Simple sophistication: Mauryan silver production in north west India

Paul Craddock, Caroline Cartwright, Kirsten Eckstein, Ian Freestone, Lalit Gurjar, Duncan Hook, Andrew Middleton and Lynn Willies

SUMMARY This contribution summarizes the present understanding of the production of silver in the major mines of the Aravalli Hills in India during the last centuries BC, which was the period of their great expansion and maximum production as a remote but important part of the Mauryan Empire. The ore bodies presented great difficulties in both their mining and smelting; these were overcome to achieve an excellent recovery of the available silver on an enormous scale. Recent excavation at the sites and examination of associated material has shed light on the mining process and the extraction and assay techniques used in these mines.

Introduction

The rapid adoption of silver coinage throughout the ancient world from the middle of the first millennium BC created an unprecedented demand for silver. This led to a huge expansion in silver production and in turn to rapid developments in the mining industry, creating mines that were far larger and technically more sophisticated than any hitherto [1].

The silver mines of the Mediterranean world are well known, exemplified by the jarosite ores of the mines in the southern Iberian Pyrite Belt, most famously Rio Tinto [2, 3], and the argentiferous lead ores of Laurion in Greece [4]. In contrast, the mines that supplied the silver for the contemporaneous punch-marked coins of Mauryan India are much less well known.1 Two potential mines, Rajpura-Dariba and Rampura-Agucha, were investigated as part of a joint project between the British Museum, Maharaja Sayajirao University of Baroda and Hindustan Zinc Ltd (HZL) to investigate the silver-lead-zinc mines of the Aravalli Hills in north west India, Figure 1. This established that in the latter part of the first millennium BC zinc production had been confined to Zawar, whereas at both Dariba and Agucha the primary objective had been the extraction of silver.2 At these sites the ore bodies are principally of lead, zinc and iron sulphides. Although both Dariba and Agucha are now primarily worked for zinc, there is no evidence for early processing of the zinc ores in antiquity at these mines, such as those found at Zawar; indeed, at Agucha it is clear that zinc-rich parts of the ore body were avoided in favour of silver-rich lead minerals. At both Dariba and Agucha the lead ores have high silver contents (in contrast to Zawar) and at both sites there are the distinctive remains of silver extraction. As lead deposits are relatively common in northern India it seems unlikely that lead itself would have been the primary objective in developing these huge mines in what must then have been very remote locations. It is most probable, therefore, that the extraction of silver was the prime motive for the mines with lead as a secondary by-product. In addition, copper was also produced on a small scale at Dariba in antiquity and in the recent past, together with some limited iron production, Table 1. Previous interim reports have concentrated on the zinc industry at Zawar [1; pp. 309–316, 18–27]. Dariba and Agucha were included in one report that summarized the evidence from the mines [28] and another that outlined the smelting and cupellation processes [29].

Since those reports were published further scientific work on the silver-smelting debris excavated from these sites has provided considerably more evidence on the extractive metallurgy. These studies suggest that the processes were distinctive, partly because of the nature of the ores used and, although
apparently rather primitive, they nevertheless achieved a good extraction of the available silver.

**Topography, geology and mineralogy**

The Aravalli Hills run as a series of parallel ridges approximately north east from Gujarat through Rajasthan and into Haryana, ending c.100 km south west of Delhi, Figure 1. In the southern part the hills form ridges standing some hundreds of metres tall but towards the north east they rapidly sink into the Mewar Plain with only the peaks rising above the plain at Dariba and with no surface indication whatsoever at Agucha.

The ridges are formed of Precambrian rocks tilted almost vertically, Figure 2b. They were originally of sandy dolomite and limestone rocks, but although these are largely unaltered at Zawar, at Dariba and Agucha they have metamorphosed to a hard calc-silicate rock. The metalliferous ores are located in both the calc-silicate and the immediately adjacent graphite schists. These latter deposits are made up of quartz and graphite as well as more complex minerals including mica, sillimanite, potassium feldspar, etc. [30]. These complex silicates contain aluminium as a major component, which was to have serious consequences for the smelting of the ores associated with them, as evidenced by the slags (see the section on smelting below). The calc-silicates typically contain minerals such as wollastonite (CaSiO₃) and diopside (CaMgSi₂O₆), which would have presented far fewer problems at the smelting stage.

At the surface the lodes have been leached and sometimes gossanized. Beneath this zone, secondarily enriched, oxidized deposits of silver-bearing anglesite (PbSO₄) commenced, and below these there may have been deposits of silver-bearing cerussite (PbCO₃) in the Aravalli Hills of north west India, together with the ancient port of Bharuch or Broach (B). Map: Antony Simpson

The East Lode was not being worked at the time of this survey, but drilling had encountered workings at a depth of over 200 m below the surface; a piece of bamboo recovered from one dam up to the next, continuing to the surface, as recorded and illustrated in some nineteenth-century Japanese mines [34; Figure 2], or to a main water-raising shaft nearby.

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The mines

Although geologically very similar deposits at Dariba and Agucha were worked at approximately the same time, there are significant differences in the mining evidence and they will be considered separately.

**Dariba**

At Dariba two parallel lodes were exploited in antiquity: a westerly lode (further subdivided into a North Lode and South Lode) and the East Lode, Figure 2a. To the south east of the main mines there is almost continuous slag coverage, typically several metres deep, extending for approximately 50 hectares. The North Lode comprises a low chert-quartzite ridge containing many minor workings with small shafts sunk through the softer graphite schist deposits both for the silver ore they contained and also to access the ore in the underlying calc-silicate, Figure 2b. Much later, in the post-Medieval period, the area was reworked by opencast mining the calc-silicates, principally for the copper ore that they contained; the slags from that period accordingly have a lower aluminium content, Table 1 and Figure 3. At the southern end the ridge rises to form a very prominent hill, which is extensively gossanized. There is some unexplored evidence of surface trenching and a large post-Medieval quarry cutting into considerable deposits of earlier mine waste.

At depth, the modern mining operations encountered a major mine system consisting of a series of near vertical stopes probably dug from the surface into the graphite schist and calc-silicate deposits. There was abundant evidence of firesetting, which would have been necessary to weaken the harder rocks before they were mined with iron picks and chisels. There were some crosscuts linking the stopes, but these are likely to have been kept to a minimum to limit the damage if one of the stopes should flood. These workings have been traced for 80–90 m below the water table and, judging from the modern inflow rates, there must have been a major drainage problem.

One shaft-like stope that was explored by the project team was approximately 20 m high, 7 m wide at its base and 5 m wide higher up, Figure 4. Just below the top of the shaft a timber dam held back a pool of water in a recess cut into the wall by firesetting (Figure 5), with two shafts rising above, presumably for ventilation and drainage purposes. A ladder about 3 m long with widely spaced rungs rose into one of these shafts in which a further ladder was just visible rising upwards. A sample of charcoal from the complex was dated to between 180 BC and AD 65 (2040±50: BM-2637). It seems likely that water was bailed from one dam up to the next, continuing to the surface, as recorded and illustrated in some nineteenth-century Japanese mines [34; Figure 2], or to a main water-raising shaft nearby.

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<table>
<thead>
<tr>
<th>Sample reference</th>
<th>Context Slag type</th>
<th>Totalow /element (weight %)</th>
<th>Inclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Na₂O MgO Al₂O₃ SiO₂ K₂O CaO MnO FeO ZnO BaO PbO Cu Ag Cd</td>
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<td></td>
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<td>S1/L5 Ag/PbI</td>
<td>1.00 1.79 5.83 30.2 2.56 8.23 0.31 34.1 4.15 4.99 2.69 0.14 0.06 0.70</td>
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<td>PbS, PbS, Zn(Fe)S</td>
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<td>S1/L10 Ag/PbI</td>
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<td>S1/L2 Ag/PbI</td>
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</tr>
<tr>
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<td>PbS, Ag/PbI</td>
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<td>S1/L58 Ag/PbI</td>
<td>0.79 1.81 7.87 37.2 2.28 9.54 0.34 24.1 5.42 4.56 3.21</td>
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</tr>
<tr>
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<td>S1/L58 Ag/PbI</td>
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<td>32273V</td>
<td>S7 Ag/PbI</td>
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<td>32277Y</td>
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<td>32301R</td>
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<td>0.50 1.24 8.66 39.2 1.29 6.18</td>
<td>PbS, Ag/PbI</td>
</tr>
<tr>
<td>32278W</td>
<td>S9 Ag/PbI</td>
<td>0.36 1.27 6.65 31.5 1.46 4.71 1.16 28.8 7.01 3.96 5.76</td>
<td>PbS, Ag/PbI</td>
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<tr>
<td>32279U</td>
<td>S9 Ag/PbI</td>
<td>1.11 1.57 7.03 35.3 2.33 8.09</td>
<td>PbS, Ag/PbI</td>
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<tr>
<td>32287Y</td>
<td>S14 Cu</td>
<td>0.63 3.92 7.03 44.0 1.52 10.3</td>
<td>Cu(Fe)S</td>
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<td>28499T</td>
<td>S14 Cu</td>
<td>0.28 3.11 6.49 35.0 0.79 11.7</td>
<td>Cu(Fe)S</td>
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<td>32290T</td>
<td>S14 Cu</td>
<td>0.76 3.21 4.24 43.4 0.93</td>
<td>Cu(Fe)S</td>
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<tr>
<td>32291R</td>
<td>S14 Cu</td>
<td>1.67 3.83 5.22 41.9 1.35</td>
<td>Cu(Fe)S</td>
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<tr>
<td>32292P</td>
<td>S14 Cu</td>
<td>0.33 3.02 5.02 36.4 0.85 11.9</td>
<td>Cu(Fe)S</td>
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<td>32293S</td>
<td>S15 Cu</td>
<td>0.48 4.37 2.82 38.4 0.63 12.8</td>
<td>Cu(Fe)S</td>
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<td>32299X</td>
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<td>32041S</td>
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<td>Cu(Fe)S</td>
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<td>32280X</td>
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<td>Cu(Fe)S</td>
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<td>32281V</td>
<td>S9/L4 Fe</td>
<td>0.31 0.21 3.04 22.3 0.41</td>
<td>Cu(Fe)S</td>
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</table>

Notes
The slag compositions were determined by inductively coupled plasma-atomic emission spectroscopy and the inclusions were analysed using scanning electron microscopy with an energy-dispersive X-ray analyser. The '<' symbol denotes less than the figure quoted, i.e. beneath the quoted detection limit. Precision should be c±1–5% relative for SiO₂ and FeO, c±5–20% for the remaining oxides and c±10–50% for the minor/trace elements; the precision deteriorates as the detection limit is approached. The letters 'NA' indicate the inclusion was not analysed.
from a core at this depth was radiocarbon dated to between 39 BC and AD 534 (1790±120; NPL 209). Drainage at this depth must have been a major problem, especially as the graphite schist was permeable.

At the surface the calc-silicate lode must originally have been of the order of 30 m wide, although it has been almost totally removed by mining in antiquity leaving a major open-cast hole approximately 100 m wide, over 300 m long and
of uncertain depth, Figures 2 and 6. The opencast workings produced enormous quantities of waste and here the ancient miners would have encountered a problem. While such huge quantities would have to be dumped near the mine, only limited amounts could be deposited on the west side because the steep slopes of the South Lode sweep down almost to the edge of the opencast. Most material was dumped in very high tips along the length of the east side of the opencast, Figure 6. However, as the ground is alluvial and very unstable, without support the waste tips would have collapsed into the workings and lode that underlie them.

Until recently the depression has been filled with water, 10 m or more deep, which for over a year provided the modern beneficiation plant with 600 tonnes of water a day without substantial reduction in the level. When the depression was drained it revealed an extensive timber revetment supporting the east side, running for at least 150 m and extending around the south east corner of the pit.

Very limited excavation by the project team showed that the revetment was in three, or more likely four, lifts each 0.4 m high (Figure 7), creating a benched (stepped) side to the opencast. There may of course be further lifts still buried under the mud.

Table 2. Composition of silver-lead slags from Agucha

<table>
<thead>
<tr>
<th>Sample reference</th>
<th>Context</th>
<th>Oxide /element (weight %)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Na₂O MgO Al₂O₃ SiO₂ K₂O CaO MnO FeO ZnO BaO PbO Cu Ag</td>
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<td>32071U</td>
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<td>1.60 4.18 15.0 48.2 3.69 78.4 0.23 13.1 0.12 0.08 3.62 0.0140 0.0031</td>
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<tr>
<td>32070W</td>
<td>S1/L3</td>
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<td>S1/L4</td>
<td>2.07 3.65 13.6 44.6 2.87 89.9 0.46 17.3 0.20 0.08 4.25 0.0149 0.0024</td>
</tr>
<tr>
<td>26059U</td>
<td>S1/L4</td>
<td>1.47 3.99 12.9 48.6 2.76 85.7 0.23 13.9 0.25 0.06 5.65 0.0290 0.0025</td>
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<tr>
<td>32073Q</td>
<td>S1/L4</td>
<td>1.29 3.72 12.1 40.6 1.33 7.08 0.38 12.6 0.20 0.06 2.30 0.0314 0.0033</td>
</tr>
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<td>26060X</td>
<td>S1/L5</td>
<td>1.52 4.44 15.4 48.1 3.22 78.8 0.24 13.2 0.95 0.05 3.52 0.0145 0.0055</td>
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<tr>
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<td>S1/L5</td>
<td>1.53 3.39 11.4 40.3 2.14 76.0 0.41 20.1 0.25 0.09 10.5 0.0145 0.0050</td>
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<td>32077T</td>
<td>Surface</td>
<td>1.59 3.97 12.3 45.8 2.30 10.7 0.54 16.4 1.1 0.19 3.28 0.0253 0.0021</td>
</tr>
</tbody>
</table>

Notes
The slag compositions were determined by inductively coupled plasma-atomic emission spectroscopy.
Precision should be ±1–2% relative for the major oxide (SiO₂), ±5–10% for Al₂O₃, FeO and CaO, and ±10–50% for the remaining elements/oxides; the precision deteriorates as the detection limit is approached.

Table 3. Composition of the pieces of argentiferous lead from Agucha

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<tr>
<th>Sample reference</th>
<th>Element (weight %)</th>
<th>Sample weight (mg)</th>
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<td>As</td>
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<td>46312V</td>
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<td>46315P</td>
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<td>46314R</td>
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<td>0.525</td>
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<tr>
<td>46314Rii</td>
<td>0.093</td>
<td>0.525</td>
</tr>
</tbody>
</table>

Notes
The compositions were determined by inductively coupled plasma-atomic emission spectroscopy.
The results are expressed as weight percent and have been normalized to 100%.
The '<' symbol denotes less than the figure quoted, i.e. beneath the quoted detection limit.
Precision should be ±1–2% relative for the major element (Pb), ±5–30% for the minor elements, deteriorating to ±50% at the detection limit.
Two analyses were carried out on the piece of argentiferous lead with sample reference 46314R.
floor of the opencast. Each lift consists of vertical squared posts, closely spaced, held in place by three sets of horizontal pairs of timbers at right angles that extend back to the next lift and which are pinned by long timbers across the front that are themselves pinned at the back. Behind the vertical posts, smaller horizontals prevent material passing through the gaps, Figure 7. The timbers were joined by simple but strong mortice and tenon joints, such as were also found on some of the underground timbers. The wood of the main revetment timbers was identified as *Terminalia arjuna* (arjuna or arjun tree), two samples of which gave radiocarbon dates of between 394 BC and 50 AD (2140±100: NPL 208a) and between 392 and 176 BC (2220±50: BM-2635).

Removal of water from the pit would have been an enormous task. It may have been done by human labour or by oxen, which today are used to draw water from deep wells. Observation of the operation of a modern well suggests that about 40 pairs of oxen operating night and day – a total of 160 pairs in all – would have been necessary to drain the mine.

The East Lode revetted opencast is one of the most remarkable mining structures to have survived from antiquity. Indeed, if the revetment runs for the length of the opencast, as seems probable, it is also arguably the largest timber structure to survive from antiquity. To conceive, fund and coordinate such a project could only have been undertaken by a single powerful authority, surely in this case the Mauryan state, determined to ensure the supply of silver for its mints.

**Agucha**

At Agucha, before recent mining operations began, the only surface evidence for early mining was a shallow valley or trench that constituted the severely eroded remains of a major opencast, Figure 8. Unlike Zawar and Dariba there is no evidence for Medieval or post-Medieval working of this deposit. To the east of the workings, in the area known to be a Mauryan settlement, were extensive slag deposits over an area of approximately 30 hectares [35]. The mine trench extended for approximately 1.6 km, varied in width from 10 to 110 m and was approximately lentoid in plan at the surface. During the development work for the modern mine it was noted that the zinc-rich deposits had been ignored but that the pods of argentiferous lead had been almost totally removed.

From the team’s investigations and those conducted subsequently by the HZL geologists during the development of the modern mine, it is possible to suggest the following sequence of events:

- **Phase 1.** Probably shallow and irregular tunnelling into the graphite schist and calc-silicate surface outcrops as in the North Lode at Dariba, selectively following richer shoots or horizons of argentiferous lead ores within the upper oxidation zone.
- **Phase 2.** Open working of the deposit with the hanging (east) wall supported by timber to allow maximum depths to be reached. From the observations made of the base of...

![Figure 3. Plot of Al₂O₃ against FeO for the Dariba and Agucha slags. The Dariba copper slags are post-Medieval and their aluminium contents are lower than those in the earlier silver-lead slags as they tend to have come from calc-silicates rather than graphite schists.](image-url)
the ancient opencast this was also likely to be entirely within the gossanized secondary oxidation zone.

- Phase 3. Possibly partly contemporary with the open working, shafts were sunk to work the deposits at greater depths than could be worked economically by opencast mining, Figures 8 and 9. This would continue until limited by water inflow, with the deepest workings only accessible during a series of dry years. It is likely that the two roughly parallel levels at this horizon (Figure 9) were driven towards the end of this phase. They would have acted as drainage adits at the base of the main workings and work below them could only have been conducted in the drier years.

- Phase 4. The sinking of a shaft from outside the opencast to a depth of some 40 m and, possibly, a new shaft from a point high on the side of the opencast, while also deepening other shafts in similar locations to intersect with the lower workings. These shafts would allow water to be hoisted out of the workings and, with the sealing of the older shafts in the opencast, lessen the risk of flooding from the surface.

- Phase 5. The workings were deepened still further by constructing underground shafts, possibly in separate ventilation and drainage districts that were isolated from the main shafts to avoid the risk of local underground inrushes. The workings at these depths seem much less extensive than those that are shallower, presumably selectively following only the richer ore shoots. The pattern of workings shown in Figure 9 includes duplicate deep shafts, which may have been for ventilation purposes. Alternatively the deepest shafts may have been sunk so as to isolate the workings from flooding each other and with each deep shaft linking to shafts in old workings to form separate ventilation and drainage districts. This is a reasonably obvious practice, which was used in more modern times and may perhaps also have been used at both Zawar and Dariba in antiquity, where isolated workings seem to have been pursued at depth [28]. Hoisting of water would have needed to be virtually continuous, although with inevitable seasonal variations and disruptions. The deepest evidence of early working discovered at Agucha during the recent mine development was bamboo brought up by drilling from 160 m below ground level; as at Dariba, working at this depth must have represented a major drainage challenge.

Mining summary
At both Dariba and Agucha the earliest workings are likely to have been in the gossanized graphite schist deposits near the surface and, to a lesser extent, in the calc-silicate; the main silver-bearing material was argentiferous lead with some extraction from freibergite at Agucha. The mining would have progressed deeper into the deposits, probably still concentrating on the graphite schists for argentiferous galena and freibergite, while calc-silicate deposits near the surface also began to be mined from the opencast.

Process metallurgy
After mining, the first stage in the processing would have been beneficiation – the concentration and preparation of the ore. The ore would have been beneficiated by crushing, as evidenced by the huge mounds of bean-sized rock fragments at both Dariba and Agucha. At Dariba an outcrop of the hard calc-silicate rock had a series of large mortars carved into its surface in which the ore had been crushed, probably with large, iron-shod pestles. Water-based separation of the concentrates by some form of panning or buddling of the finer crushed material was likely. The final result would have been
a coarse grade of material ready for smelting, with particles down to the size of a pinhead, and a finer sludge-like product. The latter material would probably have been made into balls with dung and charcoal dust prior to charging into the smelter, a common practice among lead and copper smelters in India up to the nineteenth century [1; pp. 152 and 164].

The limited surface excavations carried out at Dariba and Agucha were mainly confined to sampling a selection of slag heaps with a little excavation where chance exposures in present-day ditch or well sides had revealed interesting material. Both sites had enormous quantities of silver-lead smelting slags from the Mauryan period, but while the sites excavated at Dariba produced ceramic evidence that related mainly to primary smelting, at Agucha attention was focused on a small assemblage of cupellation debris.

**Smelting**

**Slags**

The silver-lead smelting slags from both Dariba and Agucha are very heterogeneous and often contain macroscopic fragments of the gangue minerals, particularly quartz, associated with the ore [36]; in comparison, contemporary iron-smelting slags from Dariba have a free-flowing fayalitic structure. Analysis revealed a high barium content for the Dariba silver-lead slags (Table 1) and a high aluminium content, especially for the slags from Agucha, Table 2. In contrast, the Dariba iron-smelting slags have lower aluminium contents, Table 1. The aluminium would give the slags a high melting point and would also cause the slags to be very viscous at the estimated smelting temperatures of between 1000 and 1300°C, Figure 3. This situation was inevitable given that the host-rock of the ore at Dariba and Agucha included aluminous graphite schists. However, the survival of mineral fragments such as quartz and potassium feldspar (Figure 10) is less easily explained and suggests that either the process was quite short or possibly that additional quantities of crushed mineral were added at a late stage in the smelt, as exemplified by the so-called free-silica slags that are prevalent at Phoenician and Tartessian silver-smelting sites in southern Iberia [38]. In some of the nineteenth-century hearth processes for extracting lead that were carried out in Britain, lime was added to the slags at a late stage in the operation [39; pp. 232–235].
Alternatively, the high melting point and viscosity could have been responsible for the inhomogeneity and for some of the mineral remaining unmelted.

Scientific study of the ceramics from the associated smelting units suggests a short smelt and on balance this is the most likely explanation for the survival of gangue minerals in the slag. A short process time would be expected to lead to the presence of many blebs (inclusions) of lead metal trapped within the viscous slag (as is the case with the free-silica slags from southern Iberia), but the slags from Dariba and Agucha have relatively few blebs of either lead metal or lead sulphide. It is possible that the slags were worked with iron tools to squeeze out the molten lead while they were in a paste-like condition, as was the practice in some post-Medieval British hearth-smelting processes, but these have very different compositions and lead contents [39; pp. 225–244].

The slags from both Dariba and Agucha have quite low lead contents, which might suggest that the ores were low in lead minerals and that it had been necessary to add additional lead metal to the smelt in order to collect the silver. However, the original ores contained predominantly lead minerals and thus the addition of lead should not have been necessary; instead, the low lead content suggests that the recovery of both lead and silver was rather efficient.

Figure 8. A plan of the workings at Agucha immediately prior to modern mining. Diagram: Hindustan Zinc Ltd
Apart from the slags themselves the heaps at the mines contained a variety of ceramic fragments associated with the smelting and refining processes. These included quite thick pieces of crude curved ceramic, slagged and burnt on their inner, concave surfaces. The curves suggested hemispherical shapes of between 30 and 50 cm diameter that could have been linings for either smelting hearths or bowl furnaces. The same deposits also produced fragments of tuyeres, crucibles and many fragments of potsherds that had seemingly been reused in some high temperature process that had brought about their partial glazing, slagging and vitrification.

The ceramics were made from coarsely tempered ferruginous clays which, in common with most ceramics used in extractive metallurgical processes in antiquity, are not particularly refractory [40]. Analysis of those thought to have been associated with the smelting operations at Dariba showed the ‘clay pastes’ (i.e. excluding grains coarser than about 50 μm) to have low to moderate amounts of sodium and potassium and rather variable amounts of calcium. The angular temper ranged in size from silt to grains several millimetres across and is likely to have been obtained from a sedimentary deposit. These aplastic grains are mainly quartz and feldspar but there is also a suite of minerals more clearly diagnostic of metamorphic rocks; these include staurolite, garnet, amphibole and kyanite, all of which are present in the deposits. Fragments of slag were observed rarely and are probably fortuitous additions.

A very noticeable feature, again common to early metalurgical ceramics from all over South Asia, is the evidence of large quantities of vegetal temper, particularly the husks and stalks of cereal plants. The highly comminuted nature of some of the stem fragments is typical of tempers containing dung and it is likely that, in addition to crushed rock and coarse sands, the clay bodies would usually have been tempered with considerable quantities of chaff and dung. This practice continued into the post-Medieval period as evidenced by the smelting debris excavated at both Zawar and Dariba as well as the nineteenth-century descriptions of traditional smelting practices in South Asia that were made by geologists [1, p. 174]. On firing, the chaff would soon burn out leaving many voids that, although weakening the ceramic, would make it very resistant to thermal stress. In particular, the clay linings could accommodate thermal gradients of many hundreds of degrees centigrade over just a few millimetres as incipient cracks would be stopped at the first void.

**The process**

The composition of the slag-like material on the curved ceramic fragments is identical with the slags themselves and thus these ceramics are likely to be the walls of the smelting unit. The degree of vitrification suggested maximum temperatures in the region of 1150°C, which is consistent with a smelting process. However, the rate at which the vitrified textures of the furnace lining fragments give way to unvitrified ceramic indicates a relatively steep thermal gradient during use. This suggests that the process for which the installations were used was of short duration, probably not more than about an hour at maximum temperature, reinforcing
the evidence for the short process implied by the survival of mineral fragments in the slags.

One curved fragment (BMRL 27298) has a well-formed rim where its diameter is greatest, with the usual evidence of vitrification/slagging. This could either have formed the base of a bowl furnace or the lip of a hearth. The flow patterns on this piece showed the slag had run down and away from the rim. Thus this ceramic was positioned with the rim uppermost during use, i.e. the smelting installation was set in the ground as a hearth rather than inverted as a freestanding furnace. It is perhaps significant that the excavations in the ancient deposits at both Dariba and Agucha failed to produce a single piece of rim from an upstanding furnace, although large numbers were excavated from contemporaneous deposits at Zawar and also from the post-Medieval deposits at Dariba. This provides further evidence that the early silver-lead smelting was carried out in hearths similar to those in nineteenth-century Japan that were described and illustrated by William Gowland [41; Figure 7], rather than in freestanding furnaces.

The glazed sherds found at Dariba were thought at the time of excavation to have been associated with cupellation, but the identification of minor amounts of zinc in their vitrified surfaces makes this interpretation impossible, as the argentiferous lead being cupelled would not have contained any zinc, Table 3. Instead they must have been associated in some way with the smelting of the lead ore – which contained zinc – possibly as hearth linings.

**Cupellation**

At Agucha an eroded slag heap was excavated, which provided the slag sample presented in Table 2 and fragments of curved ceramics similar to those encountered at Dariba. However, attention was concentrated on one of the recent but now abandoned wells (the well to the left of ‘incline’ on Figure 8), where refractory material could be seen near the top of the well side. Excavation showed that the well had cut through a series of ancient pits in which very fragile ceramic material had survived in an excellent state of preservation (Figures 11 and 12), together with fragments of ore, argentiferous lead and litharge. Similar features and material were revealed in the two pits on opposite sides of the well, although they were not from exactly the same stratigraphical horizon; the slightly later pit had a radiocarbon date of between 743 and 386 BC (2380±40 BM-2489). Both areas contained substantial amounts of refractory material that was apparently connected with cupellation. In this process
the argentiferous lead was exposed to a hot oxidizing blast sufficient to convert the lead to litharge and leave the silver as metal [1; pp. 221–232].

Given the location of the site within the general area of the slag tips it was inevitable that slag would be present, but only a small amount was found. None of the abundant refractory material here seemed to relate to the primary smelting of ore to metal, but rather to be cupellation debris from two quite distinct activities: the small-scale assay of ores to determine their silver content and the production of silver from argentiferous lead by large-scale cupellation. The first activity was evidenced by the numerous small clay vessels that were heavily lead-glazed and had clearly been exposed to high temperatures in an oxidizing atmosphere; indeed, some still had their tuyeres attached. These must surely be small cupels and they were found in association with separate pedestals, which have been interpreted as stands to support the cupels in the hearths, Figure 11. Together with the small pieces of argentiferous cerussite and argentiferous lead, these refractories suggest that the mine assay office was in the vicinity. The evidence for the second operation was a segment of a litharge cake,6 the extensively vitrified and glazed ceramic fragments that could be reconstructed to form a hood (Figure 12) and a fragment of a large tuyere set in clay. 

Assay cupellation

The small cupels have only a tiny capacity of a few hundred grammes of lead and would have been totally inappropriate to the cupellation of argentiferous lead on an industrial scale. However, every silver mine needs an assay office where the silver content of each batch of ore could be determined by first smelting to yield argentiferous lead, followed by cupellation to ascertain if it was worth mining. The small fragments of cerussite ore and the five small pieces of argentiferous lead (weighing 109 g in total) also found at this location support this interpretation of the function of these cupels.7

The clay pastes used for the cupels, tuyeres and stands vary slightly but are all characterized by an abundance of poorly sorted, angular grains, typically 0.1 to 0.5 mm in diameter, but ranging in size from silt grade (< 60 μm) to coarse sand (up to c.1 mm). The relative proportions of the finer and coarser aplastic grains vary; typically they are composed mainly of quartz and feldspars, along with green-brown pleochroic amphibole, garnet and occasional fragments of metamorphic rocks. The proportions of amphibole and garnet vary from sherd to sherd. The fine clay matrix contains rare opaque grains and flakes of white mica.

The extent of the vitrification/glazing on the cupels, together with the position of the tuyere on the complete tuyere/cupel assembly (BMRL 26304: Figure 11), suggests that each cupel was heated individually from above, with the highest temperatures achieved at the surface of the charge, within the opening of the cupel.

The base of the cupel would have been embedded in loose material at the bottom of the cupellation hearth, protecting it from the lead-rich fumes and shielding it from the heat applied from above; as a result, these areas have no glazing and none of the cupels examined showed any evidence of vitrification. Refiring experiments, taking into consideration the likely fluxing effects of the lead, established that the cupel/tuyere/pedestal assemblies were exposed to temperatures below 950°C during use and any initial firing before use. This is towards the minimum that would have been required to complete the cupellation of the argentiferous lead. When found, the cupels were empty but they would have contained a disc of litharge with any silver present as a separate phase. At least towards the end of the process, it would have been necessary to raise the temperature to about
1000°C, sufficient to melt the silver, which has a melting point of 961°C.

**Production cupellation**

Simple visual inspection of the fabric of the hood fragments revealed that it was coarser than those described above. Petrographic examination showed it to contain abundant, very poorly sorted aplastic inclusions, which range in size from silt to very coarse sand; the grains are typically sub-angular but some are sub-rounded. The size distribution of the aplastic grains is bimodal, with very fine sand/silt (<0.1 mm) and medium-coarse sand (>0.25 mm) both common. In other respects the fabric of the hood fragments is very similar to the other ceramics, including the presence of sparse wheat and barley chaff fragments, visible mainly in the hand specimens.5

The differences between the clays and tempers used for the cupels, pedestals and tuyeres were probably fortuitous; they may reflect the use of clays and temper from different sources within the same local area. However, the use of a coarser clay fabric for the hoods seems likely to have been deliberate, probably because these were intended to be exposed to a far more severe thermal environment and were consequently much larger and thicker.

The hoods were exposed to temperatures in the region of 1100°C confirming the macroscopic visual observations that these materials were exposed to a significantly higher temperature regime than the cupel assemblies. These high temperatures were maintained for many hours, once again very different from the heat regime to which the small cupels had been exposed.

The segment of litharge came from a disc that would originally have been approximately 6 cm in diameter, 3 cm thick at its centre and would have weighed over a kilogramme. This segment is likely to have been produced in a cupellation hearth, of the type proposed by Conophagos to have been present at Laurion [4; p. 308, 43], or described and illustrated by both Agricola [44; p. 468] and Biringuccio [45; p. 166] in sixteenth-century Europe. It is likely that the heavily vitrified and glazed ceramic linings are from hoods that would have partially enclosed such hearths. At Agucha these may have been set in the ground in a manner similar to the small cupellation hearths at Lydian Sardis [42; pp. 81–83 and 208–209]. The principal evidence for this at Agucha is a large thin-walled tuyere set at a shallow angle in a clay support with a flat bottom; it is usually assumed that such flat-bottomed tuyeres were set on the ground [46]. Thus this tuyere would have produced a blast directly over the molten argentiferous lead, creating the necessary oxidizing atmosphere. The deep penetration of vitrification and the extensive surface glazing of the hood fragments show that they must have been in operation almost continuously for many hours, processing numerous loads of metal before needing replacement.

**Broader significance**

The archaeological and scientific examination of the remains of silver smelting in the Aravalli Hills has helped to resolve some of the problems regarding the Hellenistic and Roman accounts of India, especially the apparently contradictory evidence concerning whether or not India produced silver. The mining engineer Gorgus of Alexandria, who accompanied Alexander on his expedition to India in the third century bc to assess its mineral wealth, produced a report that was referred to by Strabo in his *Geography* (15.30): “It is said that in the country of the Sopeithes [in present-day north western India or Pakistan] … gold and silver mines are reported in mountains not far away; excellent mines, as has been plainly shown by Gorgus the mining expert” [47; VII pp. 52–53]. Similarly Megasthenes, who also accompanied Alexander and subsequently travelled widely in the Mauryan Empire, reported that India had much gold and silver [48, p. 31].

Other accounts of metal resources include the *Periplus*, an invaluable Roman guide to the seaborne trade in the Indian Ocean that was probably compiled in the first century bc. It described in some detail the trade of the major port of Barugaza (now known as Bharuch or Broach: Figure 1) in the Bharuch District at the mouth of the Narmada River on the Gujarat coast. The *Periplus* included tin, copper and lead (together with gold and silver bullion in the form of coins) among the imports, but with no mention of any metals or minerals among the exports [30; p. 27, 51; pp. 44–48]. In his *Natural history* (34.163) Pliny asserted that the Indians had no tin, copper or lead [52; pp. 244–245]. This suggested to most later scholars that the Indians did not have these metals locally [53; pp. 267–269], which puzzled Casson [50], who pointed out that there are abundant ore deposits of copper and lead close to the major trading ports and that Strabo specifically mentioned items made of “Indian copper” in his *Geography* (15.69) [47; pp. 122–123]. This apparent contradiction can now be explained quite easily: Strabo based his work on the accounts of Gorgus and Megasthenes compiled around 300 bc, when the major mines in the Aravalli Hills were flourishing, but by the turn of the millennium when the *Periplus* and the *Natural history* were compiled these mines were out of production, creating shortages that could only be met by imports.

The discovery of the age and extent of production in the Aravalli Hills has gone some way to locating the source of the silver in the punch-marked coins, although unpublished lead isotope analyses of the coins show that the metal cannot have come solely from sources in the Aravalli Hills.9

To achieve silver production on the scale indicated at Dariba and Agucha, major problems had to be overcome. The mines must have experienced great difficulties with drainage, both in the opencarts, where removal of enormous quantities of water would have been continuous, and in the deep workings, which operated over 100 m below the water table. Although the slags provide evidence that smelting these intractable ores must also have presented considerable problems, the silver content of those slags is low, showing that the seemingly simple extraction process was in fact quite sophisticated.

The mines were worked on a colossal scale for several hundred years around the fourth century bc and were clearly well organized and efficiently run with a huge labour force. Those responsible for their operation – almost certainly the Mauryan state – could clearly call on virtually limitless resources to produce the wealth of the Mauryan Empire. For, as Kautiliya (2.12.37) well understood, “mines are the source of treasury, from the treasury comes power to the state” [14; p. 102].
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References

Notes
1. Silver production in South Asia in antiquity has previously been little considered. Patterson, for example, in her major study of silver stocks in the ancient world [5], took a not uncommon Hellenistic-Roman viewpoint and failed even to mention South Asia, although the existence of an Indian silver coinage on a scale corresponding to that of the ancient Greeks has long been recognized. In India itself little evidence of ancient silver production had previously been reported before the project described here uncovered extensive evidence in the Aravalli Hills, Ball, for example, stated that “there appears to be no very direct proof forthcoming that silver was ever produced to any large extent in the peninsula” [6; p. 231]. Coins began to be minted in north India from the mid-first millennium bc with between 20 and 30% of copper, which will have contributed its temper all contain a high proportion of domesticated plants, including wheat (Triticum sp.), millet (Pennisetum sp. and Setaria sp.), sorghum (Sorghum sp.), barley (Hordeum sp.), rice (Oryza sp.) and chickpea (Cicer sp.). This shows that there must have been substantial arable farming, almost certainly established adjacent to the mines by the authorities, specifically to feed the communities working there. An interesting and relevant instruction contained in the Arthaśāstra (2.15.60) is that the director of forest produce “should cause charcoal and husks to be taken to metal workshops and for plastering walls” [14; II pp. 129-131].
2. In common with early limehogs from elsewhere, the limehog cake examined here (BMRL 33960) is a mixture of lime oxide and lead silicate. It contains 120 ppm of silver, which is very low compared, for example, with the quantities found in limehog cakes from the Lydian refinery at Sardis, in Turkey, which varied between about 200 ppm and several percent of silver [42; p. 160, Table 6.2]. The Mauryan treatise, the Arthaśāstra (2.13.49) mentions the use of bone in the cupellation process [14; II p. 114], but the low phosphat content of the limehog cake and the small cupels show that bone was not a significant component in this case.
3. The cerasite has a silver content of 170 ppm, which is not very rich. In contrast, the five pieces of argentiferous lead have silver contents varying between 800 and 1700 ppm, indicating that they come from rich ores. They also had approximately 0.4% antimony and 0.6% arsenic, suggesting that the lead had come from a freibergite ore.
4. Gorgus’s report, as quoted by Strabo (15:30) was not particularly flattering: “But since the Indians are inexperienced in mining and smelting, they also do not know what their resources are, and handle the business in a rather simple manner.” The research presented here suggests he was mistaken and was the first in a long line of westerners to make pejorative remarks about Indian extractive metallurgy based on an incomplete understanding of the process [49].
5. It is problematic to use lead isotope analysis to determine the source of Indian silver coins because for the majority the silver is alloyed with between 20 and 30% of copper, which will have contributed its own lead isotope signature [9; p. 495, Table 33].