, London 1967, p. 51). He states that the Corinthian helmet appears to be a Greek invention of the late 8th century B.C., and that it went out of use abruptly in the early 5th century B.C. (*ibid.*, p. 94).

[21] *Ibid.* Holes are found around the rim of some helmets, perhaps for the attachment of a lining, but not on all examples, e.g., Isthmian nosepieces IM 1494, IM 1477, IM 1274, IM 1422, IM 1478; cheekpieces IM 1704, IM 1849, IM 1853. We are indebted to Dr. Jackson for this information and for other help besides.

wax replica there is danger of the mold collapsing as the melted wax runs out. This is prevented by the "chaplet" system wherein many thin, short, bronze or copper wires are pierced through the wax replica so that their ends become embedded in the clay mold on either side. When the wax is melted out, the chaplets act as struts which prevent the mold walls from moving or fragmenting. When the bronze is poured, the struts become incorporated in the casting, and when the clay is removed they exhibit the projections of the original configuration.

If the chaplets were copper instead of bronze they would not necessarily melt and would simply be invested in the casting but not integral with it. Corrosion would proceed at different rates and the pins would become loose and even dislodge. In many of the nose-guard fragments at Isthmia (e.g., IM 1450, IM 1632) some of the pins are in place and some have indeed been dislodged, and tiny holes are evident at least part way into the thick bronze. In other examples no pins are evident.

Machining Processes

In the broadest context the term "machining" embraces all metal-removal processes. It is almost inevitable that finished products will be finally finished by metal removal. Raw castings have rough surfaces and superfluous appendages such as gates and risers which are important to casting and freezing but redundant for the shape and use of the final product. Accordingly gates and risers are cut off. The surface blemishes and the riser stubs are filed until such protrusions disappear. The filed surfaces and the moderately rough surfaces are rubbed with abrasives (grinding and polishing) to produce an aesthetically acceptable surface finish.[22] Surface defects that are holes or depressions must be filled. There are a number of bronze fragments at Isthmia that show rectangular patches in place. The hole defect was widened to a square recess and a tight-fitting patch was hammered into place (or perhaps soldered).[23]

Formed sheet-metal products usually have irregular edges which must be trimmed by chisel or file or both. Attachment of knobs or handles was usually accomplished by riveting which requires the making of holes. The hammering process leaves surfaces pebbled with peen marks that can be removed with abrasives.

All of these examples bespeak the need for machining tools which are likely to include chisels, burins, saws, awls, files and abrasive powders (silica or emory). Evidences for their existence are on the products themselves. There are, for example, readily visible file marks on the arrowhead (two-fold symmetry) in Plate 106:f. The recess for the rectangular patches and the rough cutting of the patch for statue repair require a chisel.

[22] A red-figured amphora in Boston shows Hephaistos as a smith polishing a shield with something that looks like pumice (A. Burford, *Craftsmen in Greek and Roman Society*, London 1972, p. 194, fig. V). Several pumice stones have been found in Athenian foundries (Mattusch, *op. cit.* [footnote 13 above], p. 353, notes 30, 31, pl. 86).

[23] See Brown, *op. cit.* (footnote 16 above), p. 32, fig. 28 and Mattusch, *op. cit.* (footnote 14 above), pp. 384–386, pls. 99 –102.

Considering the volume of metal machining that accompanied the great quantity of bronze and iron products represented in the deposits at Isthmia, very few tools have survived. There is a badly rusted but recognizable chisel (Pl. 107:d). Chisels have been found at Nemea and in the Athenian Agora, where a saw was discovered as well. All of these vestigial tools are of iron (perhaps carburized). Because of their poor preservation the tool inventory of a workshop must be largely inferred. Iron seems to be the metal most commonly employed, but the remains are rusted so badly that it is not yet possible to know what hardening process was used. Bloom iron would be a poor tool material even if cold worked.

Plate 105:f shows fragments of a bronze sheet with a line of very small and closely spaced holes that were presumably used for stitching the metal onto a lining. Much of the sheet bronze went into shields and body armor. A shingle configuration of small pieces of bronze sheet stitched to leather or linen provided both protection and flexibility. Bronze scales were stitched to the linen backing of a corselet from the late 6th century B.C.[24]

Allowing for growth of corrosion products, these holes must have been originally about 1.5 mm. in diameter with an edge-to-edge spacing of about 2 mm. Hundreds of these small holes would have been required in a completed suit of armor. There must have been some reasonably simple way to make these holes. It would not be a simple task even today. The modern technique would be to use either the twist drill or the punch-die set. Both of these methods require very hard steel and are relatively modern developments.

In the absence of a martensite steel, one feasible method is to use an awl against a hardwood backing. The awl forms a small bulge which ultimately ruptures the metal at the crown of the bulge. Thereafter the awl is used to expand the hole by flaring. The flaring produces a set of raised projections on the back surface of the sheet which must be removed by filing. There is no evidence of a raised profile on the fragments shown in Plate 105:f. In addition, the holes are positioned very close to the edge of the piece of sheet. The deformation action of the awl consequently would generate a series of edge bulges which could not be filed off without bringing the holes too close (or past) the new position of the edge of the metal sheet. This problem could be obviated by fabricating a sheet-metal unit double the finished size, running two rows of holes down the center, and separating the sheet into two pieces by a chisel cut, along a line between the two rows of holes. If the holes were indeed formed by an awl, the problems and questions focus on the awl itself. The point of the awl must be very sharp and the metal must be very hard at the extremity. What metal was used for the point of the awl, the edge of the chisel, the edge of the burin, the teeth of the file and the saw, and what treatment was used to attain high hardness can only be conjecture.[25]

[24] See Snodgrass, *op. cit.* (footnote 20 above), p. 92.

[25] J. Healy's discussion of treatments for hardening iron is difficult to follow, and he gives few examples or analyses (*Mining and Metallurgy in the Greek and Roman World*, London 1978, pp. 231–234). See also R. Tylecote, *A History of Metallurgy*, London 1976, pp. 43–45. Stephanos of Byzantium (ed. W. Din-

Plate 107:c shows an ornamental bronze knob (IM 2361 a) which appears as a graded stack of six disks with rounded edges and of sequentially decreasing diameter. Both the assembly and the individual disks appear to have perfect rotational symmetry. The six disks could be separate castings strung on the stem of a pin with perfectly centered holes, or the disks could be an integral casting. The latter is unlikely because the flow of liquid metal through the constrictions would be prevented by freeze-off. The constriction in the casting, however, could have been larger and have been reduced later by a metal-cutting operation. In either event the rotational symmetry of the sub-units or the integral unit needs the essential configuration of a lathe with its grips, bearings, rotational capability, and rigidity so that metal cutting (probably filing) can proceed.[26]

Bronze Wire and Tube Products

Wire and wire products seem to be relatively rare. Plate 108:a shows two bronze needles (IM 103, IM 104) which explain why. The needles, as with other samples of wire, have been formed by hammering. Apparently the draw-die and draw-plate techniques were not used by the Greek craftsman at Isthmia. Hand hammering as a process for making wire is slow, makes an irregular cross-section diameter and shape, and restricts both the wire lengths and the wire diameters. The drawing of wire through a series of conical dies, on the other hand, at once provides circular section and uniform diameter, unlimited ranges of diameters and lengths, smooth surface and high productivity.

Wire forming by hammering does allow for ornamental options. Plate 108:b illustrates a narrow ribbon that would be made by hammering wire into a flat strip and indenting it incrementally along the ribbon length with a profiled hammer and matching groove in an anvil.

Nails and rivets are considered basically to be wire or rod products. Bronze nails and rivets seem to be quite common at Isthmia (see Plate 107:e). They are made individually. Cast-bronze rods are hammered to appropriate round or square profiles and cross-sectional dimensions. They are cut to length, and the nails are tapered or pointed

dorf, Leipzig 1825, p. 270, lines 13–16) notes that iron from different cities had various uses, that from Lakonia being best for files, augers to cut iron, dies and tools to cut stone; Lydian iron was to be used for files, knives, razors and engraving tools.

[26] Pliny (*N. H.* VII.198) attributes the invention of the lathe to Theodoros of Samos in the mid-6th century B.C. The idea may have been taken from the practice of shaving a vase while it rotated on the wheel head. The earliest epigraphical reference to metal objects being turned is found in an inscription from Eleusis (*IG* II², 1675, lines 22–23) giving specifications for bronze dowels (*poloi*) to fasten the column drums for the Porch of Philon on the Telesterion, constructed *ca.* 330–310 B.C. See G. Varoufakis, "Materials Testing in Classical Greece, Technical Specifications of the 4th c. B.C.," *Journal of the Historical Metallurgy Society* 9, 1975, pp. 57–63; D. K. Hill, "The Technique of Greek Metal Vases and Its Bearing on Vase Forms in Metal and Pottery," *AJA* 5, 1947, pp. 248–256. I am indebted to Dr. H. Blythe for these references. An extensive study of Roman lathes has been made by A. Mutz, *Die Kunst des Metalldrehens bei den Römern*, Basel 1972. See also Brown, *op. cit.* (footnote 16 above), p. 34 and figs. 33–35. Healy thinks that decorative filials were usually cast by the lost-wax process, *op. cit.* (footnote 25 above), p. 250, note 175.

at one end by hammering. The head is formed by gripping the shaft of the nail or rivet with wedges in a hole in the anvil. Sufficient stock protrudes above the hole. The projecting portion is hammered end-on so that it mushrooms. The thickened end can be flattened or contoured according to the hammer-face profile. Rivets usually have a hemispherical profile, which is an ornamental choice. Nails are usually flat headed, which is more functional. The ancient nails had larger diameters and thinner heads than are common today (except for certain roofing nails).

Tubes and tube shapes divide into two categories: seamless and seamed. The seamed tube subdivides into those whose seams are welded or soldered and those whose seam consists simply of two abutting edges. Of course, the seamless tube is much stronger and more easily allows secondary fabrication such as bending. It can also channel fluid flow without leaking.

Until modern times seamless tubes were, at least initially, castings (see Plate 105:c,d). Thick-walled bronze tubes seem to have had some important use as a number of them have also been found at Olympia and Delphi. One fragment at Olympia is 0.45 m. long, an exceptional length for such a casting since there is the obvious difficulty in stabilizing the position of the core.

The example (IM 782) in Plate 107:b shows that the principle of forming bronze sheet over a rod-shaped mandrel to make a tube was understood. The seam is tight; there is no visible gap. The seam has probably been soldered; unsoldered seams usually show a gap due to elastic spring-back after cold forming.

Iron Forging

A sufficient variety of iron objects have been recovered at Isthmia, such as axe, adze and axe-adze heads (e.g. IM 387; Pl. 108:c), clamps (for stone blocks), spear points, spear butts (e.g. IM 3447; Pl. 108:d), rivets, nails and agricultural tools, to indicate that within these categories iron was probably more commonly used than bronze. Iron objects are all basically hot forged and then cold finished when appropriate. The product after smelting is a slag-filled sponge of what is almost pure iron, in terms of both carbon and other elements.[27]

Sockets in axe and adze heads were formed by hot piercing. This is done on an anvil with a sharp-edged punch and a matching hole in the anvil. Part of the process in forming the hole involves cutting and pushing the iron ahead of the punch, and part involves displacing the metal laterally. This seems to have been a poorly designed process as most of the objects recovered were broken across the socket hole; i.e., in forming the hole metal was mostly removed rather than displaced so that the residual metal was inadequate for the service.

Sockets for spearheads and spear butts were forged as flat plates appended to the head or butt. The plates were then formed around a mandrel into a seamed tube with-

[27] A good representation of an iron foundry and smelting furnace appears on a black-figured pitcher in the British Museum (Tylecote, *op. cit.* [footnote 25 above], p. 45, fig. 34).

out any sort of bond between the abutting edges. The tube socket was attached to the spear shaft by spring fit coupled with a nail or rivet through a pierced hole (Pl. 108:d).

The iron clamps used in the stone architecture of the Classical temple at Isthmia were of the double-T shape, and on many of them the leading is preserved. In principle the lead provided not only a filled fit to the carved stone recesses but also good rust protection for the immersed iron. In some of the samples, however, when the lead was tested by drilling it was discovered that the entire clamp was made of lead and that there was no iron in it. It may be that the lead was thought strong enough to prevent the stone blocks from shifting (an erroneous assumption), or it may be that we have here an early instance of construction-contract malfeasance.

Conclusion

The craftsmen who made the metal objects recovered at Isthmia were very skilled in both the casting and the forming arts applied to bronze and iron. With simple tools they were able to produce quantities of sophisticated products with great aesthetic appeal and good uniformity of dimensions and finishes. Much can be deduced about fabrication processes, but the key questions which cannot yet be answered concern the nature of the metalworking tools, in particular the achievement of adequate hardness.

Questions of where all the artifacts from the Sanctuary at Isthmia were manufactured cannot be answered at this time. There is substantial evidence that a bronze foundry existed on the site. In other publications we will analyze the evidence for bronze and iron smelting at Isthmia. On the basis of these indications of industrial activity, one could reasonably conclude that at least some, though certainly not all, of the metals objects found at the site were made and finished there. Which type they were and how many were produced is impossible to say, though it is likely that the armor, weapons, and tools were made elsewhere.

While the sanctuaries at Delphi and Olympia are much richer than Isthmia in the number and quality of bronze objects that have been preserved, there is considerable similarity in the indications of the metalworking processes used, complexity of crafting, and functional and aesthetic designs. In particular, the remains or residues of foundry operations have been found at all four of the Panhellenic centers, Olympia, Nemea, Isthmia, and Delphi. This need not be very surprising. Furnaces and kilns as represented by the remains and by representations on vases seem to be of such simple design that they could have been built as needed, then discarded and destroyed when the work was completed.[28] Before and after the great festivals itinerant craftsmen carrying simple tools could have worked at the sanctuaries, supplying votives for the temple and commemorative statues of the victors.

[28] The temporary nature of furnaces and metalworking establishments is seen in the area of the Athenian Agora, where only one or two large castings were made before debris was thrown into the casting pit and the foundry walls taken down. The same seems to be the case for the foundries at Olympia and Nemea. See footnote 15 above.

CONTEXTS OF METAL OBJECTS

PLATE NO.

104:a Two lead strips, IM 458, IM 459: Temple, Tr. C9

104:b Bronze spills and drips, IM 2817: Circular Pit, Tr. H
Others not inventoried: N. Temenos Dump; N. Road Cut Tr., N.B.[29] 10, p. 167

104:c Bronze riser, IM 3252: Circular Pit, Tr. H

104:d Bronze gate, IM 2329: E. of Temple, Tr. E Central C
Uninventoried spills, drips and spoiled castings from the same context (not illustrated)

104:e Broken fragments of cast bronze
IM 796: Temple, Tr. C-8
IM 110: Temple, Tr. S-2
IM 2628: E. Temenos Dump, Tr. NE-C
IM 724: N. Temenos Dump, Ext. Tr. 3rd N.T.
IM 3183: Temple, Tr. NE-J
IM 3232: E. Temenos Dump, Tr. NE-D, S. Section (surface)

105:a Compacted bronze sheet, IM 475: Temple, ES, Tr. J

105:b Compacted bronze sheet
top row Two pieces not inventoried: I.D. lost[30]
bottom row IM 475 (see 105:a)
not inventoried: I.D. lost, but from same deposit as top row
IM 474: Temple, ES, Tr. G

104:f Unfinished casting of bronze figurine, not inventoried: SE of Temple, near Roman Altar, N.B. 49, p. 73

105:c,d Cast bronze tube misrun, IM 2808: E. Temenos Dump, Tr. NE-D, S. Section

105:e Cast bronze handle, IM 1793: N. Temenos Dump

106:a Rim of cast bronze bowl with embossed decoration
IM 781: Temple, Tr. C-3
IM 2333 b: E. Temenos Dump

106:b Bronze animal, lead filled, IM 2235: E. Temenos Dump, Tr. ET-VI

106:e Three-barbed cast bronze arrowhead, not inventoried: N. of Roman Altar, inside E. Stoa, Tr. NRA-a, N.B. 48, p. 16

106:f Two-barbed cast bronze arrowhead, not inventoried: E. Gateway in Early Roman Temenos, N.B. 48, p. 121

106:c Finger from bronze statue, IM 225: N. Temenos Dump, Ext. Tr. 2nd N.T.

106:d Thin-walled bronze funnel, IM 2768 a: Circular Pit, Tr. H

[29] N.B. = Excavation notebook.

[30] Certain identification tags and envelopes containing artifacts were obliterated or destroyed during a flood in the basement of the Corinth Museum while objects from Isthmia were stored there prior to construction of the Isthmia Museum.

107:a	Thin-walled bronze cauldron, IM 3274: E. Temenos Dump, Tr. NE-D South
107:d	Iron chisel, not inventoried: N. of Roman Altar, Tr. NRA-D, N.B. 48, p. 92
105:f	Bronze sheet with small holes, not inventoried: I.D. lost[31]
107:c	Bronze knob, IM 2361 a: E. of Temple, Tr. E Central C
108:a	Two bronze needles IM 103: Temple, N3B, Hole IM 104: Temple N6
108:b	Bronze ribbon, not inventoried: N. Temenos Dump, Tr. Ext. 2nd N.T., N.B. 6, p. 50
107:e	Two bronze nails IM 971: Rachi, Tr. IV IM 2169: E. Temenos Dump, Tr. ET III
107:b	Bronze seamed tube, IM 782: Temple, Tr. C-3
108:c	Iron axe-adze, IM 387: Temple, Tr. C-4
108:d	Iron spear butt, IM 3447: W. Foundation, Tr. L

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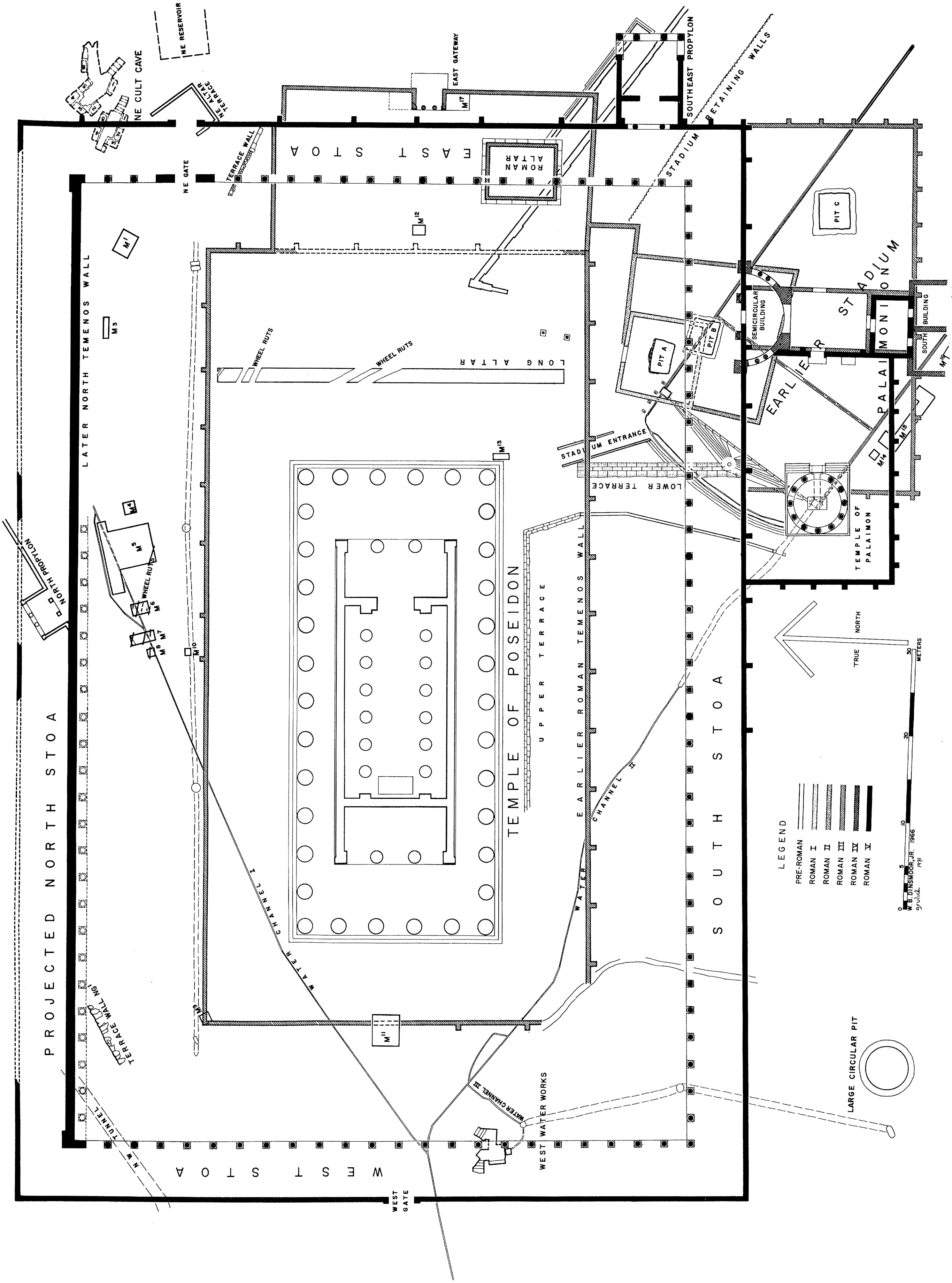
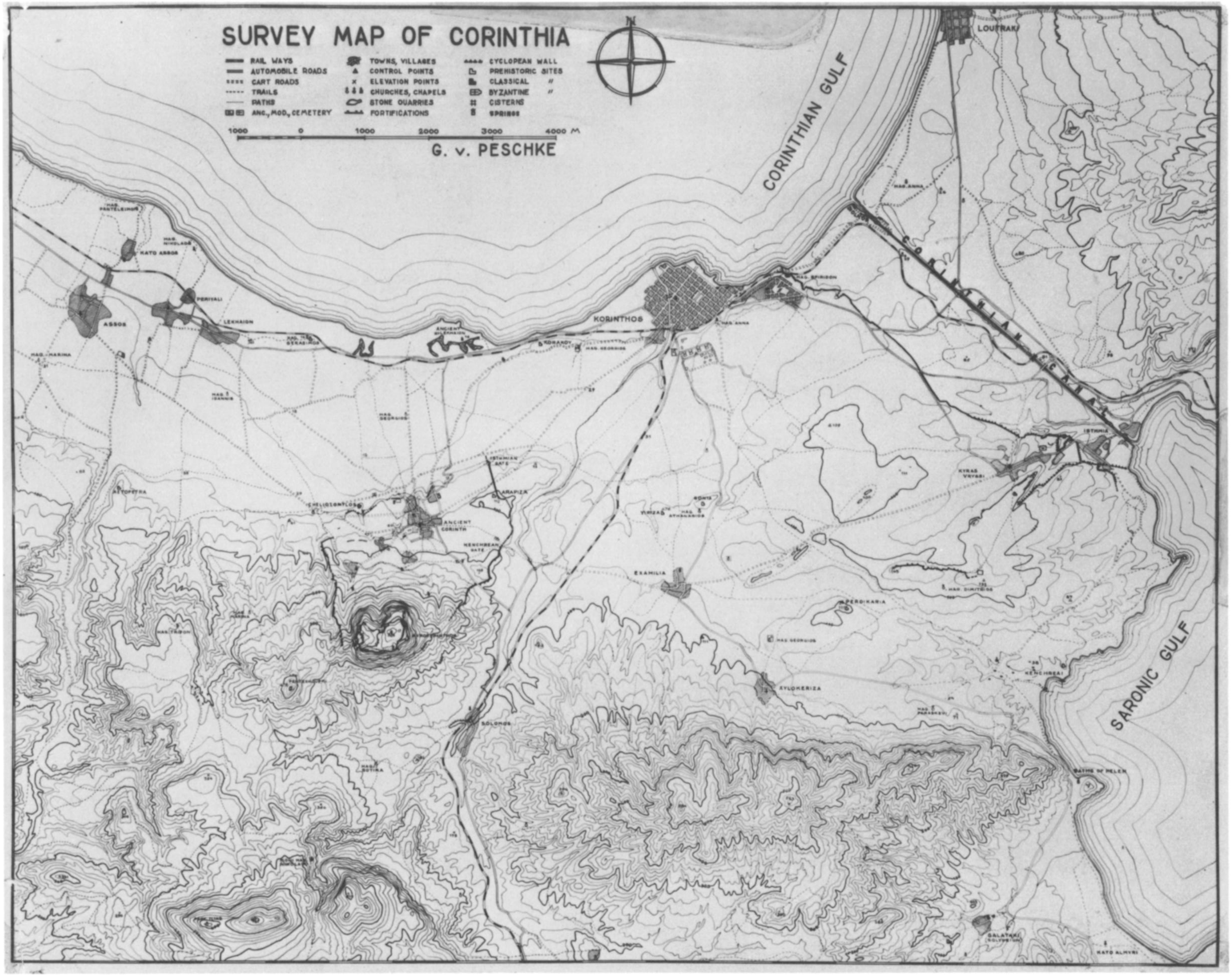
[31] *Idem.*

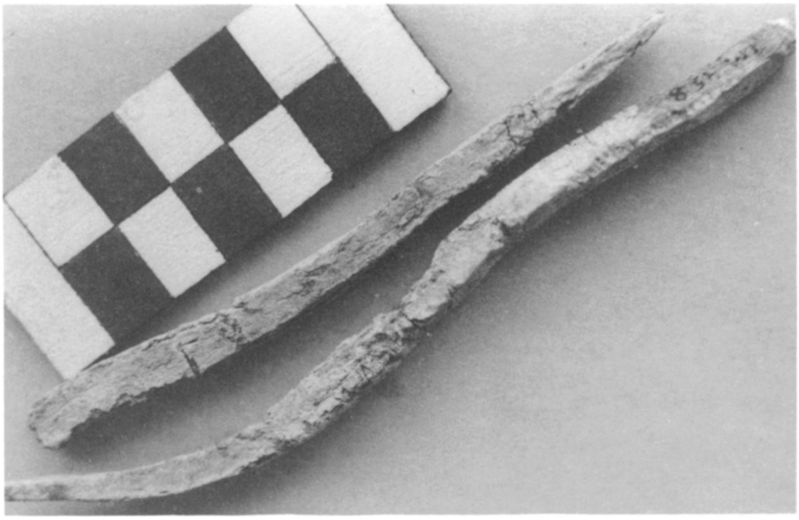


Period plan of the Sanctuary of Poseidon (O. Broneer, *Isthmia* II, plan III)

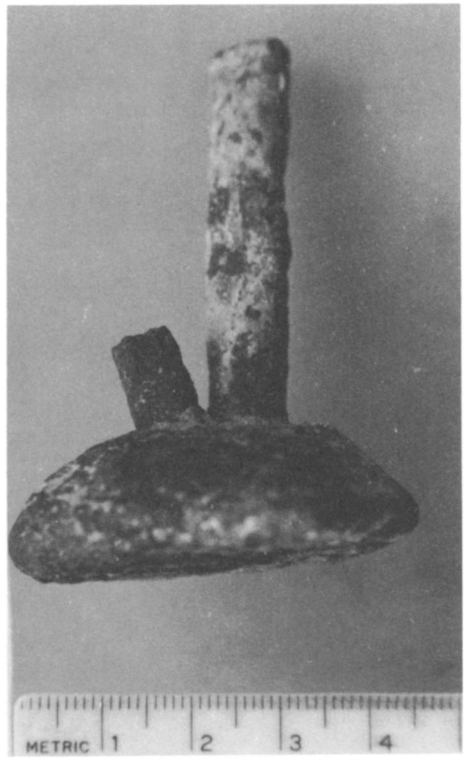
W. Rostoker and E. R. Gebhard: Techniques of Metal Manufacture at Isthmia



W. ROSTOKER AND E. R. GEBHARD: TECHNIQUES OF METAL MANUFACTURE AT ISTHMIA



a. Hand-crafted lead rods of unknown function: IM 458, IM 459

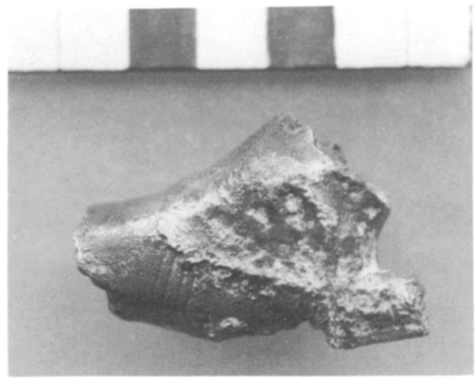


c. Bronze riser with two runners: IM 3252

b. Spills or drippings of bronze separated from a crucible full of liquid or a leaking mold. Lower center: IM 2817

d. Bronze gate: IM 2329

e. Bronze fragments produced by deliberately fracturing castings. Top: IM 796, IM 110, IM 2628. Bottom: IM 724, IM 3183, IM 3232

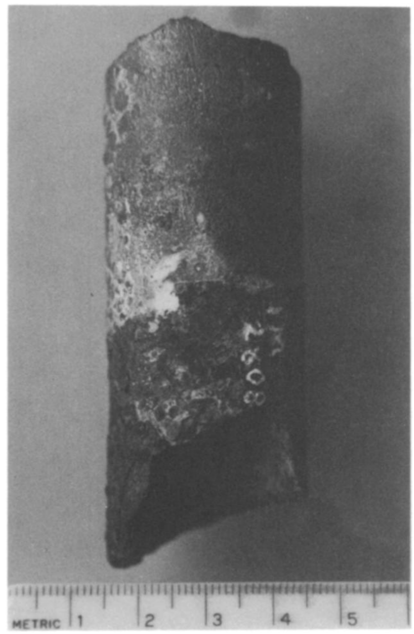


f. Fragment of unfinished casting of bronze animal figurine (not inventoried)

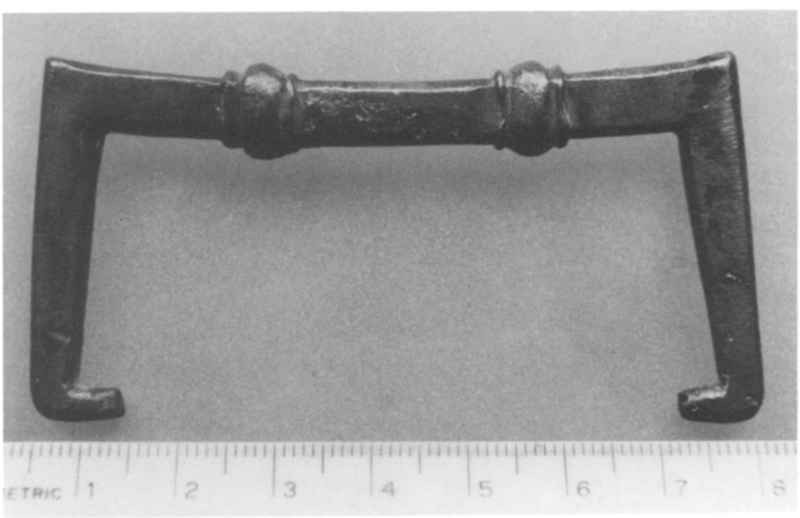
a. Compacted sheet bronze: IM 475

b. Compacted sheet bronze: IM 474, IM 475, and others

c. Cast seamless bronze tube: (end view): IM 2808

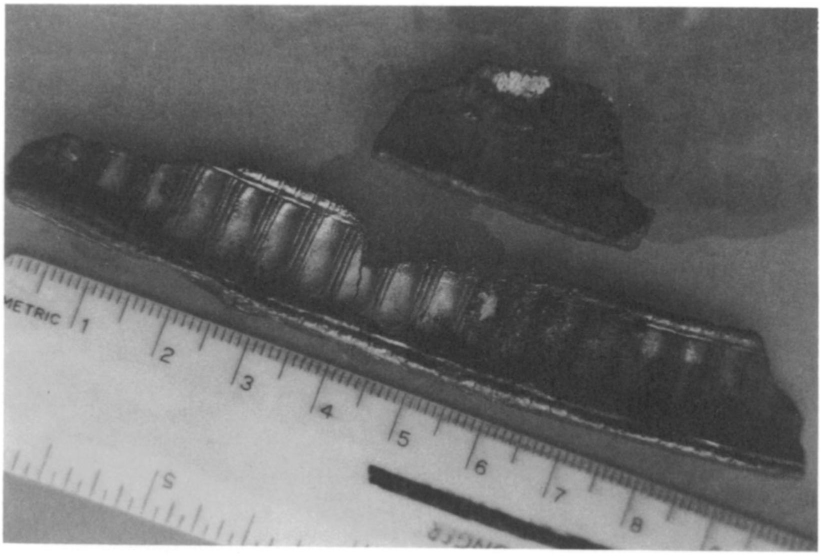


d. Cast seamless bronze tube: IM 2808

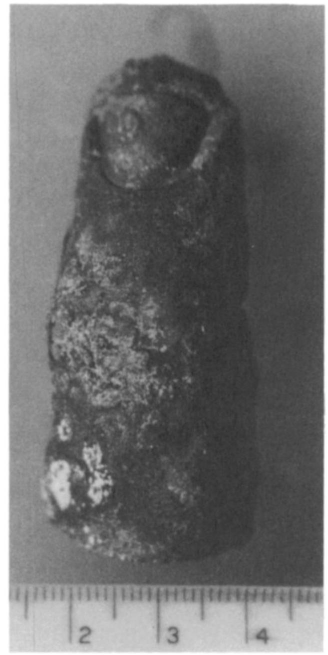


e. Cast bronze handle: IM 1793

f. Bronze sheet fragments (not inventoried)

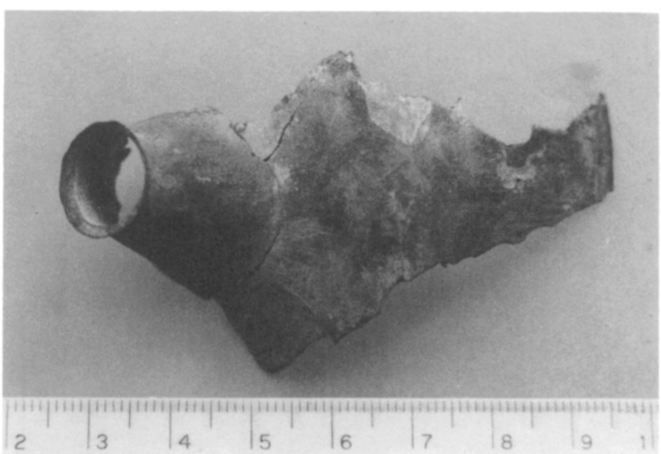


a. Fragments of rim of cast bronze bowl: top, IM 781, bottom, IM 2333b

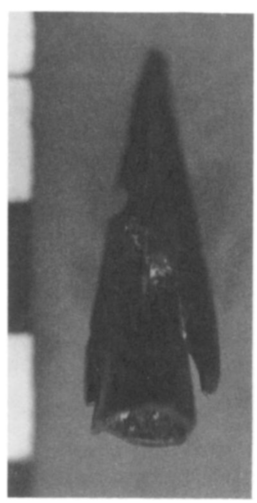


c. Solid-cast bronze thumb: IM 225

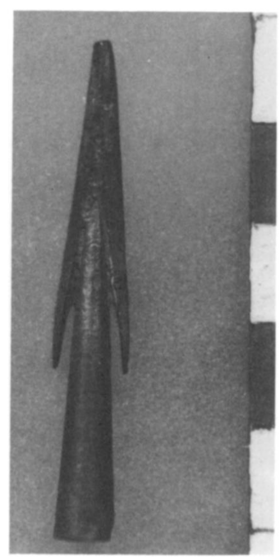
b. Fragment of hollow-cast bronze animal figurine filled with lead: IM 2235



d. Fragment of bronze funnel formed from thin sheet: IM 2768a

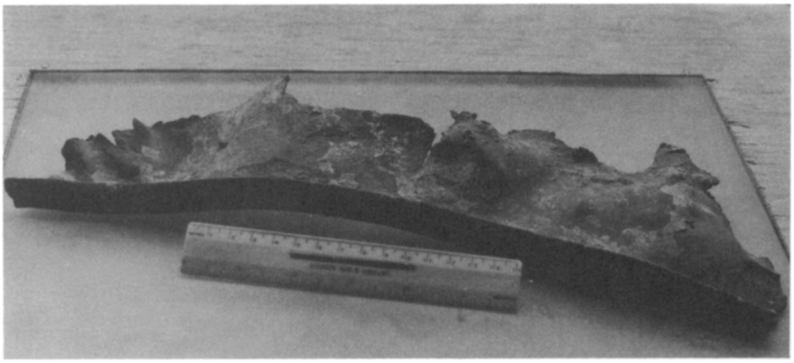


e. Three barbed

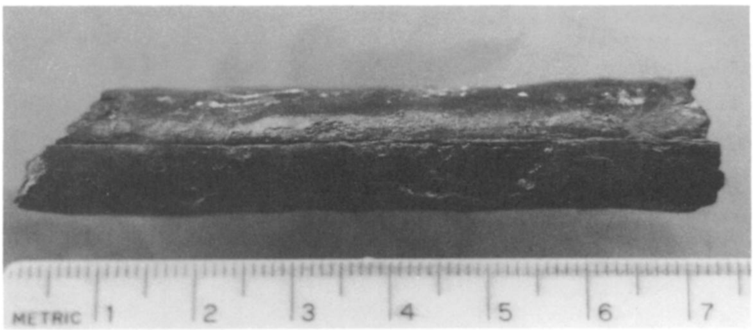


f. Two barbed

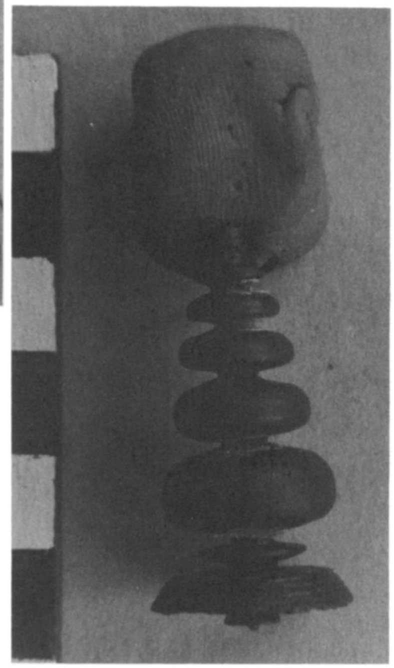
Cast bronze arrowheads (not inventoried)



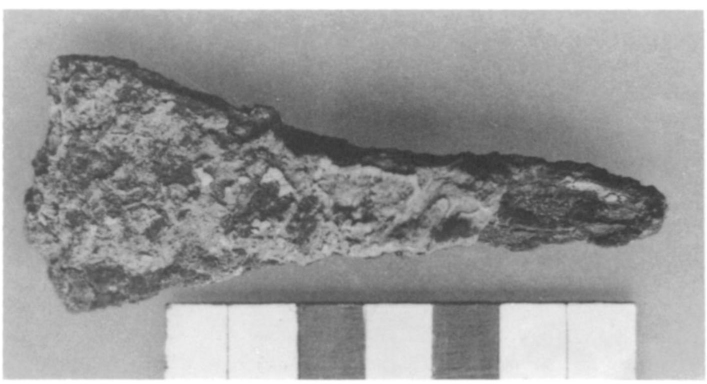
a. Fragment of thin-walled bronze bowl: IM 3274



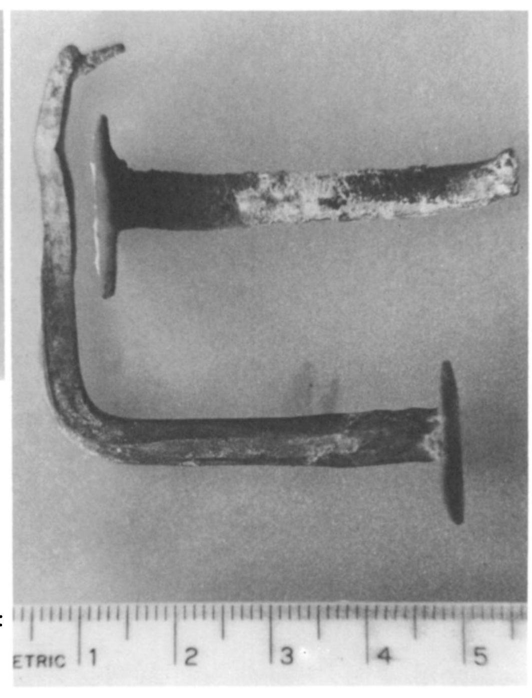
b. Fragment of seamed bronze tube: IM 782



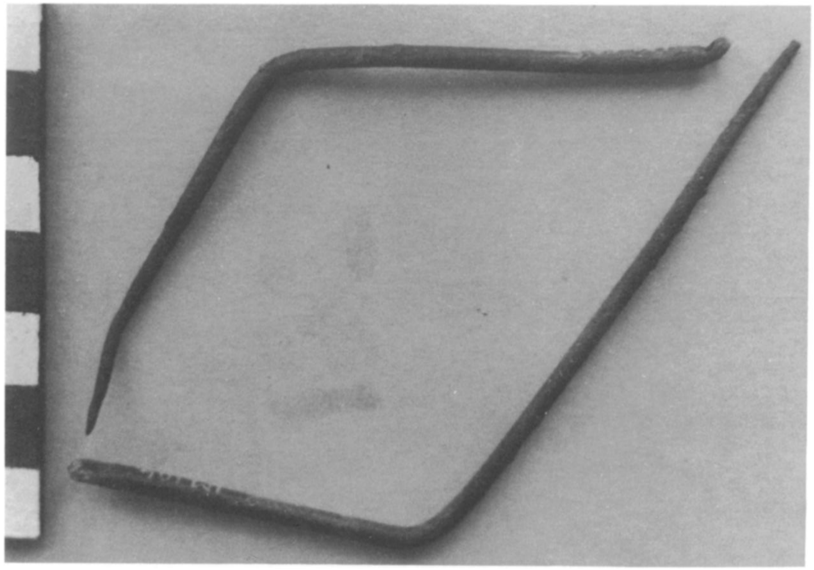
c. Bronze knob: IM 2361a



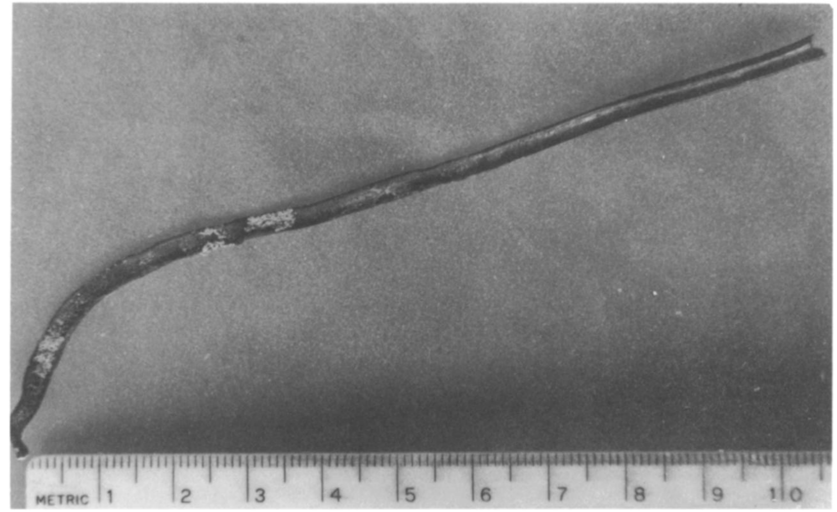
d. Remains of iron chisel (not inventoried)



e. Bronze nails formed from hammered rod: IM 971, IM 2169



a. Hammered bronze needles: IM 103, IM 104



b. Ribbon hammered from bronze wire, indented with hammer on anvil (not inventoried)

c. Iron axe-adze head: IM 387

d. Iron spear butt: IM 3447