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Research Article

Amalgamation and Alluvial Gold Mining at Ancient Sardis, Türkiye

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Abstract

Even though gold was widely used in the ancient world there are few studies of the mining technology used to obtain the precious metal. Ancient Sardis is one of the most well-known of these ancient gold occurrences. At Sardis and elsewhere in the ancient world, gold was washed from alluvial occurrences using gravity methods combined with mercury (amalgamation), a method that is still used today in small-scale alluvial gold mines worldwide. The 'Present is the Key to the Past' allows us to examine modern gold mining in order to evaluate ancient methods. Given, that industrial amounts of gold are produced in only two ways, either by cyanide, which was first used in the 1880s in the US, or ages-old gravity separation/amalgamation, then amalgamation must be re-examined as the gold mining technology used to produce alluvial gold at ancient Sardis. Regional geology, geoarchaeology, and the evaluation of: 1) the availability of cinnabar, the ore of mercury; 2) an ancient mercury retort near Konya; 3) ancient use of cinnabar as a funeral pigment and as a source of mercury that was used for gilding and amalgamation; 4) the fine-grained alluvial gold at Sardis; and 5) the mercury content of Sardis' alluvial gold (11,615 ppm Hg) and end-product gold, a Byzantine coin (<1 ppm Hg) are consistent with the conclusion that mercury amalgamation was the mining technology that supplied gold, as electrum, to ancient Sardis' craftsmen.

Keywords

Regional Geology, Gold, Mercury, Amalgamation, Ancient Mining, Türkiye

1. Introduction

Amalgamation is used widely today in small-scale alluvial gold mines around the world and, given that 'The Present is Key to the Past', then this widely used artisanal method is key to understanding alluvial gold production in the ancient world, specifically at Sardis. This process begins with washing the gold-bearing sediment to obtain a gold-bearing concentrate; then mercury is added that selectively amalgamates only the gold; then the gold-mercury amalgam is removed; and finally, the gold-mercury amalgam is burned to volatilize the mercury leaving an anthropogenic gold 'nugget'. As used herein, gold refers to the silver-bearing alluvial gold, also known as electrum, found at the Pactolus River alluvial gold occurrence at Sardis (Sart Çayi, Manisa), Türkiye [62, 81, 47, 38] (Figure 1). Recent analysis indicates that Sardis' alluvial gold contains 19,347 ppm (parts per million) ppm silver, 966,000 ppm gold, and 11,615 ppm mercury (Table 1).

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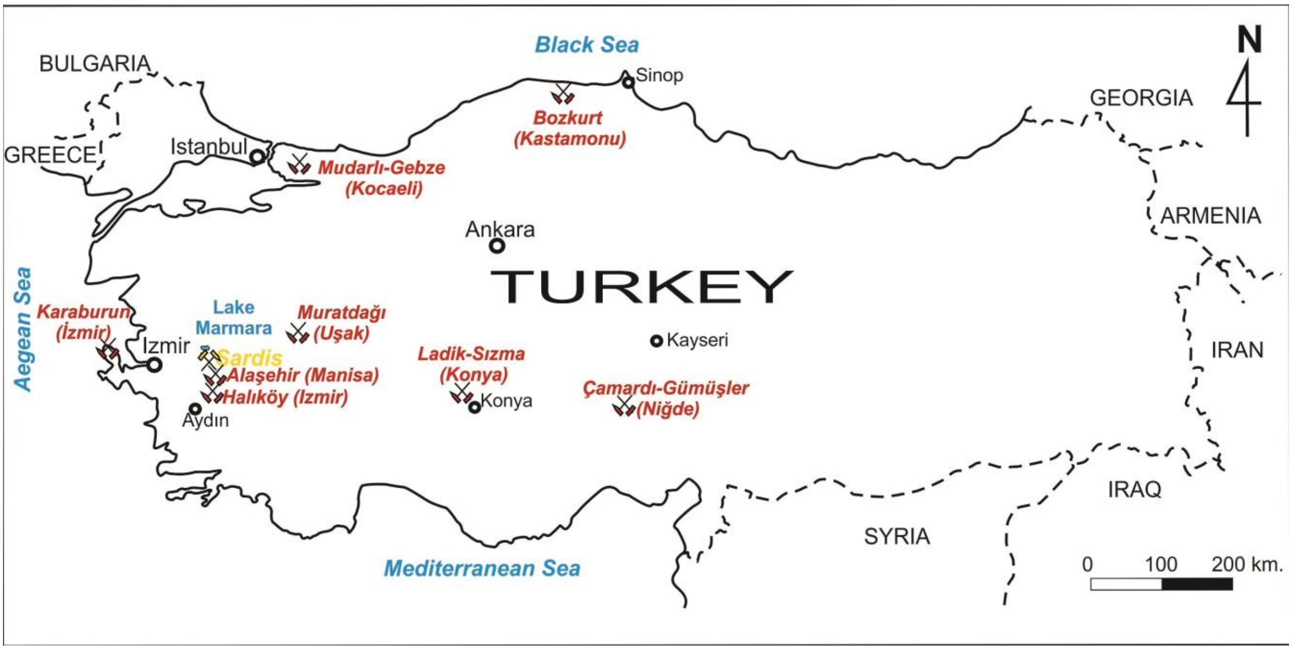

Figure 1. *Approximate locations of mercury districts in Türkiye [10, 7].*

Table 1. *Analyses from mercury mines, a Byzantine gold coin*, and Sardis alluvial gold+, Türkiye.*

	TK161	TK162	TK163a	TK163b	TK164	TK165	TK166	TK167	TK168*	TK241+
Au (0.003)	0.005	0.008	<0.003	0.004	<0.003	0.003	1.290	0.031	99.4%	96600
Ag (0.2)	<0.2	0.2	<0.2	<0.2	<0.2	<0.2	7.0	<0.2	nr	19347
As (2.0)	11	2634	125	828	156	2149	599	592	nr	nr
Ca (1.0)	355162	42603	2789	120278	3258	1576	1244	3769	nr	nr
Cd (0.1)	0.3	<0.1	<0.1	0.3	0.3	<0.1	<0.1	<0.1	nr	nr
Cr (1.0)	81	96	209	727	582	477	382	131	nr	nr
Cu (1.0)	9	1585	19	105	11	42	38	30	nr	nr
Fe (10)	7165	37432	24540	68736	8398	101353	14695	36497	nr	nr
Hg (0.1)	4.7	405.7	15.2	10.3	770.1	97.6	4.3	84	<1	11615
La (10)	17	27	13	27	<10	<10	33	<10	nr	nr
Mg (1.0)	4274	775	249	2027	293	400	452	5800	nr	nr
Mn (1.0)	346	152	46	310	64	182	58	418	nr	nr
Mo (1.0)	2	8	5	7	8	7	23	3	nr	nr
Ni (1.0)	2	13	74	775	76	679	51	52	nr	nr
P (10)	134	556	319	380	37	598	115	1510	nr	nr
Pb (1.0)	20	511	13	9	10	23	40	21	nr	nr
Pt (0.1)	-	-	-	-	-	-	-	-	1020	nr
S (10)	67	21231	4686	6274	527	17677	4728	1269	nr	nr
Sb (0.3)	<0.3	181.1	19	132.8	12.4	141.7	1272.7	9.8	nr	nr
Se (5.0)	7	<5	<5	<5	<5	<5	<5	<5	nr	nr
Th (0.1)	1.7	11	9	8.5	3.0	7.8	9.2	8.9	nr	nr

	TK161	TK162	TK163a	TK163b	TK164	TK165	TK166	TK167	TK168*	TK241+
Tl (0.1)	0.1	3.9	3.8	5.4	0.4	7.8	0.2	0.2	nr	nr
U (0.1)	0.1	0.3	1.6	3.0	0.6	1.1	1.1	0.6	nr	nr
V (2.0)	3	5	<2	30	<2	6	25	22	nr	nr
W (1.0)	<1	2	1	7	<1	1	3	<1	nr	nr
Zn (1.0)	16	1011	14	292	16	78	201	101	nr	nr

Multi-element ICP [Inductively Coupled Plasma] analyses [parts per million; detection limit given to right of element, in parentheses; nr - not requested; *fragment of an ancient Byzantine gold coin, + alluvial gold, ore grade analysis for Au (%), Hg, Pt (ppm), Hg detection limit of 1 ppm]; American Assay, Sparks, NV, (SP0116032, SP0152165).

Sample Descriptions

TK161 [0715294/4543335 UTM] near Koçaeli (Mudarli-Gebze); grab sample from calcite veins, reddish blebs, quartz, rusty pyrite along NS structure; several large meter-sized pits, not a major producing area; no hot springs evidence, no acid drainage.

TK162 [454392/4275474] Karaburun mine and plant, burned material from wall inside ~4 m well-constructed brick and basalt block chimney that served to vent gases from mercury plant that is downhill.

TK163a [454392/4275474] Karaburun, rock fragments from huge wastepile, some burned, reddened, scoriaceous fragments.

TK163b [454392/4275474] Karaburun, large [20m x 100m x 100m =~200,000 m^3 est.] wastepile, not as burned, not scoriaceous, but clearly crushed, perhaps volcanic material.

TK164 [455395/4275406] Karaburun, unaltered wastepile, gray silicified limestone, pyrite, rust stained.

TK165 [455516/4274877] Karaburun, area sample of hematite-altered rock from mine area.

TK166 [602834/4216521] Haliköy Şubesi mine, sample of scoria on fire-brick from chimney, all adits closed, cannot sample inside mine, no surface outcrops, mine now produces antimony.

TK167 [602867/4216218] Haliköy Şubesi, grab sample from dark, reddened, calcined tailings at ramp/loading area.

TK168* gold coin (0.7 g sample): Byzantine Empire, Maurice Tiberius, struck 583 AD, Constantinople Mint; helmeted and curassed facing bust holding globus cruciber, DM MAVRC TIB PP AVI / Angel standing facing holding long Chi-Rho-headed cross and globus cruciger, Victoria AVGGG officina letter I, CONOB below, ancient graffiti below bust, 22 mm, 4.37 g. (G. Vandevoort, http://www.ancientresources.com, 1 March 2016)

TK241+ 0.3 mm alluvial gold grains from Sardis

Gold mining in Anatolia, western Türkiye, dates to ~3000 BC when alluvial gold was mined from Astrya approximately 25 km from ancient Troy [8, 5]. At Sardis, alluvial gold mining dates to ~700 BC and gold is still produced today as a byproduct from economic occurrences of heavy mineral-containing sand and gravel. And, as part of a modern economic evaluation of the alluvial gold occurrence at Sardis, mercury was necessarily used in order to selectively amalgamate the mm-sized gold flakes in the sluice concentrates [74].

Amalgamation, which dates to Roman times and earlier [1, 36], was discussed as the possible mining technology used to recover gold at ancient Sardis by Craddock [27] who proposed that if mercury had been used, then low levels of mercury would be detected in the analyses of the end-product gold. Therefore, gold coins from the British Museum's Sardis collection were analyzed, and since no mercury was detected in the coins using SEM-EDX, then Craddock [27] concluded that amalgamation was not used—however, no alternate gold mining technology was proposed.

Most importantly, there are only two methods to mine industrial amounts of gold: 1) the centuries-old use of gravity separation, first in water, and then combined with the addition of mercury (amalgamation), and 2) the use of sodium cyanide (NaCN). Since the use of cyanide dates to the 1880s [30], then, chronologically, amalgamation must be examined as the technology for alluvial gold mining at ancient Sardis.

2. Mercury and Alluvial Gold Mining

Placer, or alluvial gold was ancient man's primary source of gold and provided two-thirds of the gold that was ever produced [12, 8]. Nuggets and coarse gold would have been easily picked from the streams and gold-pans; however, recovering the fine-grained gold (mm-sized and smaller) would have required: 1) washing the gold-bearing sediment to eliminate light minerals and thereby leaving a gold-bearing, heavy mineral concentrate known as 'black sand' that may have included cinnabar, diamond, garnet, magnetite, platinum, zircon, and other heavy minerals; 2) selective removal of the mm-sized gold flakes from the black sand by the addition of mercury (amalgamation); 3) and then, as now in Colombia, Ecuador, Guyana, Indonesia, Perú, and Venezuela, the gold-mercury amalgam is burned to volatilize the mercury and recover the gold [15-17].

3. Regional History, Mercury, and Gold Mining

Sardis, the capital of the ancient kingdom of Lydia, was the western stronghold of the Persian Empire following its capture by Cyrus in 546 BC. The Royal Road, a major trading route with ancient Persia, terminated at Sardis [2] and the region is known as the cradle of metallurgy. Sardis' mineral wealth, especially gold, and the use of other mineral resources, is exquisitely demonstrated by a 5th century BC gold earring, with platinum (iridium, osmium), that also incorporated blood-red cinnabar in the design [81, 8]. Gold from Sardis was used for jewelry, pendants, and chains [31], and, more importantly, was parted to recover silver and gold for coins as early as the 7th century BC [26, 65]. Gold appliqués were associated with ancient funeral rites and were also attached to clothing for decoration [68, 35].

In the Byzantine world that included parts of Spain, Italy, North Africa, and Asia Minor (Türkiye), cinnabar, the ore of mercury (HgS), was widely used as a pigment (vermilion), as a funeral preservative, and retorted to produce mercury that was used for gilding or amalgamation. A kilogram of mercury, thought to have been used to extract gold, was reported from the al Mina site on the Syrian coast that dates to the 5th century BC [77, 26].

However, the earliest written description of the use of mercury for alluvial gold mining was given by al-Biruni, an 11th century Persian scientist. Small pits in the Sind River bed were filled with mercury; the mercury trapped or amalgamated the alluvial gold in the river sediments and then the gold-mercury amalgam was recovered, squeezed in a cloth to remove some of the mercury, and then the gold was burned to volatilize the mercury [3].

Any discussion of ancient gold mining technology in the region must reference the Golden Fleece, which is the legendary mining method used to recover alluvial gold at ancient Sardis [42, 44, 66, 38]. This method is analogous to the use of animal skins, burlap, and specialized carpets that are used at present-day small-scale gold mining sites in Ecuador, Perú, and Venezuela in the initial stages of gold washing and concentration; however, the final recovery of the gold is done using mercury [21, 15]. Other non-mercury methods for gold recovery are known in South America: wind-winnowing (Spanish, *aventadero*) [62]; the use of plants in place of mercury in Chocó, western Colombia [54, 18], and Perú [50], and Spain [37]; and a flotation system using biodegradable chemicals in Perú [4]. Several other methods of gold production such as ground sluicing and hushing are described [26]; however, these methods are little used and do not produce industrial amounts of gold. A review of alluvial gold mining technology, past and present, is provided by [53].

4. Regional Geologic Setting and Metallogeny

Türkiye is in the Tethyan Eurasian Metallogenic Belt that extends for roughly 10,000 km along the ancient Tethys seaway that separated the supercontinents of Gondwana and Laurasia during the Mesozoic Era. This ancient seaway tracked from Spain to northern India and was closed during the Miocene by the collision of the African and Indian plate with the Eurasian plate. Therefore, Türkiye's regional geologic setting is complex and includes colliding, sliding, and subducting tectonic plates that have produced earthquakes, geothermal energy, and polymetallic ore deposits that contain gold, silver, mercury, lead, copper, and platinum. The cinnabar and gold occurrences of western and central Anatolia are Miocene and formed in a back-arc extensional regime similar to the Basin and Range, western US [58].

These metallic mineral deposits have been mined since ancient time and provided silver, copper, iron, lead, tin, and other metals used by the Romans and Greeks [14, 81, 33, 34, 80, 79, 59, 68, 41, 63]. Coal is abundant in northern and western Türkiye and is typically low-rank (lignite to subbituminous) [61]; however, thus far, there is only speculative evidence for the use of coal as a fuel in ancient time in the region. Other minerals such as sulfur were used to soften wool and pigments were obtained from limonite (yellow ochre), realgar (reddish-orange), and cinnabar (red) [68]. Ancient Roman mining records have been found near Ovacik-Bergama, Kucukdere-Havran, and Sogut-Bilecik [8] and crushing stones used to grind ore were found near Gümüsköy and Kütahya [46].

Modern mercury mining in Türkiye predates 1900 and the mining register for mercury in Türkiye began in 1923 [57]. Mercury production ended ~1986 when Türkiye last produced 275 tons (t) (~8000 flasks) of mercury from the mines at Karaburun and Konya [69]. The mercury reserves of Türkiye, mainly in the Aegean Region, are approximately 3,820 metric tons [76].

In 2011, Türkiye produced 25 t of gold from open-pit mines and, in 2016, the Sardis mine was still operational and produced aggregate, quartz, perlite, and heavy minerals such as zircon and corundum for industrial use and gold; however, gold was produced only as a byproduct [64, 75, 79]. In 2019, Türkiye produced 38 t of gold from large-scale open-pit mines that used cyanide [42] and byproduct gold production was not available. Other gold occurrences are known in western Türkiye and there are numerous copper, tin, and lead occurrences throughout the country [33, 34, 59]. Türkiye has a gold endowment of approximately 31 million ounces; however, alluvial/placer deposits are limited and none are currently economic with the exception of byproduct gold produced at Sardis [64, 79].

5. Geologic Setting of Sardis

Sardis is approximately 90 km east of Izmir (Figure 1) and, regionally, is underlain by metamorphic rocks (schist, phyllite, and marble) and younger sedimentary units composed of sandstone, conglomerate, and recent alluvium. Sardis' gold was initially deposited in veins in the metamorphic rocks and then, these rocks weathered and released the gold that was then transported and concentrated in a nearby basin [44]. These gold-bearing, poorly-sorted, basin-fill conglomerates (Figure 2) were then cemented, uplifted (Figure 3) and weathered again with the gold being reworked and redeposited in the alluvium of the Pactolus River. Therefore, gold at Sardis may be mined from: 1) uplifted, cemented quartz-pebble conglomerates, and 2) from the recent alluvium in the Pactolus River.

Figure 2. *Poorly sorted gold-bearing quartz pebble conglomerate at Sardis, Türkiye.*

Figure 3. *Faulted and uplifted basin-fill conglomerates at Sardis, Türkiye. Sardis' ancient refinery is in the foreground.*

6. Re-Consideration of Amalgamation at Sardis

Amalgamation was originally considered as the mining technology used at Sardis [27] who proposed that if mercury had been used to amalgamate the gold, then low levels of mercury would be detected in the analyses of end-product gold. Therefore, coins from the British Museum's Sardis collection were analyzed, and since no mercury was detected using SEM-EDX, he concluded that mercury had not been used.

Given his [27] conclusion that amalgamation was not used at Sardis and to logically re-consider amalgamation as a mining technique at ancient Sardis, it is important to establish and integrate regional geological and archaeological evidence that is consistent with amalgamation. That evidence includes: 1) availability of cinnabar and mercury; 2) evidence for ancient mining and mercury processing such as the ancient mercury retort near Konya; 3) use of cinnabar for ancient funeral rites documented at the Çatalhöyük archaeological site; 4) regional Roman use of cinnabar as a pigment and as a source of mercury for gilding and amalgamation; 5) mining engineering implications for the recovery of the fine-grained (~0.03 mm) alluvial gold at Sardis from conglomerates and black sand; and 6) interpretation of the chemical analysis of end-product gold, a Byzantine coin and alluvial gold from Sardis (Table 1).

6.1. Availability and Uses of Cinnabar and Mercury

Cinnabar, the common ore of mercury is known in at least eight districts, all in western Türkiye [57, 70, 10, 7] (Figure 1). Archaeological evidence indicates that cinnabar was first mined more than 8000 years ago in Türkiye—cinnabar was used as a funeral pigment at Çatalhöyük and was also retorted to obtain mercury as indicated by the ancient retort (Figure 4) found in the Sizma district, northwest of Konya. Sizma is the most important mercury occurrence in Türkiye and, based on gouges in the Büyük Maden mine, where cinnabar veinlets had been worked, geologists concluded that Sizma was mined for its mercury by the Greeks and Romans as early as 6300 BC and is the world's oldest underground mine [7, 80].

As part of this study, site visits were made to cinnabar/mercury occurrences at Mudarli-Gebze, Karaburun, and Haliköy (Figure 1) to determine mercury content of the ores, mine waste, and look for evidence for ancient mining. Modern mining, however, has overprinted any evidence of ancient mining and the veins and interior of the mines are collapsed or are otherwise inaccessible. Therefore, geochemical sampling was limited to stockpiles, mine waste, and scoria from smelter stacks. At the Karaburun plant (Figure 5) one sample from a stockpile contained 770 ppm Hg (Figure 6); a sample from a small, mined-out, hematite-altered open pit contained 97 ppm Hg; and samples from all locations contained 4.3-770 ppm Hg (Table 1). Sooty, burned material from the Karaburun chimney wall (Figure 7) contained 405 ppm Hg. Karaburun collectively refers to the Kalacik, Karareis, and Küçukbahçe mines that closed in the late 1980s; however, these mines still contribute to mercury and heavy metal contamination in nearby marine sediments [20].

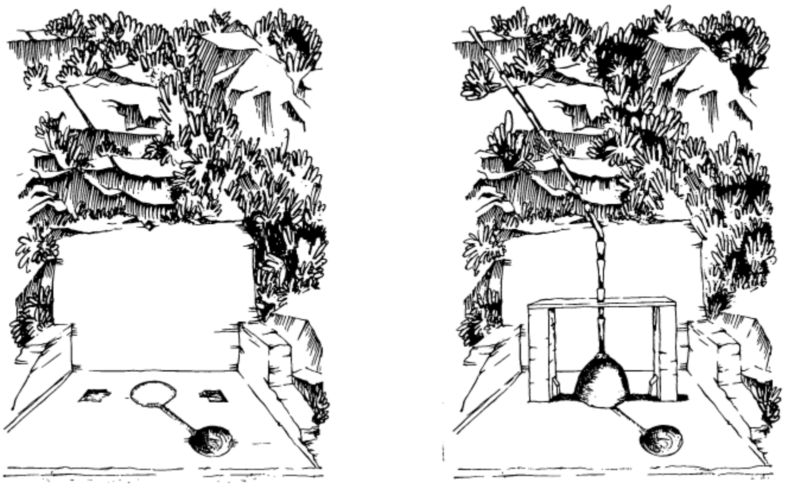

Figure 4. *Sketch showing existing Konya retort site (left) and how it was probably used (right). Cinnabar was smelted, with charcoal, inside of an inverted ceramic bowl that served as a condenser. The ceramic flue eliminated sulfurous gases uphill and mercury collection trough is in lower right [7].*

Figure 5. *Karaburun mercury plant in the foreground and the smelter chimney uphill in the distance. The rough rock wall in the foreground may indicate an older site.*

Figure 6. *Karaburun stockpile with a sample that contained 770 ppm Hg (Table 1; sample TK164).*

Field notes-TK164 [455395/4275406] at Karaburun; unaltered wastepile, gray silicified limestone, pyrite, rust stained. [156 ppm As; 770 ppm Hg; area sample TK165 from nearby mine area contained 0.003 ppm Au, 2149 ppm As; 97 ppm Hg; 141 ppm Sb; Table 1].

Etibank, a Turkish company, was the largest producer of mercury in the 1970s and its' Haliköy Şubesi plant produced mercury from the mines near Aydin (Figure 1) [69]. Mine production has now shifted to antimony; however, calcined waste material from a loading area (Figure 8) at Haliköy Şubesi contained 84 ppm Hg (Figure 9) (Table 1, TK167). A sample of scoria from inside the dismantled Haliköy Şubesi smelter stack contained 1.29 ppm Au, 7 ppm Ag, and 1272 ppm Sb (Figure 10; Table 1, TK166).

Figure 7. *Karaburun chimney from which an interior sample that contained 405 ppm Hg and 21231 ppm S was taken (Table 1; sample TK162).*

Field notes-TK162 [454392/4275474] at Karaburun mine and plant, burned material from wall inside ~4 m well-constructed brick and basalt chimney. This chimney served to vent gases from mercury plant that is downhill. [0.008 ppm Au; 2634 ppm As; 405 ppm Hg; Table 1].

Figure 8. *Halaköy Şubesi mercury mine loading dock with calcined tailings.*

Field notes-TK167 [602867/4216218] loading area at Halaköy Şubesi, grab sample from dark, calcined tailings at ramp/loading area. Walked gullies, lots of milky quartz, weak Fe stain, no cinnabar veinlets.

Figure 9. *Halaköy Şubesi loading dock tailings from which a sample with 84 ppm Hg was taken (Table 1; sample TK167).*

Field notes-TK167 [602867/4216218] at Halaköy Şubesi, grab sample from dark, reddened, calcined tailings at ramp/loading area (see below) [0.031 ppm Au; 592 ppm As; 84 ppm Hg; 9 ppm Sb; Table 1]. Walked gullies, lots of milky quartz, weak Fe stain, no cinnabar veinlets.

Figure 10. *Halaköy Şubesi smelter stack scoria with 1.29 ppm Au, 7 ppm Ag, and 1272 ppm Sb (Table 1; sample TK166).*

Field notes-TK166 [602834/4216521] at Halaköy Şubesi, produced mercury (1950s), all adits now closed, cannot sample inside mine, no surface outcrops, Etibank owners, mine now produces antimony. Sample of scoria on fire brick from chimney [1.29 ppm Au; 7.0 ppm Ag; 599 ppm As; 4 ppm Hg; 1272 ppm Sb; 4728 ppm S; Table 1].

6.2. An Ancient Mercury Retort

The Sizma mercury district, ~6 km from Konya, has 15 mercury occurrences and is the most well-known mercury producing district in Türkiye [73, 57, 5]. In 1905, an English archaeologist discovered a tablet at an archaeological site near Konya (Figure 1) that was dedicated to Zizima, the ancient Phrygian goddess of mining and from which the name for the Sizma mercury district is derived [6]. An ancient cinnabar mine that had been used as a goat shelter was also discovered in a cave near Konya. Deep grooves had been cut into the rock to follow the cinnabar veins and fire-setting had been used to shatter the ore for removal.

In 1969, a mercury retort (Figure 4) was found ~2 km south of Ladik. Cinnabar was known at the nearby Çirakman and Muratdağ mines, all of which demonstrate ancient cinnabar mining and processing in the district. Greek and Latin inscriptions found on quarried marble blocks nearby document the age of the retort site [57, 7]. And, even though the mines at Konya are now closed, mercury mining has contributed to heavy metal contamination in the region [48, 39].

The retort found near Ladik had been carved into marble, was ~3 m on a side, and on the upper surface of the marble block was a 50 cm diameter circular depression with a 1 cm deep groove around the outside of the depression (Figure 4). The mercury ore, cinnabar, was mixed with fuel such as charcoal in the depression, ignited, and then covered with an earthenware pot. The mercury would be collected as the volatilized mercury cooled and condensed on the walls of the pot and droplets of mercury would be recovered in the groove while sulfur would have been vented through a ceramic flue uphill and some distance away [6, 7]. For comparison, the mercury plant at Karaburun has a similar geometry; however, at a larger scale, to the ancient Konya site—retorts were located downhill and a chimney to vent the sulfurous gases is uphill (Figure 5). Composition of these volatilized retort gases is indicated by a scrape from the blackened interior burned walls of the Karaburun chimney that contained 405 ppm Hg and 181 ppm Sb (Figure 7; Table 1, TK162)

could be mined, ground, mixed with a binder, and used as a pigment (vermilion) without much additional processing [51, 62]. Cinnabar was used as a funeral preservative in Spain ~5000 years ago [52] and its use in ancient Türkiye as part of an ancient funeral ritual is indicated by cinnabar-painted skulls found at the Çatalhöyük archaeological site that is ~ 65 km southeast of Sizma and that dates to 6280 BC [7]. A gold figure from central Anatolia, The Seated Goddess with Child (Metropolitan Museum of Art, New York), shows that cinnabar was used for decoration on this 13th century BC gold artifact. Regionally, the walls of ancient Pompeii were painted red with cinnabar more than 2000 years ago [51] and medieval stuccoes at the Alhambra were decorated with cinnabar [19]. And, even though cinnabar is known to be toxic, it is still used as a pigment for some art applications today [71, 45].

6.3. Gilding and Amalgamation

Given, that cinnabar was the only mineral mined in the area, then it follows that the Konya retort (Figure 4) was used for processing cinnabar into mercury for ancient industrial uses such as gilding and gold amalgamation [7]. Because of its malleability, gold may be hammered into a foil which can then be mechanically attached to paper, wood, stone, gypsum, or other metal surfaces. Fire-gilding entails mixture of gold flakes with mercury (Turkish, *tombak*, Archaeology Museum, Manisa) then application of the gold-mercury paste, followed by heating with a blowpipe to volatilize the mercury leaving a golden gilded surface.

Therefore, it is implicit to establish that the precursor to the gold foil must have been a ‘nugget’ or ingot of some sort that could be easily hammered into a foil. Given the absence of gold nuggets at Sardis [74], then the source of this precursor ‘nugget’ would have been an anthropogenic gold ‘nugget’ (with some copper and silver) formed as the last stage of amalgamation when the mercury-gold amalgam is burned leaving a sponge-like texture in the button of gold (Figure 11). Similar-appearing anthropogenic ‘nuggets’ are on display at the Archaeology Museum, Istanbul.

Examples of the use of gold foil can be found at the Archaeology Museum, Istanbul and also at the Hagia Sofia where the Byzantine Christ Pantocrator has a golden background formed from gold foil-containing tesserae. The hammered gold foil was laminated between two sheets of glass which were then broken and the fragments pieced together as the mosaic tesserae (written comm., Prof. L. E. Butler, Art History, George Mason University, 27 Sept. 2016).

Figure 11. *Anthropogenic gold nugget from Puerto Maldonado, Perú showing sponge-like texture resulting from burning (Spanish, refogado) the mercury-gold amalgam to volatilize the mercury.*

6.4. Regional Use

In the Byzantine world, Almadén, Spain was known as a source of cinnabar and mercury as early as 332 BC [9]. Cinnabar was used to decorate the walls of Roman villas at ancient Pompeii more than 2000 years ago [51] and cinnabar was also used as makeup or rouge. Sometimes referred to as ‘ruddle’ in ancient literature, cinnabar was exported through the Black Sea port of Sinop (Figure 1) from which the mineral name cinnabar may have been derived [7]. However, for this study it is important to acknowledge that by 77 AD, Rome imported 4-5 t of mercury annually from Almadén specifically for amalgamation [32].

6.5. Conglomerates, Black Sand, and Fine-Grained Gold at Sardis

The sedimentary setting of the gold at Sardis has important regional implications that permit comparison with Byzantine gold mining at Las Médulas, Spain. Gold is a heavy mineral and ubiquitous heavy minerals, such as magnetite and zircon contained in the black sand must be removed. If present, rare nuggets [78] can easily be recovered from an alluvial gold occurrence; however, recovering sufficient fine-grained gold such as at Sardis, for jewelry or coins would have been challenging without mercury.

The gold at Sardis is hosted mainly in reworked sedimentary rocks comprised of poorly sorted conglomerate and sandstone (Figure 2). Additionally, the conglomerates have been faulted, uplifted, and are geomorphologically similar to the Las Médulas, Spain gold occurrence which was the most important gold occurrence mined by the ancient Romans. At Las Médulas, the Romans used hydraulic mining (*ruina montium*)—this required a system of aqueducts that provided water under sufficient head to pressure-wash and degrade the outcrop which released the gold and then the muddy gold-bearing sediment was washed over riffles that trapped the gold particles [35]. Mercury from the mines at Almadén was also used to amalgamate and recover the gold [37]. The Roman miners, therefore, had experience with hydraulic mining and amalgamation which would have been used at Sardis.

However, is there evidence for hydraulic mining at Sardis? There are at least 130 m of tunnels that were thought to have been used to augment the water supply of ancient Sardis [44]; however, herein an alternative interpretation is that the tunnels were used to provide water to hydraulically mine (*ruina montium*) gold from the gold-bearing Sardis conglomerates and are analogous to the systems of aqueducts used at Las Médulas.

Gold has a very high specific gravity (~19) and when panned, minerals of high specific gravity (ex. diamond, 3.52; garnet, 3.56; rutile, 4.3; zircon, ~4.5; magnetite, ~5; cassiterite, 6.8-7.1; platinum, ~14-19;) may also be found in the gold pan concentrate. Therefore, a method that will *selectively* remove only the fine-grained gold from the black sand, such as amalgamation, must be used. Even the Golden Fleece would not yield a pure gold concentrate and the persistent and abundant heavy minerals must be removed. At Sardis, the heavy mineral assemblage includes cassiterite, chalcopyrite, cinnabar, garnet, hematite, ilmenite, magnetite, pyrite, rutile, and zircon [74, 59, 64]. Gold separation is done today at the Pomza (Sardis) mine using several techniques, one of which is a large shaker, or Wilfley table, that uses flowing water and a system of riffles to sort the minerals according to specific gravity. Because of the high specific gravity and lentil-like shape of the gold, the Wilfley system provides a gold concentrate (Figure 12, Pomza Export; http://www.eilepomex.com). The heavy minerals are removed, sold for industrial use, and gold is recovered as a byproduct.

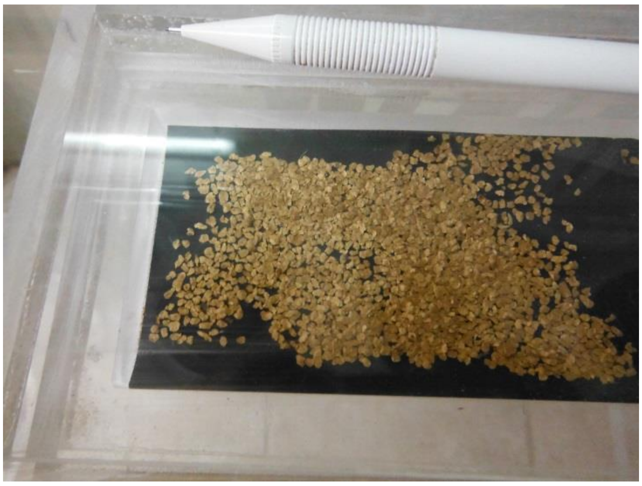

Figure 12. *Byproduct Sardis gold at Pomza Export office showing lentil-shaped grains.*

Gold separation from alluvial material is difficult. In another example, gold was also recovered as a byproduct in California, US from black sand at sand-gravel operations by: 1) magnetic, 2) high-tension, or 3) flotation methods. And, much like Sardis, the mineralogy of these deposits includes black sand comprised of ilmenite, magnetite, zircon, and platinum-group metals [40]. Therefore, at ancient Sardis, amalgamation would have been the only technology available to selectively remove only the fine-grained alluvial gold.

If available, nuggets would have been easily removed from the concentrates at ancient or modern Sardis mining operations. However, there are no museum samples, nor literature evidence to indicate that gold nuggets were ever found at Sardis [74], instead, the alluvial gold (Turkish, *altin*) is fine-grained and flat (Figure 12). In a study of the economic potential of placer gold at Sardis, [74] described the gold flakes as small with an average diameter of ~30 microns (0.03 mm) and the largest grain was ~3 mm. He concluded that, as a principal product, gold of this size would be very difficult to recover by mechanical concentration, and therefore, not economic. His mining engineering evaluation of the Sardis deposit showed that free gold ranged from 9-130 mg/m^3 and, in order to make this determination, it was first necessary to recover the gold from sluice concentrates by amalgamation and then nitric acid was used to dissolve the mercury.

6.6. Analysis of a Byzantine Gold Coin

The final argument is geochemical, that is, determination of the amount of mercury, if any, contained in an end-product Byzantine gold coin (Figure 13, Table 1). This follows Craddock's [27] original proposal that if mercury had been used at Sardis, then low levels of mercury would be detected in the gold analyses. However, in those previous studies of gold from Sardis, mercury would not have been detected by SEM-EDX because of: 1) the potentially low levels of mercury (<20 ppm) as indicated by the South America gold studies [16], and 2) the proximity of mercury and gold on the Periodic Chart and therefore, the lesser mercury peak would have been overshadowed by the stronger gold peak.

Figure 13. *Byzantine gold coin (Table 1; sample TK168, with 99.4% Au and 1020 ppm Pt); Byzantine Empire, Maurice Tiberius, struck 583 AD, Constantinople Mint. Helmeted and curassed facing bust holding globus crucíber, DM MAVRC TIB PP AVI / Angel standing facing holding long Chi-Rho-headed cross and globus cruciger, Victoria AVGGG officina letter I, CONOB below, ancient graffiti below bust, 22 mm, 4.37g (Gabriel Vandevoort, http://www.ancientresources.com, 1 March 2016).*

Turkish law will not allow catalogued artifacts such as gold coins or gold foils to leave the museums for analysis, much less be subjected to destructive analysis such as ICP. Therefore, an authenticated Byzantine gold coin was purchased in the US and a 0.7 g portion was submitted for ICP analysis (Figure 13; Table 1, TK168). The data show that the coin is 99.4% gold and 1020 ppm platinum—gold is normally soft, malleable, and has a Moh's hardness of ~2.5-3. The naturally occurring platinum (iridium and osmium) [13], with a Moh's hardness of 6-7, would have given hardness and durability to Sardis' ancient coins. The gold content of this coin is comparable to the gold content (>99%) of Sardis' coins analyzed by XRF (x-ray fluorescence) [25]. Most importantly, there is <1 ppm Hg in the coin analyzed for this study, a fact that given the evidence for amalgamation, must be discussed.

Alluvial gold from Argentina [22], Colombia [16], Perú [62, 16], Türkiye (this research, Table 1), and Venezuela [16] all contain 'high' mercury content, that is >5000 ppm, or more. And mercury is produced as a byproduct from Andean and western US gold-silver mines [15], therefore, the 'high' mercury content of alluvial gold may reflect metals in the primary gold occurrence. However, the 'high' background mercury of alluvial gold may also result from: 1) cinnabar/mercury outcrops near the stream; 2) airborne mercury contamination released from coal-burning or underground coal fires; 3) mercury released from alluvial gold mining in the region; or 4) volcanic eruptions. For example, a gold grain from the alluvial gold mining area of Similkameen River, Canada contained 22.9% Hg (229,000 ppm) [23] and indicates the contribution of contaminant mercury released in small-scale gold mining areas.

The mercury-gold amalgam in the gold pan contains >300,000 ppm Hg—this amalgam must be burned, as would have been done in the past, to volatilize the mercury, leaving end-product gold with only trace amounts of mercury [15]. Analysis of pre-Columbian gold artifacts from museums in Bogotá and Lima typically indicate <20 ppm Hg—consistent with a reduction of >99% of the background (~5,000 ppm Hg) or amalgam (~300,000 ppm Hg) mercury content after two burns to volatilize the mercury [16].

Microprobe analysis of Sardis alluvial gold indicates bismuth, copper, lead, mercury, nickel, platinum (iridium, osmium), silver, and several other elements in the gold; however, no ppm or percent was given [74]. Analysis of Sardis alluvial gold, the precursor material to ancient end-product gold and silver coins, contains 11,615 ppm Hg, 19,347 ppm Ag (Table 1) as well as other elements. We therefore conclude that the 11,615 ppm Hg in the precursor alluvial gold from Sardis, as well as mercury that was used for amalgamation, has been mostly volatilized leaving <1 ppm Hg (Table 1) by at least three high-temperature heating/burning episodes of unknown duration:

1. heat from a blowpipe as shown by [28, 68] that would have been analogous to the blowpipe (Spanish, *soplete*) used in pre-Columbian metallurgy or two burns using a gas torch used during modern amalgam burning [62, 15, 16] and subsequently, during the two-stage silver parting process at Sardis that included:
2. heating during salt cementation at temperatures of ~650°C followed by
3. heating and parting of the silver at temperatures of ~800°C [29, 55].

Amalgamation of alluvial gold and subsequent parting processes ultimately provided gold and silver for Sardis' ancient coins.

Gold foils with 4.7-17.3% silver [65] and gold-silver-copper foils (Spanish, *tumbaga* or Turkish, *tombak*) in the collection at the Archaeological Museum, Manisa would more closely represent the pre-parting composition of Sardis alluvial gold [74]; however, neither mercury nor platinum content was reported for these samples. These gold-silver-copper foils were likely hammered from an anthropogenic 'nugget' resulting from amalgamation (Figure 11) and burning of the gold.

Until ~1900, platinum was only known from gold-bearing alluvial sources [54] and since platinum melts at >1,700°C, it would have been little affected by amalgam burning and silver parting temperatures. Alluvial platinum is known at Sardis and microprobe analyses of a 5th century BC gold earring from the region indicated platinum [81, 74, 25]. The platinum in the earring and gold coin (Figure 13; Table 1, 1,020 ppm Pt) indicates an alluvial source for the metals and not intentional alloying of the metals.

The amount of gold in the Byzantine coin, >99%, approaches the amount of gold in modern, very pure, highly refined mint or bullion gold expressed as four 9s (9999) and demonstrates the efficiency of ancient Sardis' metallurgy. The platinum would have added hardness and durability to the softer, malleable gold.

7. Retorting Mercury from Cinnabar

Alluvial gold deposits in Türkiye were exploited 7,000 years ago [43] and the small grain size of the gold at Sardis would have required mercury amalgamation to selectively recover the fine-grained gold from the black sand concentrate. Some native mercury may have been obtained from cinnabar outcrops; however, retorting mercury is a straightforward process that requires cinnabar ore, retorts, fuel, and a condenser to trap and cool the volatilized mercury vapors. The cinnabar ore must be heated to at least ~200°C to liberate the mercury from the sulfur.

The region's oldest mercury retort dates to 8,000 years ago in the ancient Konya mercury district, Türkiye and it consisted of a large block of marble upon which the ore was placed along with charcoal fuel. A large clay bowl over the fire cooled and condensed the mercury vapors while allowing the sulfur vapor to escape through a chimney made of ceramic tubes [7]. Other examples of ancient mercury retorts include: 1) Arabic *xabecas* at Parque Minero, Almadén, Spain [72]; 2) rows of double ceramic pots shown in Agricola's De Re Metallica [1] (Book IX, p. 427); and 3) a pre-contact double-ceramic mercury retort from Sierra Gorda, Queretaro, Mexico [49] where there are many ancient cinnabar mines and retorting mercury dates to the 10th century BC [24]. These and other descriptions and sketches of a variety of other mercury retorts from China, Germany, and Mexico were compiled by [26]. Ancient mercury retorts were known in Perú at Huancavelica [67] and at Chonta where a chimney and buildings that housed retorts and condensers in the 1840s still remain.

Figure 14. *Cinnabar ore (~50 g).*

Figure 15. *Double-ceramic testi-kabab retort with clay seal, vent to right.*

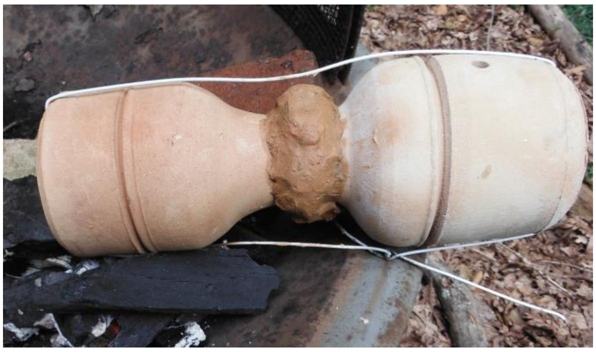

Figure 16. *Backyard testi-kabab retort in place with charcoal fuel (~600° F).*

Figure 17. *Mercury droplets in black mercury-rich residue (>100 ppm Hg) along rim of ceramic testi-kabab retort. For comparison, the blackened interior of a mercury smelter chimney at Karaburun, Türkiye had >400 ppm Hg. The sooty material consists of chlorides and sulfides of mercury and droplets of mercury [25]. And, at the mercury retorts at New Almaden, California this black sooty residue was scraped and removed to obtain additional mercury [11].*

Only retorting would have provided the amounts of mercury needed to produce the tons of alluvial gold produced before the arrival of the Europeans in Perú. Approximately 2 kg of mercury are needed to produce 1 kg of gold [21] using the artisanal amalgamation and gold burning processes.

Other examples of retorts include those at New Almaden, California where the retorts consisted of iron whaling oil-try pots that were inverted over the cinnabar ore, sealed, and then fired with wood. The cinnabar ore inside the metal pot was heated, the mercury volatilized, sulfur was released and the mercury vapors cooled and condensed, resulting in mercury [11]. In Indonesia, where small-scale gold mining with mercury is widespread in over 30 provinces [56] and up to a ton of mercury can be produced daily, using locally available cinnabar, from a simple, backyard wood-fired retort. This mercury is then sold directly to local small-scale gold miners or exported [60].

Therefore, given the geological evidence for the regional availability of cinnabar-mercury occurrences in Türkiye (Figure 1) and the widespread use of mercury for gold amalgamation in the past that continues to the present, it remains only to show how cinnabar could easily be retorted by using materials readily available in the ancient world. Therefore, a simple retort using *testi-kabob* clay cooking pots was modeled from: 1) the racks of double-ceramic retorts shown in Agricola's De Re Metallica [1] Book IX, p. 427) and, 2) a pre-contact double-ceramic mercury retort from Sierra Gorda, Queretaro, Mexico [49]. This rudimentary process produces a sooty, mercury-rich residue (>100 ppm Hg) and metallic mercury (Figures 14-17) that would have been collected and then used for ancient small-scale alluvial gold mining.

8. Conclusion

The geoarchaeological evidence presented herein includes: availability of cinnabar and mercury; an ancient retort; and the small grain size of the gold, all of which are consistent with amalgamation as the mining technology used to recover the fine-grained alluvial gold at ancient Sardis. Amalgamation is a rudimentary process that requires mercury, which was retorted from cinnabar occurrences in the region, and recovering the gold from the amalgam requires heat to volatilize the mercury leaving the gold/electrum for continued processing into jewelry and coins. As an analogy, this artisanal process is widely used today in many small-scale alluvial gold mines around the world and provides a sound replication model for understanding alluvial gold mining at ancient Sardis.

Abbreviations

ICP	Inductively Coupled Plasma
ppm	Parts per Million
SEM	Scanning Electron Microscopy
XRF	X-ray Fluorescence

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Author Contributions

William Earl Brooks is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

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