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A Metallurgical Expedition through the Persian Desert

A team brings traditional metallurgy to bear on archeology.

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Forty years ago a number of European countries were vying to be known as the original home of the blast furnace. Today the competition has moved in space to the Middle East, and in time to the much earlier beginnings of the smelting of ores to metals.

Some scholars believe the first applications of fire to ores occurred at the large village of Çatal Hüyük in Anatolia, at about 6000 B.C.; others believe the primordial smelting hearth was to be found at desert Timna, in Palestine, at about 5000 to 4000 B.C. (*1*).

A limited claim has been made for Tal-i-Iblis in southern Iran (Figs. 1 and 2), where copper-stained fragments of crucibles, copper artifacts, and other metals dating back to the 5th millennium B.C. have been found by Joseph Caldwell. Iblis offers the oldest extant evidences of heating of copper in crucibles, a peculiar art identified at very few chalcolithic sites in the Middle East. Crucibles were used for mixed casting and smelting at Amouq in Syria (3rd millennium B.C.) and at Timna (1st millennium), as well as at Iblis (*2, 3*). They thus appear from the Mediterranean to the Persian Gulf, and belong to the period 5000 to 1000 B.C. But they are a distinctly isolated phenomenon in the broader story of the development of copper and lead smelting, which is thought, from slags, to have occurred at Çatal Hüyük as early as 6000 B.C.

The uniqueness of Iblis was reason enough for its selection, by my associates and me, as the scene of a three-dimensional undertaking in the summer of 1966, involving both an archeological and a metallurgical investigation.

1) The ancient province of Carmania (later known as Kerman), where Iblis is located, may have been a copper-smelting area for much of the 6000- or 7000-year period since Iblis first yielded metals; quite possibly it was a jumping-off point for the spread of metallurgy and pottery-making into India (*4*).

2) The province also yielded lead, iron, and zinc oxide, in phases suggesting the importance of studying the interrelationships of these metals in the history of smelting.

3) The old mines, slag heaps, and oasis settlements of the central Persian desert linking such sites as Tepe Sialk and Iblis are repositories of ancient and traditional lore.

4) It seemed to my associates and me that such a reconnaissance would have the additional merit of providing data on ecology over a wide area, of importance to our understanding of the fuels consumed in smelting and to reconstruction of the settlement patterns of the men who worked and traded in metals.

Our metallurgical party was led by Cyril S. Smith of the Massachusetts Institute of Technology. Its other members were Radomir Pleiner of the Archeological Institute in Prague; Gholam-Hossein Vossoughzadeh of the Ministry of Economy in Tehran; and myself.

Mineralogical and Historical Setting

The Zagros and Alborz mountains form the lip of a basin whose bowl is the Central Persian Desert, an area of 390,000 square kilometers (150,000 square miles). Called "Biyabanak," this zone of mountain, sand, and salt has diversified deposits of minerals, prominent among which are gold, lead-silver, copper, iron, antimony, zinc, nickel, and chromite. Lead and copper appear in small deposits around the whole rim. Gold is largely limited to the Mouteh-Golpaigan-Malayer region northwest of Esfahan. Though magnetic ores of iron are found at isolated points around the rim—at Semnan, Bafq, Kashan, and Asna—the chief locale of historical exploitation of iron was a zone across the southern part of the basin, from northern Fars into southern Kerman province. At Anarak-Nakhlak nearly all the minerals of the desert come together in remarkable and evident juxtaposition; thus this region was one of the earliest homes of metallurgy anywhere in the world.

Human hands first dug Iranian coppers about 6500 B.C., to judge from recent excavations at Ali Kosh near the Mesopotamian border, where a native copper bead has been found (*5*). Five 5th-millennium mounds, all excavated within the past 40 years, mark the advent of metallurgical activity and settlement on the desert rim. They are Tepe Sialk, Chesmeh Ali, Tepe Hissar, Tepe Anau, and Tepe Yarin. Tal-i-Iblis is the southernmost of this group of ancient testimonials to the art of

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Fig. 1. Map showing the route of the 1966 metallurgical expedition in Iran.

smelting. It closes the circle of metal about the great desert.

Historically, of all the desert provinces, Carmania affords the most complete written record of metal working. In 305 B.C., Onesicritus, Alexander's vice admiral in the Persian Gulf, told of the production in Kerman of silver, copper, and iron ochre (presumably he was referring to the island of Hormoz). He also mentioned gold dust washed down by a river, and spoke of mountains, one of arsenic, the other of salt (*6*).

By the 10th century A.D. the province was famous for its export of zinc oxide, or *tutiya* (from the Persian word *Dud*, meaning smoke), a medication used especially for the eyes. The Arab geographers Moqaddasi and Mostofi visited the area of Kuhbanan and Ravaer in northern Kerman in the 10th and 11th centuries A.D. and described in some detail the smelting of both cannular *tutiya* (or tutty) and iron (*7*, p. 309). Marco Polo found this area famous for its "Iron, Steel, and *Ondanique*." He admired the "steel mirrors of great size and beauty," saying, "they also prepare both *Tutia* (a thing good for the eyes) and Spodium" (*8*). We know from other evidence that the zinc oxide was a by-product of lead mining, which goes far back into antiquity. In 1188 Afzal Kermani (*9*, p. 48) spoke of gold dust in the Jiroft region.

Though many of the ancient smelting sites had been obliterated by the 20th century, travelers and geologists before 1940 found Kerman province a region active in the production of both copper and lead-silver by traditional methods, and a number of them mentioned considerable evidence of iron smelting in the Baft-Jiroft range. Of importance for our expedition were the excursions of Major Percy M. Sykes through Kerman in about 1900. Sykes traversed the Mashiz area and passed the copper-rich diggings of Cheheltan, which in ancient times supplied Iblis (*8; 9*, p. 61).

Our own foray into the Persian desert to gather traditional lore was guided by writings of Arab geographers of the 10th and 11th centuries, travels of European mining engineers of the 1930's and 1940's, and geological surveys of the contemporary Iranian Ministry of Economy.

Reports of silver output in the Nain-Anarak-Nakhlak area go back to Ibn Haukal, an Arab geographer of the 11th century; but an inked stone has been found in debris at Nakhlak that bears markings which may be Pahlavi writing of the Sassanian period (*6; 7*, p. 294; *10*). The central-desert oases of Jandaq, Khur, Tabas, and Naiband are variously described by the Arab geographers. The Naiband lead mines are recorded in the excursions of Swiss and German geologists of the early 1940's (*7*, p. 325; *11*).

The gold mines of Mouteh were our biggest surprise. Unmentioned in any known historical or geological source, these forlorn but wealthy pits of a bygone era have been rediscovered only in the past decade and put to modern uses only in the past 3 years.

Our reconnaissance involved nearly 4800 kilometers (3000 miles) of travel (Fig. 1), clockwise from Esfahan to Tabas and Kerman-Mashiz, then back to Yazd, Dehbid, and Esfahan. We passed through a sequence of the ages of gold, silver-lead, copper, and iron—one surprisingly in keeping with the myths of Mediterranean peoples, though somewhat skewed with respect to the actual history of metallurgy.

We traversed three ecological zones —the zone of the salt-oriented plants like *taq, qich,* and *shur*; the pistachio of the lower mountain slopes, around Mouteh, Kuhbanan, and Mashiz; and the high-mountain vegetation (plants like *arjen* and *hom*), between Mashiz and Baft in southern Kerman province. We visited classic oases of palm, and crossed deserts of sand and salt.

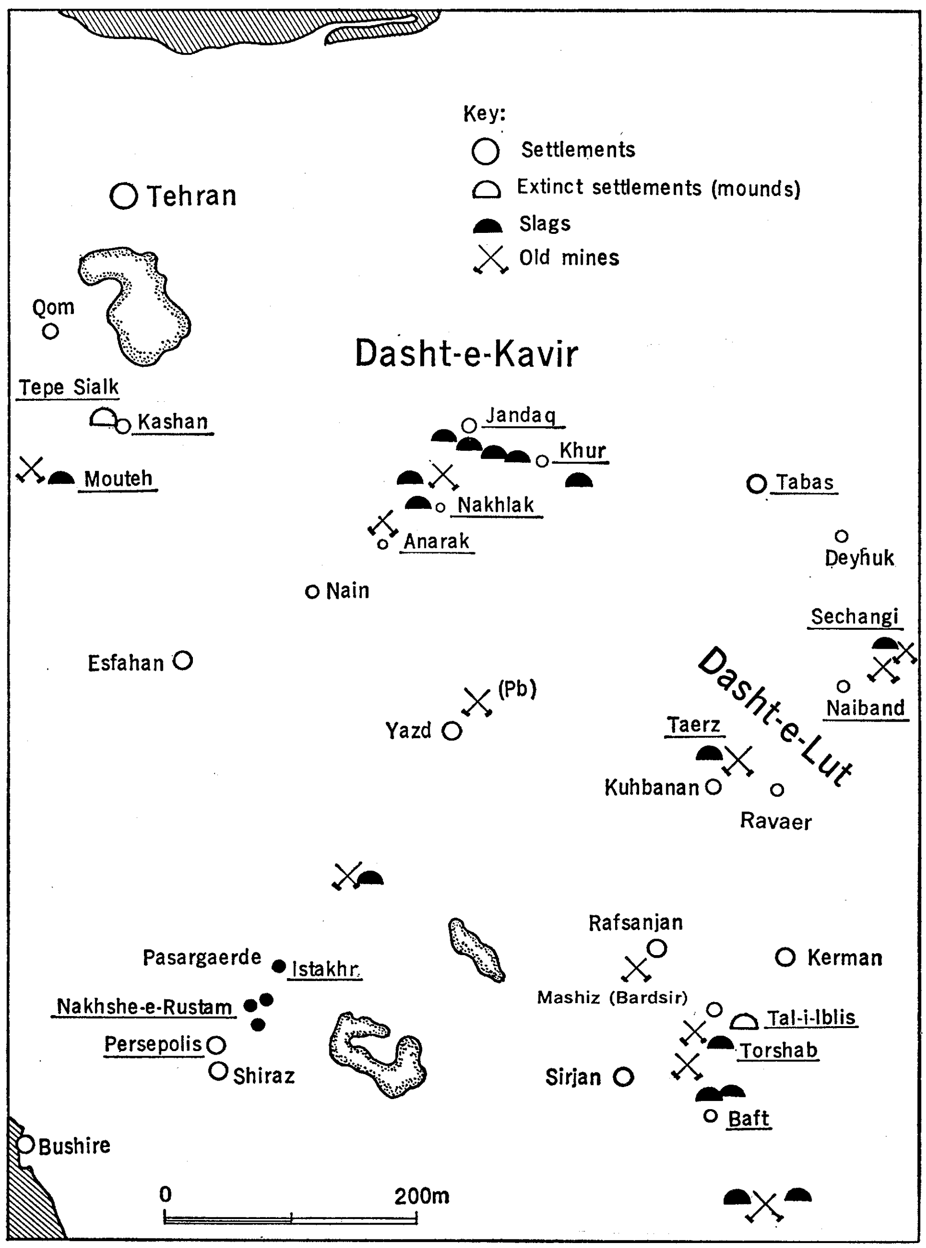


Fig. 2. Detailed sketch map of the sites visited. Underlining indicates sites where investigations were made.

Mouteh and the Age of Gold

Mouteh is a zone of quartz located west of the Tehran-Esfahan road about 165 kilometers north of Esfahan and 175 kilometers west of Kashan. It is not the only place at which gold has been dug in Iran; mines in Azerbaijan were mentioned in former times. Geologists believe, however, that Mouteh is one of the more important deposits of gold ore to be found in Iran.

The mineral zone extends from the Qom river to Golpaigan. The presence of nearly 100 old vertical surface diggings, generally no more than 15 meters deep, led to its discovery. Surveys by Russian engineers place the reserve at possibly 1 million tons. It is thought to be one of the richest veins in the world. Three mines are currently worked; five could be. Plans are being made to pipe the water necessary for a flotation plant.

We visited two early diggings some 8 kilometers apart, Darreh Ashki (vale of tears) and Chah Baq (garden well). The old pit at Darreh Ashki (Fig. 3) is 4½ to 6 meters in diameter, intersecting underground, at a depth of about 15 meters, the modern shaft (which has the usual trappings of a modern mine). In the loose dirt we found grinding stones, which are common at these sites. These were 40 to 48 centimeters in diameter. Also we photographed three pots and a hammer from similar digs; their identification is important to the dating of the main period of metal working at Mouteh.

At Chah Baq, gold powder has been found in the stream bed, and this suggests washing. The nature of traditional metal working was explained to us by Ali Yazdanpanah, an old Anaraki miner. After grinding by stone, the workers either (i) washed the gold in wooden bowls, a method which permitted the gold to settle and removed the lighter sediments, or (ii) sluiced the gold into a sheepskin, *à la* Jason and the Golden Fleece. Since Iran's rivers were exhausted of placer gold in very ancient times and Iran became dependent on Siberian gold in the days of the late Achaemenians and early Seleucids, it could be that Mouteh played a role in the domestic supply of gold from the days of the late Sassanians well into the Islamic era, possibly into the 17th century (*12*). The almost total absence of gold objects in the Sassanian period—of gold coins, bowls, and art objects—points to a severe shortage of gold, at least relative to the abundance of silver, of which nearly every precious thing seems to have been made.

Mouteh thus reflects a widespread trend toward underground mining of scarce gold throughout the Mediterranean and Caspian basins. Its subsequent neglect is hard to explain, if neglect it was.

Nakhlak and the Age of Lead-Silver

Silver appears in the third metal-producing stratum of Sialk; lead, in the earliest levels of Anau and in the later artifacts of Tepe Hissar. Throughout the Biyabanak we were told that the intensive search for silver began in the days of a legendary king, Shaeddad, whom Iranians identify as Nimrud. From collateral evidence it appears that Shaeddad was one of the Sargonid Assyrian kings who ventured deep into the Iranian desert—very possibly Esarhaddon (681 to 669 B.C.) or Ashurbanipal (669 to 626 B.C.).

Between Nakhlak and Bayazeh, a distance of more than 200 kilometers, one sees along the road numerous heaps of lead slag, some in a very advanced state of disintegration (attributable, perhaps, to the hand of man as well as to the weather). We did not visit the main slag heaps along the Nakhlak *kavir* or salt desert (many buried in sand), but we could readily accept Ger-

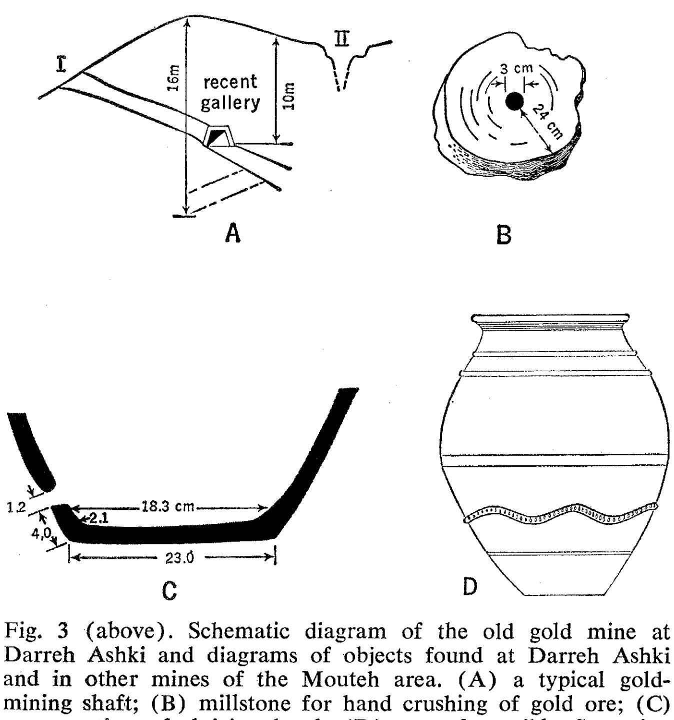


Fig. 3 (above). Schematic diagram of the old gold mine at Darreh Ashki and diagrams of objects found at Darreh Ashki and in other mines of the Mouteh area. (A) a typical gold-mining shaft; (B) millstone for hand crushing of gold ore; (C) cross section of sluicing bowl; (D) pot of possibly Sassanian origin.

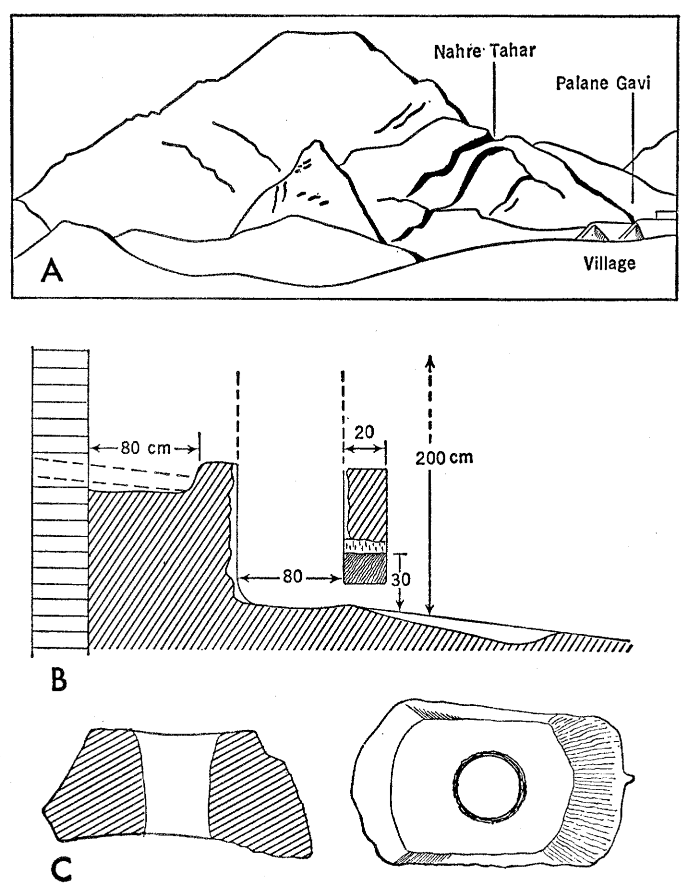


Fig. 4 (right). (A) Sketch showing the location of the old digging near Nakhlak, and schematic diagrams of (B) remains of the old lead smelting furnace at Nakhlak and (C) an iron sledgehammer.

man estimates of the 1940's that several hundred thousand tons of slags of various ages dot those areas of the Biyabanak where desert plants flourished.

The mines of Nakhlak represent the easternmost extension of the Anarak zone of ores; they are an assemblage of venerable pits and slag heaps on which modern shafts and a modern flotation plant have been superimposed.

One approaches the community of Nakhlak by a graded desert road, which passes several slag heaps before turning into the mountain niche occupied by the village and mine. The village is a dun assemblage of mud huts and tiny palm and *gaz* trees, split by a spring and dominated by the rectangular brick buildings of the mine, by ore and slag heaps, and by an old smelter now gradually going out of operation.

The older workers distinguish two eras at Nakhlak, the "cerussite" and the "galena" eras. This distinction is applicable, in varying degrees, to all of the lead mines that we visited. The era of mining the sulfide galena began at Nakhlak only about 100 years ago, with a new invasion of Anarak miners. Prior to that time the miners had concentrated on the east-west surface fault lines which, owing to hydrothermal deposition and geologic weathering, contain cerussite ore ($PbCO_3$), a type of lead ore with a considerably lower silver content than galena. The reasons for mining cerussite were threefold. (i) Cerussite lies at the surface. (ii) It is much more readily smelted than galena and gives off less noxious fumes. (iii) Galena lies below the water table, and mining it requires pumping or bailing operations.

The long "prehistory" of lead mining at Nakhlak is written solely in the pits and shafts of the veins of cerussite, which generally do not go below 60 meters because of the water. The present-day miners at Nakhlak had preserved very little of the past—very few lamps, picks, camel skins, and cowhides. The stone tablet mentioned above is the only existing written record of Nakhlak, though legend records a cowhide with Hebrew writing. Nor did we find any old timbers that might permit of radiocarbon dating. Throughout our 2-day visit to Nakhlak we were trying to look back 7500 years through a keyhole that revealed only the last 100 years.

We observed the two phases—cerussite and galena mining—at Palane Gavi, an old digging in the fault line of the mountain (Fig. 4). The original shaft was 60 meters deep; about 50 years ago it was deepened to 140 meters. Still in existence near today's slag heaps was the remnant of the hearth of a primitive furnace in operation as recently as 30 years ago, when German engineers designed the modern smelter. The former furnace, about 2/3 meter in diameter, is used today for baking bread. There was a battery of such furnaces. The story of their operation was told by travelers of the 1930's, such as Alfons Gabriel; it was a grim one in human terms.

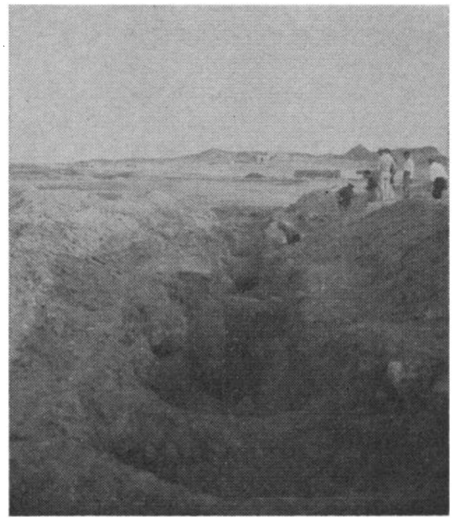


Fig. 5. Sechangi lead mines at Naiband.

The ores were carried by camel or donkey to the areas where desert fuels were available, for smelting. A typical smelting site is an isolated mound perhaps 20 meters in diameter, with remnants of the furnace at the center and slags in varying stages of decomposition spread out to the edges. We took samples from two such sites, one approximately 2 kilometers east of Nakhlak, the second a kilometer to the north; the lead content of 10 percent in the one sample of slag studied bespeaks a primitive reduction process. As we crossed the desert we found evidence of increasingly less primitive methods. We were also able to procure samples of litharge from a site at which silver was cupelled from the lead—again an operation of considerable interest in the light of our gradually unfolding knowledge of the use of arsenic and vinegar as possible adjuncts of the so-called "Anarak" methods of oxidizing the lead and deriving the silver.

Later, in smelting experiments of our own at Tal-i-Iblis, we attempted to reconstruct the ancient methods of smelting (as we had done in 1962 in experiments at Anjileh, near Yazd). But here I might summarize what Hassan Nejat of Nakhlak and Ali Yazdanpanah of Mouteh told us about traditional techniques. The standard furnace was 2 meters high and 100 centimeters in diameter. It was made solely of dried clay, special ceramic clays being used on the inside of the hearth. Such furnaces were run 12 hours a day and were repaired every 2 to 3 months. The bellows (an example of which we later saw at Taerz) were paired vertical types about 2 meters wide, feeding into a common tuyere. A day's charge was 35 kilograms of charcoal, 30 kilograms of lead ore, and 30 kilograms of iron ore.

This bellows-blown furnace served, with only slight variation, for the smelting of lead, copper, or iron ores, though at Anarak smelting was largely confined to copper; at Nakhlak, to lead. Iron ore (Fe_2O_3) was used as an additive in both copper smelting and

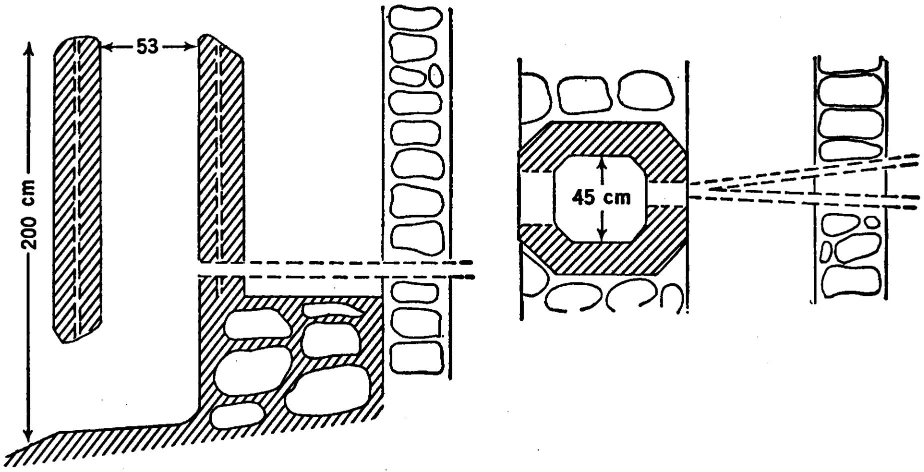


Fig. 6. Schematic diagram and cross section of the primitive lead-smelting furnace at the Taerz mine.

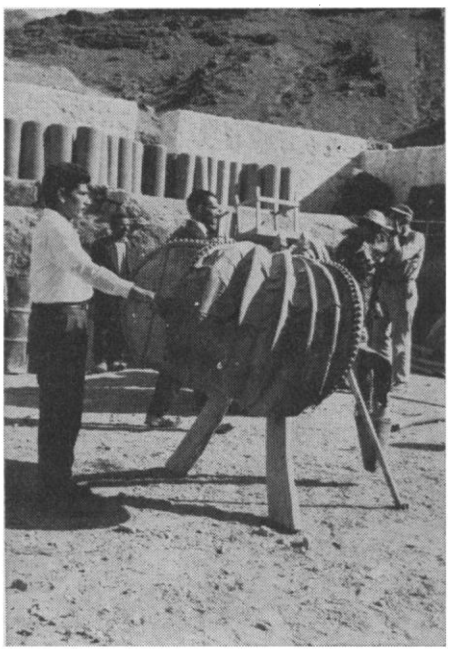


Fig. 7. Twin bellows for the smelting furnace of Fig. 6.

lead smelting, a practice which was also noted in Palestine by Rothenburg, and which was of utmost importance in that it stimulated the identification and ultimate exploitation of iron and advanced the use of sulfide ores of lead and copper (*3*). For smelting the chalcocite ores of Anarak, lime was also a useful additive. For 1 ton of cerussite, 400 kilograms of Fe_2O_3 were added; for 1 ton of chalcocite, 300 kilograms of Fe_2O_3 and 100 kilograms of lime were added (*13*).

Also employed in the desert was a wind furnace called a *falaqeh*, a large roasting or smelting device 5 meters high and 2 meters in diameter (resembling the modern blast furnace). This furnace was used mainly for smelting carbonate ores (like malachite); such smelting proceeded very fast.

We learned that one wild pistachio tree might yield 360 kilograms of firewood for the furnaces. Unfortunately, no figures were available for the *taq* (*Haloxylon amodendron*) or the tamarisk, desert bushes used for fuel in the smelting operations so heavily concentrated along the salt *kavirs* toward Khur. The *taq* grows to a height of 3 or 4 meters, has a trunk 3/5 meter in diameter, and has pendulous needles rather than leaves. In former times, some areas of the desert sustained what the Persians called *jangaels* or forests, really stands of desert mesquite-like bush. This wood, though scarce, made superb fuel for smelting. One can see stumpy remains of former *jangaels*. Elsewhere the trees have begun to reestablish themselves despite modern depredations by goats. Even the dried vine of the wild watermelon or the wispy *shur* sufficed to fuel the smelting furnaces of this desert zone.

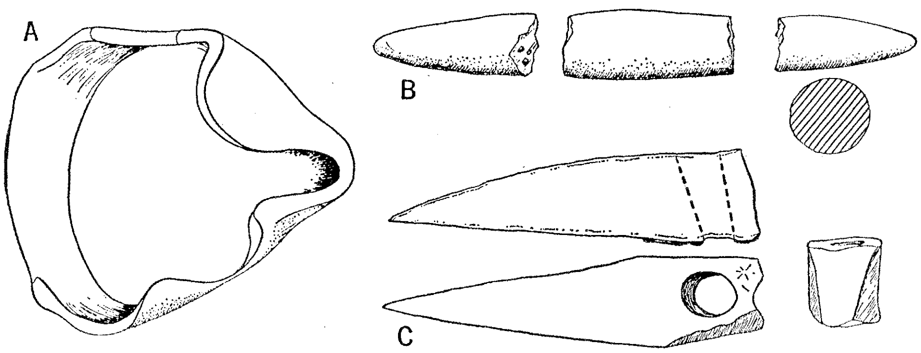
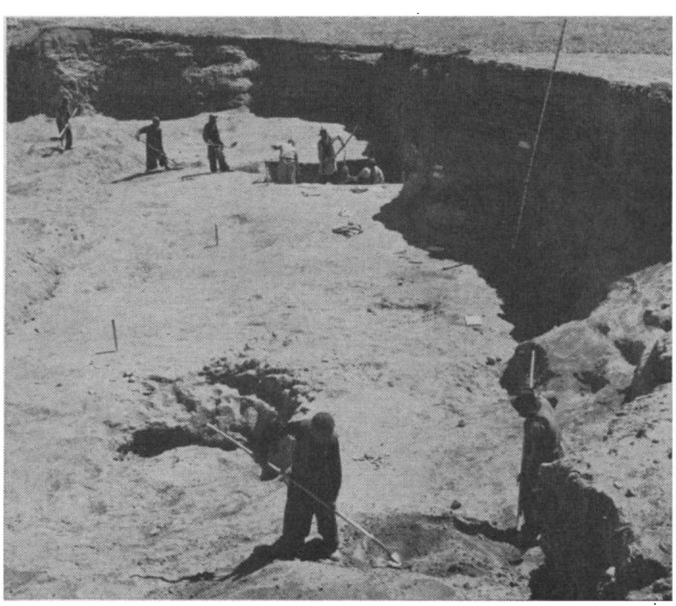


Fig. 8. Objects from ancient lead mines in the Taerz area. (A) Miner's lamp from Taerz; (B) a fire bar from Saavand; (C) a miner's iron pick or hammer from near Taerz.

Naiband

We reached the Naiband plateau by traveling southward nearly 200 kilometers from Deyhuk (Fig. 2) over a desert road that has long linked the villages of the upper Dasht-e-Lut. It is a Paleozoic zone of dark igneous or andesitic rock. The mines (Fig. 5) lie in the uplands some 160 kilometers east of Naiband Mountain and the village of Naiband on the Khur road. A very stony and bare country, the vicinity of the Naiband mines is mainly washes and rock, the washes greened by occasional *taq* and *qich*, the rock broken by mineral-filled fault lines that



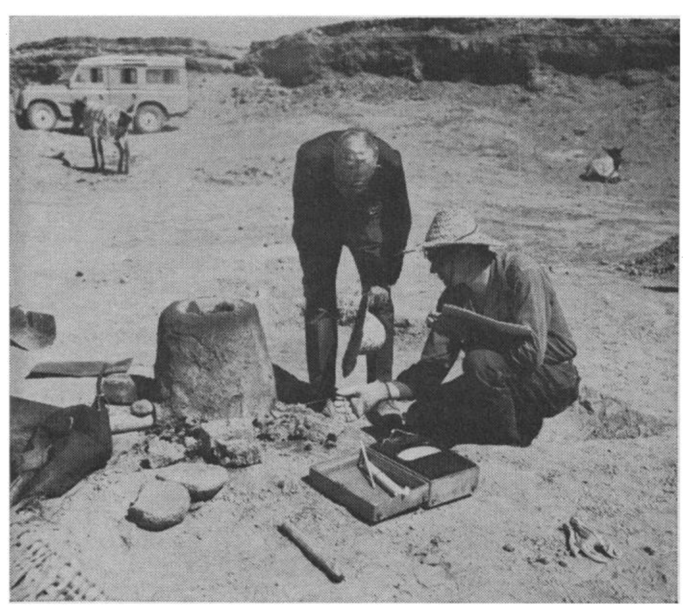


Fig. 9 (left). Excavations at Iblis, showing strata of pyrotechnological activity back to 4000 B.C. Fig. 10 (right). Smith and Pleiner test lead-smelting temperatures with thermocouple. [Photographs by Houshang Nezam] often run straight as a pencil for many kilometers. Snakes abound. Whereas at Nakhlak mining was carried on along the mountain slopes, here the old pits followed the plain, and the deposits are largely galenic. This area is called Sechangi.

Under the guidance of Mohammad Qassem Tudeshki, an Anaraki foreman, we examined an old trench 1 meter wide and 3 meters deep lying between hard igneous rocks, and yielding mixed $PbCO_3$ and PbS. Gypsum had been dug away from over the vein, and the rocks bore tool marks. We climbed down a modern shaft to view the old diggings underground, and there came upon an ancient mining timber that may be suitable for carbon-14 dating. The slags heaped about the smelting site indicate two distinct periods of working, one fairly ancient, the other fairly modern; perhaps the operations seen by European geologists in the 1930's and early 1940's belonged to this latter period. We extracted samples of furnaces, clay tuyeres, and charcoal from the slag.

At this smelting site of Sechangi were the remnants of perhaps 100 old smelting furnaces in their enfolding slags, ruined tuyeres being prominently in evidence. The furnaces had been about 1.5 meters high and had walls of stone and linings of clay. We also found smaller furnaces only 60 centimeters deep. It seemed possible that copper ore had once been smelted here, for there were droplets of copper in the slag. Chalcopyrite copper had been mined 4 kilometers to the north of Naiband and 50 kilometers to the south. Magnetic iron ore was also to be found in these rocks; iron ore had been used in smelting the lead. The ores and slags from this site proved to have a remarkably high zinc content.

The Taerz Mines

At Taerz, one enters an ancient mining zone made famous by the Arab geographers and by Marco Polo. It was probably this cluster of small mining villages that Marco Polo wrongly regarded as the great metallurgical community of Kuhbanan. We were convinced, both by the moderately high zinc content of Taerz lead ores and by the fact that, in our own attempts to reproduce the ancient smelting of lead, we produced the white fumes of zinc oxide, that we had crossed paths with Marco and were in the region where he had seen the preparation of "*Tutia*" (*8*). We remained in the dark, however, about now-extinct processes of fabricating the fine steel that Marco reported. We hope the discovery near Esfahan, by the Smithsonian's Hans Wulff (*14*), of wootz bars will do something to lift the mystery concerning "*ondanique*" in the Kerman area. "*Ondanique*" seems to have been a hard "mirror" or damask steel of possibly Indian (wootz) origin.

Taerz, the anteroom to the Kuhbanan plain, is a lovely green village surrounded by perhaps 1000 large stone cairns or tumuli 6 meters long and 1 meter high that were burial places for the ancient tribes of Kerman, or perhaps of the larger Baluchi area. They yield rings, bracelets, pottery, and swords. Such tumuli appear elsewhere in Kerman province, and are still being built by tribesmen in the Baft area above the Persian Gulf. The tumuli, together with the green village and the mountain peaks that set off the villages of Taerz and Saavand, provide a not-to-be-forgotten approach to the Kuhbanan plain—much what it must have been in Marco Polo's day, except for the lack of the smelting fires.

Under the guidance of Ali Najafian, Anaraki manager of the Taerz mines, we visited the hilly mining zone of Taerz and took pictures of an intact primitive lead furnace and bellows (Figs. 6 and 7). Most important, however, were artifactual evidences of old mining techniques in the obviously ancient shafts named Ma'adene Kohne ("old mine") Number 1 and Number 2, at Taerz proper, and at Kuhe Gujer 6 kilometers to the north (Fig. 8).

A mummy was recently found in one of the shafts; it is now in Tehran. We were given several miner's lamps, an old steel pick (from a distant site), and a seemingly partly petrified piece of wild-pistachio timbering (Kuhbanan means "pistachio mountain"). Unfortunately no stone, horn, or wooden tools or palm baskets of the type known to have been used in the region have been preserved, but the timbering is being subjected to carbon-14 dating.

The lead galenas of Taerz yield 400 grams of silver per ton. However, the mine is interesting mainly because of its interlaced veins of zinc, which today are being exploited for export to Belgium at the rate of 200 tons a month (small quantities of lead are being sent to the U.S.S.R.). Today's exploitation is exactly the reverse of that of ancient times, when miners wanted lead-silver minus refractory zinc.

Ma'adene Kohne Number 2 is a hole 10 meters in diameter and 30 meters deep in the steep mountainside. We did not pursue it, but explored Ma'adene Kohne Number 1, a mine 40 meters deep from surface to water line. Inside the modern mine we were able to see how the former miners had avoided the brown sphalerite ores, digging both above and below them to get the speckled galena.

From the experiments we later performed we judged it likely that the furnaces for producing *tutiya* and spodium described by the Arab geographers and Marco Polo were lead-smelting furnaces yielding fumes of zinc oxide as a major by-product. Since lead smelting at Taerz may well have been very ancient, there is a strong presumption that the early metal workers quickly learned to distinguish the medicinal effects of zinc oxides from the toxic effects of the oxides and carbonates of lead. Even today, villagers about Taerz use the fire bars of old smelters to heal sores on the skin.

Our visit to the village of Saavand, an old smelting site 3 kilometers beyond Taerz on the road to Kuhbanan, raised a number of technical questions, not the least being that of the burned clay bars that we found on the old smelting hillside. These bars, possibly 28 to 36 centimeters long, originally, and tapered at the ends, littered the old furnace site, along with pieces of litharge which testified to the former cupelling of silver from lead. The bars represent a complete mystery in the history of metallurgy; they are impregnated with zinc, a fact which suggests that they may have had some connection with the "grates" that Marco Polo saw being used to catch the fumes of *tutiya* as they issued from the furnace.

It was suggested to us by the Iranian miner who accompanied our team that vinegar may have played a role in lead metallurgy in Iran. The metallurgic possibilities of vinegar were explored before 300 B.C. by Theophrastus, the naturalist and pupil of Aristotle (*15*). He described the making of ceruse, or white lead, by the immersion of lead plates in vinegar.

Tal-i-Iblis

From Taerz we moved on to Tal-i-Iblis, the site of Caldwell's excavations. There we designed experiments intended to throw light on the smelting of copper in crucibles such as those found at Iblis, and on related lead and iron smelting (Figs. 9–12).

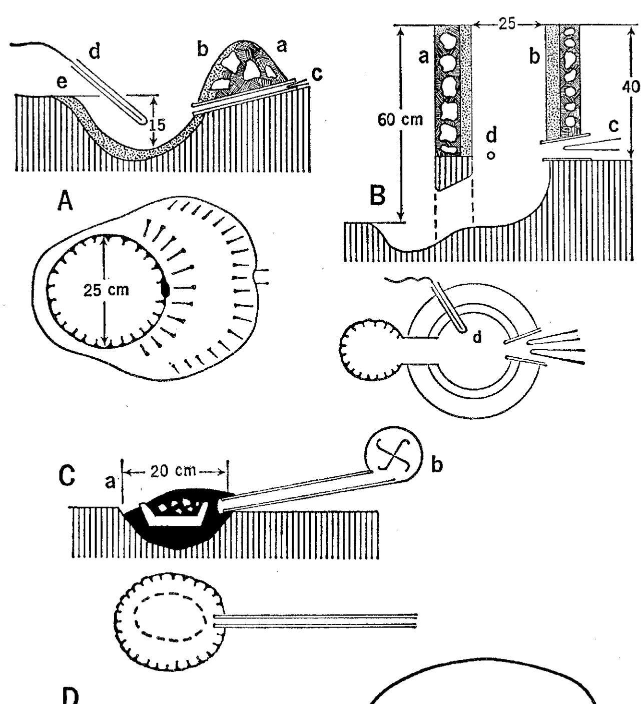
We had hoped to test out the thesis that iron was discovered in the course of the reduction of lead and possibly copper ores. This supposition, developed by Cyril Smith and myself in 1962 on a trip to Yazd and other points, had been strengthened in this journey of 1966. All the people we talked to maintained that iron oxide was traditionally a common flux in the smelting of lead ores, whether cerussite or galena. One man said that it was also exploited in copper smelting, with lime. We decided to build a furnace adequate for testing this hypothesis.

Pleiner's report (*16*) describes in some detail the furnace and two smelting hearths with which we sought to reenact some of the early history of smelting. The construction of the mud-clay furnace for the lead-iron experiment was entrusted to Mohammad-Bagher Saidi, foreman of the Anjileh lead mines near Yazd. We were well acquainted with Saidi from our previous journeys in southern Iran. The furnace that resulted was the product of Saidi's expertise in traditional Persian processes and Pleiner's familiarity with ancient European methods. The result was interesting but not entirely satisfactory.

In our attempts to smelt lead or to reproduce the lead-iron process we encountered an unforeseen obstacle. Most of the lead ores for our experiments had been brought from Taerz and proved to have a moderately high zinc content and to be intractable for precise experimentation. Though our goatskin bellows produced (according to the thermocouple) the remarkably high temperature of 1380°C in the little lead-iron furnace, we had no success in producing a visible bead of iron. But laboratory studies by Pleiner have recently shown that our lead slags contained not only metallic lead but metallic iron—the latter as a highly carburized pig iron! To this extent the experiments tend to substantiate the thesis.

Adventitiously, too, we managed to raise the white fumes of *tutiya*, along with those of lead—ample proof that the comments of Marco Polo and the Arab geographers about furnace practice at Kuhbanan were well founded. Because of the zinc, however, the slag of the furnace failed to run, and the yield of liquid lead was poor; the lead smelting hearth gave no metal at all.

We were constantly impressed with the number of variables that must have plagued the early diggers of ores and smelters of metals. In the broader context of all pyrotechnology, the slagging of metals must be understood as an exercise in glass making, just as the coloring of glass must be seen largely as an exercise in metallurgy. My own theory had been that the metals and their mother ores were identified not in isolation but by reference to each other and to fire. Such is the case for lead and its offspring, silver and iron. In our experiments the disturbing ef-



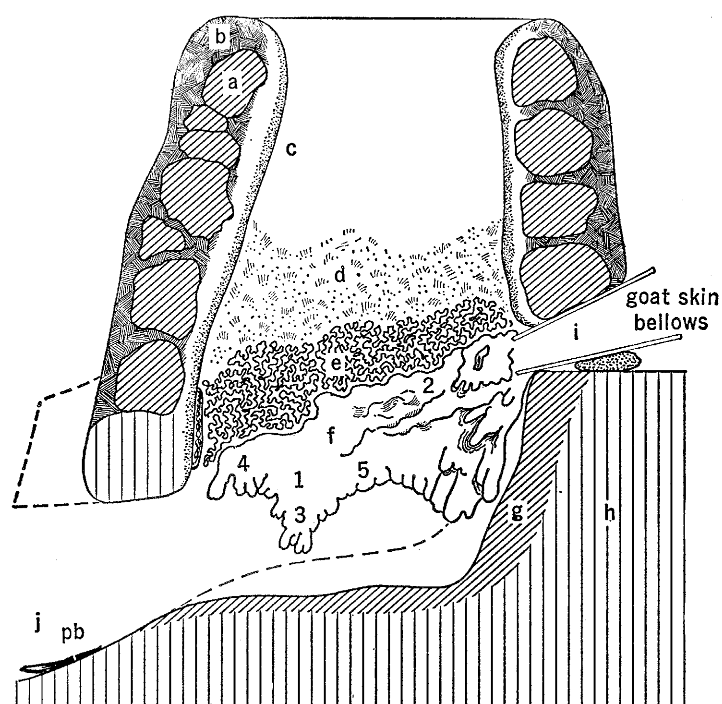


Fig. 11 (left). Diagrams of procedures and objects used in our smelting experiments at Tal-i-Iblis. (A) Open hearth with goatskin bellows, showing (*a*) clay, sand, and straw protecting wall; (*b*) sand and clay lining; (*c*) tuyere; and (*d*) thermocouple. (B) Shaft furnace with goatskin bellows, showing (*a*) walls of brick, sand, clay, and straw; (*b*) sand and clay lining; (*c*) zinc sheet tuyere; and (*d*) position of thermocouple. (C) Open hearth for smelting copper ore in (*a*) crucibles, with (*b*) ventilator. (D) Reconstruction of a crucible according to finds from the lower layers of the excavations at Tal-i-Iblis. Fig. 12 (right). Schematic cross section of the small shaft furnace used for lead smelting in our experiments at Tal-i-Iblis. (*a*) Dry bricks; (*b*) clay, sand, and straw; (*c*) sand and clay lining, burnt; (*d*) yellow and gray oxides on the inner walls; (*e*) slag; (*f*) lead slag, iron oxide, and lead conglomerate; (*g*) burnt loess; (*h*) loess; (*i*) tuyere (zinc sheet box); (*j*) lead; (1–5) samples for analysis.

fects of a slight admixture of zinc, a substance that remained unidentified during most of the history of metallurgy (*17*), was a case in point.

Cyril Smith, when he undertook the smelting of copper in crucibles, encountered other hazards. With the help of a hand compressor he achieved temperatures considerably in excess of 1200°C in a small charcoal-fueled fire in the ground. He produced a bead of copper—and melted the crucible. I myself am now convinced that the crucibles were used, not for smelting, but for casting—an operation which, according to my theories and to those of Rothenburg, may have led to smelting.

The final focus of our reconnaissance was upper Fars Province, and specifically the mountain of Heneshk, which I visited in 1961 and revisited with Smith in 1962 and with Pleiner and Vossoughzadeh in 1966. Today the site of major geological investigations, this scene of diggings and old smeltings is clearly a landmark in the history of the iron age in Fars Province. Only 50 years ago Heneshk was still reasonably well forested with wild pistachio trees. Today only one or two small trees cling to its slopes. The future will reveal the modern metallurgical potentialities of this zone.

Concluding Remarks

Our reconnaissance had two dimensions. One was the dimension of traditional practice. We explored many traditional processes and sites, and from our observations are now trying to extrapolate what we can about ancient methodology. Obviously the degree of extrapolability from evidence or crafts extant today must vary enormously from case to case. For example, one can say with some finality that cerussite was the first ore exploited for the production of lead and silver. Here traditional practice coincides with ancient practice.

Was iron ore added as a flux from the very beginning? The answer is necessarily tentative. It was evidently possible to smelt very pure ores in a small hearth with charcoal only. However, our experience with very small admixtures of impurities, as well as the experience of German engineers 25 to 30 years ago, suggests that iron ore may have been added at a very early date, possibly even before men tried to smelt the sulfide galena. That iron ore and lime were also used, in both Palestine and Iran, to help free copper of its rocky impurities suggests that ancient smelting practice was more complex than we had suspected.

On several other fronts the traditional data set one to thinking. We were told by Ali Najafian at Taerz that copper workers in the bazaars of Kashan and Yazd have always melted the native copper of Anarak for use. This was a logical supposition, to judge from the difficulty of hammering Anarak native copper, even when it is annealed. The speculation that casting of native copper could have been an early phase in the evolution of copper smelting seems permissible.

As mentioned above, *tutiya*, the old name for zinc oxide, comes from the Persian word meaning smoke. It now seems that the philological history of *tutiya* coincides with the technological. To the observations of the Arab geographers and Marco Polo that Kuhbanan was an early center of the *tutiya* trade may be added our conclusions from scrutiny of the Taerz mines and from our smelting experiments. Zinc was an unwanted and chemically complex partner of lead smelting operations. Nevertheless, the oxide was present, and even impregnated the fire bars found at the old smelting site near Taerz.

This brings up the thorny question of cupellation, which must have been the earliest method of extracting silver from lead, dating back to the period represented by the early strata of Sialk, Hissar, and possibly Iblis. We have not yet pursued the suggestion of Saidi and others that arsenic (and possibly vinegar) may have been agencies in the cupellation process. One needs to take a new look at the alchemical formularies of the Assyrians.

The second dimension of our metallurgical researches was the experimental one. Such experiments are part of the armamentarium of contemporary historians of metallurgy, having been performed by Coghlan, Tylecote, Rothenburg, and others. Indeed Smith and I had in a sense anticipated the experiments of 1966 by those at Yazd in 1962. Pleiner was fully familiar with the whole experimental domain.

The results taught us the measure of the problems, not the solutions. From our experiments in lead smelting we did learn something about temperatures and about zinc. The experiments in iron smelting were somewhat disappointing, though not entirely so; other such investigations will have to await more propitious circumstances. Crucibles with copper stains denote casting; in time, through experimentation with fluxes and alloys, such casting may have led to smelting.

References and Notes

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3. R. F. Tylecote, A. Lupu, B. Rothenburg, *J. Inst. Metals* **95**, 241 (1967).
4. An interesting footnote to our mission is the fact the Iranian government has recently announced the discovery, northwest of Rafsanjan, of one of the world's largest deposits of copper.
5. Kent Flannery, personal communication.
6. T. S. Brown, *Onesicritus: A Study in Hellenistic Historiography* (Univ. of California Press, Berkeley, 1949), p. 104.
7. G. Le Strange, *The Lands of the Eastern Caliphate* (Cass, London, 1966).
8. H. Yule, *The Book of Ser Marco Polo* (Murray, London, 1929), vol. 2, pp. 125–26.
9. P. M. Sykes, *Ten Thousand Miles in Persia or Eight Years in Iran* (Murray, London, 1902).
10. R. N. Frye, *Central Asiatic J.* **5**, 187 (1960).
11. See G. Ladame, *Schweiz, Mineral. Petrog. Mitt.* **25**, 198 (1945).
12. The Achaemenians probably got their gold from northern Iran (some sources suggest the northeast, though Strabo points to Armenia as a rich source of gold). Herodotus first speaks of the "ant-gold" of India, which Tarn interprets as an oblique reference to gold from the Altai Mountains.
13. In *Science* [**146**, 1257 (1964)] I advanced two theses about the origins of metallurgy: (i) that the annealing and casting of native copper may have preceded the smelting of metals; (ii) that the smelting of lead ores may have led to the discovery of ways to reduce iron. Quite coincidentally Beno Rothenburg was at the same time advancing thesis i, on the basis of his own classic digs at Timna, as interpreted in the light of the earlier work of Thomas T. Read and H. H. Coghlan. Thesis ii emerged from 5 years' study of traditional practice in Iran, plus our own experiments in smelting, which made clear that iron oxide was often a necessary additive for facilitating the slagging of normal lead or copper ores, even when pure. The first substantial archeological evidences of the use of Fe_2O_3 and lime as metallurgical fluxes are those of Rothenburg at Timna. From an analysis of slags and of the remains of petrified hematites found near the furnaces, Rothenburg concluded that an additive was definitely used in the smelting operations of 1200 B.C. if not in those of the early chalcolithic period. The finding of seashells along with the slags suggests that the shells supplied lime, as a flux. Naturally occurring manganese oxide, also found in large quantities at Timna, was often used as a substitute for hematite. One cannot exaggerate the importance of these finds in confirming the essential complexity of early metallurgy. See Tylecote, Lupu, and Rothenburg (*3*).
14. For Wulff's activities in this region, see T. A. Wertime, "A New Look at Ancient Technology," *Technol. Cult.* **8**, 485 (1967).
15. Sir John Hill, *Theophrastus's History of Stones* (London, 1746), p. 133.
16. Pleiner's report (as yet unpublished) to the National Science Foundation provides many photographs and drawings and covers the details of the experiments and laboratory work.
17. Zinc was not positively identified as a metal until possibly A.D. 1500, though both the oxides and the pure metal were isolated well before that time, and brass was a common product.
18. Figures 3–8, 11, and 12 are reproduced through the courtesy of Radomir Pleiner of the Archeological Institute in Prague.