INDIAN STEEL A FORGOTTEN COMMODITY OF THE GREAT TRADE ROUTES

Marek Woźniak
PhD candidate, Institute of Archaeology and Ethnology, Polish Academy of Sciences

Abstract: Among numerous exotic goods carried along ancient trade routes the so-called Seric iron is one of the most mysterious and least known. According to ancient sources, it was imported from a half-mythical land of Serica. New discoveries in southern India suggest it should be identified with the kingdom of Chera (in modern Tamilnadu) which existed between 300 BC and AD 300. This metal, one type of which was the patterned Damascene steel, was used mainly in the production of high-quality weapons. From about the 3rd century AD local production centers of crucible steel emerged also outside India.

Keywords: Indian steel, crucible steel, wootz, Damascus steel, Serica country, Tamil metalurgy

The economic and cultural role of the great trade routes cannot be underestimated, as a source of sought after exotic goods and a means of exchanging information on far-off lands and their inhabitants, a veritable "internet" of the pre-industrial age. Modern research highlights the ubiquity of such routes in all territories, indicating that professional merchants of the great ancient empires chose the best of hundreds of routes known to local communities, the ones that supplied the best goods and were the shortest viable connection between producers and the most interested and wealthy customers. The ultimate intensification of international trade and the emergence of regular intercontinental routes came with the emergence of the great, rich and populous empires of the Ancient Near East (Achaemenid Persia, Hellenistic monarchies of the Ptolemies and the Seleucids), Europe (Roman Empire) and Asia (united Chinese Empire, Magadha empire).

The military expeditions of the Greek Bactrian kings to northern India (Kalita 2009: 95–193), the sailing feat of Eudoxos of Cyzicus (Sidebotham 2011: 15, 35, 57; Hourani 1995: 24–26), and the long journey of the Chinese envoy Zhang Qian (Loewe 2000: 687–689) were some of the events that led to the emergence of two main routes connecting Asia, Africa and Mediterranean Europe [*Fig. 1*]. The older of the two was the Spice Route from Alexandria, up the Nile through Kleopatris, Myos Hormos and Berenike on the Red Sea coast, the ports of South Arabia and Ethiopian Aksum, occasionally through Dioskurida (Socotra) and on with the monsoon winds to the western coasts of India (Sidebotham 2011: 175–194; Ray 2003: 25–29ff). The other route was the Silk Road from Antioch and Tyre (through

Palmyra), northern Mesopotamia, Media, the Caspian Gates, Hyrkania, Parthia, Aria, Bactria, across Pamir to the important station of the so-called Stone Tower near Kashgar, where it forked to skirt the Takla Makan desert either from the north or from the south, joining together again at Dunhuang to reach the so-called Jade Gate, which gave entry into China (Harmatta 1994; Hill 2009). The two routes functioned separately, each fraught with its own dangers and each carrying specific goods, such as silk and highbred horses for the northern trail, spices and frankincense for the southern one. But they also connected and sold the same goods, transferred either by land or by sea, passed from hand to hand at the great marketplaces and between the caravans on the two routes.

The most important connector and the oldest branch of the two trails was the route from northern India to Bactria (through Taxila, close to today's Peshavar and the valley of Kabul river) and one of the most mysterious and possibly the most valuable commodities that was transported down both the routes was the so-called Indian steel, also referred to as "iron of the Seres".

SERIC IRON AS A COMMODITY HISTORICAL SOURCES

The earliest mention of this unusual metal, preceding the emergence of the two great trade routes, is given by Ctesias of Knidos in his *Persica*; the Greek physician and historian speaks of a gift of two swords made of Indian iron, which he received from the King of Kings, Artaxerxes II, and the Queen Mother Parysatis (Ctesias 45b;

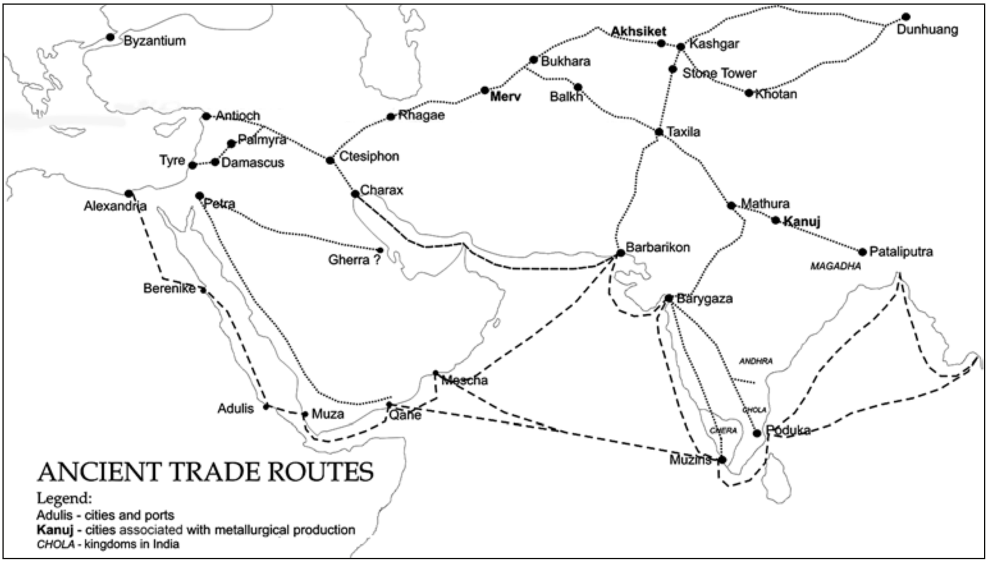

Fig. 1. The main trade routes (Drawing J.K. Rądkowska)

Srinivasan 1994: 50; Bronson 1986: 18). This brief report indicates firstly the value of the weapons made of this material, considering that the King of Kings gave them as a personal gift and that their not only prestigious importance was proverbial.[1] The second inference to be made from this source is that the iron was actually steel (of special class), suitable for producing weapons of a quality sought at the Achaemenid court. Thirdly, the source indicates that there was trade between Persia and India already at the end of the 5th or at the beginning of the 4th century BC, unless Indian steel reached Persia as a form of tribute. Whichever the case, it should be concluded that some kind of steel worthy of importing and being used by the King of Kings was being manufactured in India already in the early 4th century.

"Indian iron" appeared in the written sources with increasing frequency often over time and always in a context suggestive of its exceptional value. In relation to the Indian campaign of Alexander the Great, it was mentioned by Curtius Rufus who listed 100 talents of "white iron" among the gifts offered to Alexander by the envoys of the Malles people (Curtius 9.8.1). While we cannot know precisely what this iron was, its presence among the "finest" and "most precious to the Indians" (so Arrianus 6.14–15) could indicate steel of the kind mentioned by Ctesias. The iron's suitability as a gift or tribute is further confirmed by mentions of two swords made of patterned Indian steel in the national Persian epic poem *Shah-Name*; the swords were presented to the Sasanid ruler, Shah Hosrow Anoširvan by Rajah of Kanūj from northern India (Rabb 1896: 227; Hoyland and Gilmour 2006: 65). Not only is the value of the weapons evident, but we also are told that they were made of a specific and very costly kind of crucible steel.

The Roman period, which witnessed the greatest floruit of the great trade routes between the East and the West, brought a change in the nomenclature. "Indian steel" is no longer mentioned in sources save for the *Periplus Maris Erytrei*, a detailed maritime description of the Spices Route. The merchant and sailor who wrote it seems to have been a native of one of the Red Sea ports (Berenike perhaps), living in the mid-1st century AD (in the times of Claudius or slightly later). He listed "Indian steel" among the commodities imported from India as part of the Arab–Aksumite monopoly, to the bustling commercial harbor of Adulis (Schoff 1912: 88–89, 216; 1915: 230; Casson 1989: 28; Sasisekaran and Raghunatha Rao 1999: 264). The existence of this monopoly could have been the reason why neither "iron" nor "Indian steel" were among the goods offered to the Roman merchants in the ports of the Malabar and Coromandel coast.

In turn, Pliny the Elder described in his *Historia Naturalis* a mysterious "iron of the Seres" as the best known kind of iron (steel), the second best being Parthian steel (Pliny, *NH* 34.145). The latter, which was produced most probably in Parthian Margiana, was also famous for its quality, and "Margian steel" (the Romans apparently used the terms 'iron' and 'steel' interchangeably, Piaskowski 1974: 240) was also mentioned by Plutarch among others, when describing the material used for the heavy armor of the cataphract unit commanded by the Parthian general Surena

[1] Royal gifts are mentioned frequently in the historical sources; they usually consisted of objects of exceptional value (also financial). The King of Kings gave golden swords, purple robes, massive gold jewelry, vases of gold or silver etc.

(Plutarch, *Kras*. 24) battling against the Roman forces of Marcus Licinius Crassus at Carrhae in 53 BC. Interestingly, the Parthians seem to have produced at least part of their best steel from Seres raw material. Writing of Crassus's expedition in his *Historiae adversus paganos* (6.13.2), the Christian 5th century AD priest, historian and theologian Paulus Orosius reported a threat issued by a Parthian envoy to the Romans that they would be crushed by Seric iron instead of Parthian gold.

LOCATION OF SERICA AND DISCOVERIES IN INDIA

Modern scholarship has held until recently that "Seric iron" came from China[2] from whence it was imported to the Mediterranean and the Near East via the Silk Road. The view was based most likely on Claudius Ptolemy's reference in his *Geographia*, given after Marinus of Tyre, to the route taken by a caravan of Macedonian silk merchants who left Syria and passed through Mesopotamia, Assyria and Media before passing through the "Caspian Gates" (in modern northern Iran) into Parthia, Hyrcania and Aria. Then they crossed Bactria through the mountains of the country of Comedi (identified with Pamir) and the country of the Sacae, reaching first the so-called Stone Tower, which was at the same time a huge bazaar for merchants trading with the Seres, and after that the town of Casia, identified with Kashgar. From there they traveled through the land of the Thaguri, reaching the capital of the Seres after seven months on the road (Ptolemy 1.2.4–7).

Assuming the correctness of the identifications proposed by W.H. Schoff (1915: 227), this could have been a route following one of the main branches of the Silk Route (hardly surprising considering that we are dealing with silk merchants). The point is that the description is greatly unclear in many places and becomes quite general nearer to its end. The so-called Stone Tower (Tashkurgan in Turkiestan) is mentioned in many descriptions of the Silk Road (Stein 1903: 71–72). Its central location mid-route made it ideal as a marketplace for merchants from all over Eurasia: from Rome, Persia, China, India, etc. To believe Ptolemy, however, assuming we identify the Stone Tower with Tashkurgan, then it would have been situated south of the Takla Makan desert and not directly on any of the main roads avoiding this wasteland. At the same time it was a major crossroads, meeting with the so-called Southern Route which led (like the modern Karakorum Highway) through the valleys of Karakorum (Chunza and Gilgit, then along the upper Indus) to Gandhara and India.

At the time of writing by Ptolemy, the Saca tribes no longer inhabited any of the territories between Pamir and the Stone Tower and Kashgar. They had been pushed out by the last Iranian-speaking tribes of Yűe Czy who were moved in turn by the Altai warriors of Hsiung Nu beyond the Pamir, where they formed the Kushan state (Harmatta 1994: 175). A detailed report of this event was left by the Chinese envoy Zhang Qian, who led an expedition

2 On the Seres as the Chinese, see Leslie and Gardiner 1996: 121–126; on Roman–Chinese contacts, Leslie and Gardiner 1996: 50–185; Sidebotham 2011: 254.

to Kushan Bactria on the orders of the emperor Wu from the western Han dynasty about 138 BC (Granet 1995: 116; Loewe 2000: 687–689). In turn, the Yűe Czy or Kushans pushed out the Saca tribes to the south, to Sistan (Sakasene) and later to the east, to lands in northwestern India, where they formed the Indo-Sakian Kingdom in the Roman period (Narain 1957: 140–142; 1989: 413) and maintained relations with the Roman ports in the Red Sea basin.[3]

Ptolemy's description of the route beyond Bactria fails to give any details that would be of importance to merchants (and geographers) concerning the large and dangerous Takla Makan desert, situated in the land of Taguri but skirted by two discrete branches of the Silk Road. There is nothing about the "Jade Gate" (Yumenguan ca. 80 km to the NW from Dunhuang) considered as the proper entry to China, the Great Wall, etc. At the same time, Ptolemy reported that it took seven months of traveling to reach the capital of the Seres, excluding any chance of locating this land on the fringes of the Takla Makan desert.

Ptolemy and Marinus may have lacked data despite their extensive geographical knowledge, perhaps intentionally deprived of facts by the silk merchants protecting their trade interests. The report may have been a conflation of two or more trips along different routes, one leading to China and the other to the land of the Seres, whom the Romans knew as traders of silk, animal furs, textiles and steel, to be encountered at the Stone Tower marketplace as well as in the ports on the old Spice Route dating from Hellenistic times. This erroneous and somewhat artificial superposition of earlier information, often still from Hellenistic times, about the Seres dealing in silk in the south and the Chinese producing it in the east could explain the ages-long error. Because the 2nd century AD Greek traveler and geographer Pausanias still located Seria and the Seres not in China, but somewhere far to the south in the general area of the Red Sea, in the delta of a great river (Pausanias 6.26).[4] Moreover, he described the Seres as a nation of Ethiopians, but strictly mixed Scythians and Indians (fitting this picture best is the Barygaza port which was probably one of the most important markets for inland India).

Roman descriptions of the Seres also do not fit the Chinese. Pliny (*NH,* 6.20) described them as gentle people who avoided contacts with foreign peoples unless trading. So also Ammianus Marcellinus (23.6) who called the Seres quiet by nature, steering clear of weapons and warfare, moderate in their manners, causing no problems to their neighbors. The picture is somewhat idealized, but much better suited to the inhabitants of northwestern and western India, whom the Roman merchants met in the port of Barygaza and who must have been of the Buddhist faith in their majority

[3] As attested, for example, by a coin of the Indo-Sakian king Rudrasena III (384–390 BC) found during archaeological excavations at Berenike Trogodytika (Sidebotham 2007: 209–210; Sidebotham and Wendrich 2002: 41, Fig. 40; Sidebotham 2011: 248).

[4] Actually, he was not far wrong in this because the Red Sea and the Indian Ocean were considered as a single body of water by the ancient sailors, who knew they needed to cross it to reach India (presumably Pausanias's Seria), where silk could be purchased at the earliest time, still in the Hellenistic period. Many of Indian ports were located on the islands in the river deltas (Musiris, Barbaricon, etc.).

after years of being under the rule of the Maurias and then the Greco-Bactrians with their famous Menander. Yet it seems improbable that reports of this kind would have been passed by merchants who must have seen the dozens of forts and fortresses guarding the eastern end of the Silk Road and encountered first-hand the belligerent nomads of the steppes and the heavily armed soldiers of the Chinese garrisons at Gansu.

The description of Sera itself only deepens the doubts. Pliny (*NH*, 6.20) reports on the wool that is collected in the forests of this land, Ammianus (23.6) elaborates on this statement, saying that an exceptionally fine "wool" is made from the fluff collected from specially watered trees. The wool is used to make clothing worn once by the rich and in his times already by all.[5] This land beyond a great river[6] is surrounded by mountains extending east of Scythia, bordering with a snow desert in the north and east, and reaching the Ganges and India on the south. It is famous for its size and fertility. The description immediately calls to mind China, considering the Great Steppe with its freezing winters to the north of it and separated from a broadly understood Scythia in Central Asia by the Pamir mountains. But this description works just as well or even better with northern India, situated east of Sakasene and the Indo-Sakian kingdoms and bordering in the north with the glaciers of the Himalayas and the Tibetan Plateau, while reaching India and the Ganges River, both known to Roman merchants and geographers, who were want to locate the basin of this river on the world map in more than general terms. India was famous until late antiquity for producing cotton and cotton fabrics (Sidebotham 2011: 243–244; Power 2012: 39), soft, white and much cheaper than silk. Roman merchants could have easily mistaken the cotton puffs used to make these fabrics with the "fluff" of ceiba/kapok trees, which are still called "cotton trees" in India and which are common to almost all of the subcontinent.

The modern view, which is gradually gaining ground, is that Roman Seria (possibly from the Syngalese Seri) should be identified with the southern Indian kingdom of Sangam Chera in the territory of modern Tamilnadu (Srinivasan 1994: 50; Sasisekaran and Raghunatha Rao 1999: 263). The city of Karur was its capital and its main harbor was Musiris, a port mentioned in the *Periplus Maris Erytrei* among the written sources and marked on the *Tabula Peutingeriana* (Talbert 2010: 189; Schoff 1915: 224; Sasisekaran and Raghunatha Rao 1999: 263).[7]

5 This could never be said of silk, which even in China was worn only by the elite.

6 In this case it could be the Indus which was considered by the ancient geographers as the western border of India or with even greater probability, the great river in the mouth of which lies Muziris, the main commercial harbor of the Tamil kingdom of Chery.

7 The descriptions of Sera and to some extent also Pliny's description of the caravan route suggest that Roman merchants with their rudimentary knowledge of the Indian interior could have placed Sera in different parts of the Indian subcontinent or even thought of it as all of India. The Romans knew of harbors on the western coast of India from Barygaza to Musiris and of the Sri Lankan ports (insula Taprobane), but the commodities sold there represented all the goods brought in from the interior via different inland routes, even from China and the Malay peninsula. This must have been a major source of errors and misrepresentation. Barygaza, for example, sold priceless animal skins (presumably tiger skins), as well as excellent cotton fabrics and Chinese silk (Shoff 1915: 230).

FURNACES AND TECHNOLOGY

Recent archaeological research has yielded evidence of the "iron of the Seres" having been produced in southern India. One site in point is a settlement and ironworking center located just 1.5 km from the village of Kodumanal in Tamilnadu (N 11°6'42", E 77°30'51"), dated to the turn of the 4th century BC, that is, the beginnings of the kingdom of Chera (300 BC–AD 300) (Rajan 1997: 77–79) [*Fig. 2*]. The site was once on the trade route connecting the capital of Karur with the western coast (modern state of Kerala) through the Palagat/Palakkat pass. As noted by British travelers, this region, located in the vicinity of Chennimalai, 20 km east of Kodumanal, was still known in the 19th century for its metallurgy and exploitation of excellent local sources of magnetite iron ore (Heath 1840: 185–192; Campbell 1842; Buchanan 1988: 285). Ancient Tamil sources (Patirrupatu 5.67.74) already indicated the presence of a flourishing metal industry and trade in Kodumanal in the 1st century AD. Five seasons of fieldwork uncovered remains of metallurgical workshops, including installations that have given insight into the products made at Kodumanal and a preliminary reconstruction of the technological processes involved in this production. A primitive smelting furnace was uncovered in one of two long trenches excavated to the south of the mound concealing the remains of the settlement. It had a diameter of 1.15 m and depth of 0.65 m. The lower part, which was dug into silty ground, survived the destruction of the furnace once the smelting process was completed (Sasisekaran and Raghunatha Rao 1999: 265; Sasisekaran 2002: 23). The height is difficult to reconstruct and was estimated by the excavators at about 1.20 m (Sasisekaran 2002: 23). Remains of two other, extensively damaged furnaces were uncovered in the direct neighborhood of the first one. Other finds included ceramic flues, each 15 cm long and openings of 1.5 cm in diameter, bearing evidence of surface vitrification on the 6-cm-thick walls. There were also stone slabs that protected the bellows from the heat and numerous pieces of slag. These furnaces were used for primitive smelting of the ore, that is, producing raw bloom of iron (Tylecote 1962: 183–184). This was not the export form of iron as the same kind of iron was being produced in Europe at the time, but was certainly the raw resource used for making the highly valued high-carbon steel referred to in the Tamil sources as *urukku*, that is, melted metal (Burrow

Fig. 2. Main sites of confirmed crucible steel production in India discussed in the text (Drawing J.K. Rądkowska)

and Emeneau 1961: 569).[8] Another metalworking furnace was discovered about a hundred meters to the north of the smelting furnace, already inside the settlement. It was of oval shape (1.12 m N–S by 1 m E–W), single-chambered with walls 0.20 m thick. Surrounding it were 12 smaller furnaces connected with the main chamber by thin ceramic pipes. The diameter of these smaller furnaces was about 0.30 m at the exit (Sasisekaran and Raghunatha Rao 1999: 266–267; Sasisekaran 2002: 24). The complex served to melt steel in very high temperatures (even up to 1500°C) (Rao, Mukherjee, and Lahiri 1970; Verhoeven 1987) in crucibles (Tylecote 1962: 264). The heating process took place most likely in the main chamber, whereas the slow cooling progressed in the smaller peripheral furnaces.

Two conclusions can be drawn from the furnace design as described. First, the process was probably continuous, that is, when one set of crucibles was being heated in the main chamber, another, placed in the smaller furnaces still heated by hot air from the main chamber, was gradually cooling in the dying embers, transferred there together with the crucibles. The second observation is that the peripheral furnaces can be taken as an indication that the highest quality steel, *urukku*, called later *wootz* or *pulad/fulad* in Persia and the Arabic lands, was produced there rather than the lesser qualities of crucible steel which were cooled quickly or worked immediately after smelting.[9] The design of the furnace could constitute indirect proof that already at this early date, production in Kodumanal included not only uncontaminated slag and uniformly carburized crucible steel, but also *wootz*, which is identified as clearly patterned Damascene steel with specific properties like high elasticity and the famous sharp-edgedness.

Not finding any ceramic flues in the furnaces at Kodumanal, K. Rajan suggested natural air flow in the technological process (Rajan 1994: 66), as in some Sri Lankan furnaces (Juleff 1996; 1998). Such opinions should be treated with caution in view of the extremely high temperatures that are essential for iron to be liquefied and properly carburized. Sets of bellows used in the production of crucible steel have been attested in different parts of the world and in different ages, and are technologically indispensable. Travelers Heath and Buchanan also confirmed the use of bellows in the Salem region of Tamilnadu in the 19th century (Sasisekaran 2002: 24).

8 There are many terms for this metal in use in India. *Wootz,* which was known in western Europe from the 18th century, probably derives from the word *ukku* "steel" or *uchcha* "the highest steel" in the Dravidian language of Kannadi. The Tamil word *urukku* presumably comes from the same root. Both may be linked to the Sanskrit *ucha*. The Dravidian term for steel of the highest quality would have been borrowed by the neighboring peoples, like the Gujarati who called it *oots*, *wootz* or *wuz* (Le Coze 2003: 120–121).

9 Some scholars have suggested that patterned, hypereutectoid crucible steel produced in India and Sri Lanka should be called *wootz* and steel of the same type but made in the metallurgical centers of Central Asia and Arabia *pulad/fulad* (Feuerbach 2006: 12), basing the suggestion mainly on the differences in production technologies, which are substantial. Hypereutectoid steel was produced in Central Asia mostly by mixing and melting in a crucible appropriate portions of white pig-iron (*dus*) and iron (*narmahan*); in southern India, the main method used was rather carburizing of iron with flakes of charred wood. The problem is that methods and recipes in Persia and Arabia were very similar to those in southern India, while in northern India *wootz* was produced also by mixing of pig-iron and iron. Thus, such geographical distinctions are risky at best and differences (also with regard to the construction and size of the crucibles themselves) could be the effect of developments of an original technology in different centers and over a long period of time.

All of the analyzed remains of steel products found at the site of Kodumanal did not prove to be made of *wootz* steel (which is characterized by bands of spheroid grains of cementite, Sasisekaran and Raghunatha Rao 1999: 267–272). Lamellar structure was observed in some of the analyzed products, probably with evidence of selective carburizing of the blade,[10] which was a technique typical of the making of weapons and tools already around 1000 BC, long before crucible steel was invented around the 6th–5th century BC. This technique was never forgotten and spread to all of Southeastern and Eastern Asia; an excellent example of its application are the Malay *krises* and the traditional Japanese swords (Bhatia 1994: 356–358). One of the analyzed fragments could have been made of iron prepared during the decarburization of pig-iron as attested by graphite nodules visible under the microscope in the ferrite mass (Sasisekaran and Raghunatha Rao 1999: 269, Fig. 5; Craddock 2003: 243).

Physico-chemical proof of the production of crucible steel was discovered at the site of Mel-siruvalur, functioning from the 3rd century BC to the 3rd century AD with a recurrence of occupation in the Middle Ages (Srinivasan 1994: 52; Sasisekaran 2002: 25), located in the southern part of the Arcot district in the northeastern part of Tamilnadu (N 12°00", E 79°00"). Slag and pottery sherds from the site were accompanied by broken pieces of piriform crucibles for melting steel typical of southern Indian sites. The inside surfaces were vitrified. The site also yielded massive lids (7 cm in diameter) that once sealed the crucibles during the smelting process. Some pieces of the crucibles also had characteristic "collars" of vitrified slag formed on the walls where they connected with the ingot (Srinivasan 1994: 54). The crucible walls were from 0.80 cm to 1.50 cm.

Microscopic analysis of the slag on the inside of one of the crucible lid fragments identified tiny steel prills in it (diameter of 100 μm), splattered probably when the metal was already liquid. Similar prills were discovered already on crucible lids from the Deccan (Scott 1991: 35).

The cutting, polishing and etching of the largest pellets (80 μm in diameter) revealed their inner structure, constructed of large hexagonal grains of primary austenite (with inner, typically dendritic eutectoid perlite) surrounded by a network of interdendritic cementite crystals grouped on the borders of perlite grains (Srinivasan 1994: 55). This structure is typical of hypereutectoid steel (*wootz* too). Perlite matrix hardness has been determined at 400 VPN, which is a norm for steel with carbon content around 0.8–1%, that is eutectoid and hypereutectoid steel (Scott 1991: 82).

Research using Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS) revealed trace phosphorus responsible, according to J.D. Verhoeven (1987), for microsegregation of cementite crystals in the form of (characteristic of *wootz*) networks and bands creating an exceptional and complex pattern (called Damascene). This pattern, result of chemical and mechanical processing, was fascinating to all those who had contact with this kind of steel over the

[10] This kind of carburizing by applying special carburizing pastes and then heating a blade, hardening and tempering it, is mentioned in ancient Indian texts, e.g., with regard to surgical scalpel blades from Saśruta Samhita (about 700 BC) or the sword blades from Varahimihira (about 550 BC) (Prakash 1991: 361).

ages. Theoretically, the structure behind the pattern and source of the exceptional properties of *wootz* emerged already in the ingots and even the smallest fragments had the same structure as the whole (Smith 1960: 16; Tylecote 1962: 295). In practice, ingot needs proper processing, and observation of final *wootz* structure is possible in finished item only (Verhoeven and Jones 1987: 155–157). Other examined steel pellets from Melsiruvalur also had the same structure.

An in-depth analysis of the walls of the clay crucible fragments revealed rice husks. Once charred, this organic temper, observed also in finds from the Deccan (Lowe 1989; Voysey 1832: 246), raised the endurance of the crucibles to long-term exposure to high temperatures. It also was conducive to creating a highly reductive atmosphere inside the crucible, which had a positive effect on the process of carburization of the iron batch (Srinivasan 1994: 56).

The only doubts regarding the described finds concern their precise dating. The metallurgical center in Mel-siruvalur operated probably for a very long time with only slight technological modifications, making it difficult to date particular slag heaps and crucible fragments.

METALLURGICAL CENTERS AND THEIR PRODUCTS

There are dozens of other metallurgical centers apart from the two examined sites, scattered throughout central and southern India and dated to the so-called Megalithic period, that is, 600–500 BC to AD 200 (corresponding more or less to the times of the kingdom of Chera in Tamilnadu and the beginning of the kingdom of Andhra in Andhra Pradesh). Primitive smelting furnaces and their elements were discovered at sites like Guttur (Dharmapuri district), Kattankulathur (Chingleput district), Pakkam (southern Arcot district), Perungalur, Ponparakkottai and Tiruvalankuram (in Pudukkottai district), and Mel-siruvalur as well (often on an "industrial" scale as at Guttur, where furnaces were 2 m long and 3 m high). Guttur has also yielded pieces from pig-iron with carbon content on the level of from 3% to 5% (Nagaraja Rao 1985: 67; Sasisekaran 2002: 20). Similar products and clay ring-shaped casting molds for cooling cast iron dated to the 3rd century AD were excavated also at Kannarappalayam (Walhouse 1875) and Nattukkalpalayam in the Coimbatore district (Sandford 1895; Sasisekaran 2002: 22). All in all, the finds indicate that all of central and southern India until modern Hyderabad (save for Tamilnadu, the southern part of the Karnataka state and presumably also the northern region of Telangana to the south of the modern Andhra Pradesh state, which belonged in antiquity to the Andhra kingdom and was intensively studied in 2009–2011, see Juleff, Srinivasan, and Ranganathan 2011) constituted one large cluster of metallurgical centers producing huge amounts of iron and steel in all forms: from low-quality smelted iron for making tools and objects of everyday use to superb melted crucible, eutectoid and hypereutectoid steel (in a few variations) used for weapons of the highest quality. The latter two were exported overseas, through south Arabia and Aksum to the Mediterranean on one hand and to the north via the great internal Indian land route through Punjab, Gandhara and Bactria as well as part of the Silk Road to Persia and Central Asia, perhaps also China (import of this commodity from centers of later date in Central Asia has been confirmed for the 6th century AD (see Wulff 1966: 7).

Archaeological evidence for the production of weapons from crucible steel comes also from Gandharan Taxili (modern Pakistan). A sword made of the said steel was discovered in a 1950s excavation in the region. Seven fragments subjected to physico-chemical analyses revealed carbon content from 1.23% to 1.70% (but without confirming the inner structure of bands of cementite grains) and no slag intrusions typical of crucible steel (Marshall 1951: 535–537; Craddock 2003: 244).

One of the earliest examples of a product made of *wootz* steel is a 1st century AD nail excavated at Pattanam in Kerala (Juleff, Srinivasan, and Ranganathan 2011: 30), a site identified with Roman Musiris (Sidebotham 2011: 190–191).

Crucible steel seems not to have been produced outside of India before the 3rd century AD, at least there is no evidence for such production. Writing in the early 4th century AD, the Greek alchemist Zosimos from Alexandria was already describing the technology in use not only in India, but also in Persia (Feuerbach 2002: 47). Apart from the mention of a gift sent to Hosrow Anoširvan, there is also material evidence in the form of a double-edged sword coming from late antique Persia. It was made of crucible steel and had a silver hilt (British Museum [WAA 135747] (Lang et al. 1998: 7–14), and was dated to the end of the Sasanid period, that is, the 5th–6th century AD. Physico-chemical studies identified the technique of its production as an old Indian method of using welded stripes of crucible steel (presumably with different carbon content of the steel) to obtain lamellar structure. The sword resembled medieval Japanese weapons of the kind, but was made of much purer steel of greatly higher quality than Japanese *tamahagane* steel produced in solid state. It failed to sport the traditional "Damascene pattern" (Craddock 2003: 244–245), but having been hammered and polished appropriately, it could present an ornament similar to the Japanese *hada* or "wooden-like" patterns seen on Malay *krises*.

The classic "Damascene pattern" could have been seen on swords coming from Persia and dated to the 3rd–4th century AD, discovered in Alan graves at Klin Jar near Kislovodsk in the northern Caucasus (Feuerbach 2002: 47; 2006: 12). Their inner structure indicates that eventually vissible pattern was not so evident on the surface and the bands of spheroid cementite grains were not too thick and not too well separated. Combined with mentions of a gift sent to the Persian Shah by the Rajah Kanuj, the information given by the Arabic scholar al-Biruni (Hoyland and Gilmour 2006: 153–154) and by Zosimos shows a rapidly spreading capacity for working crucible steel in late antiquity (4th–6th century AD). New places of metallurgical production outside the old southern and central Indian locations included the middle valley of the Ganges (Hoyland and Gilmour 2006: 65) and presumably also northeastern Persia and south Arabia.

THE CRUCIBLE STEEL TRADE AND THE EMERGENCE OF METALLURGICAL CENTERS IN THE EAST

The popular *Mu'allakāt* poems of 6th century pre-Islamic south Arabia, e.g., the *qasidas* of 'Antarah ibn Shaddād al-'Absī (Danecki 1981: 91–106) and of Tarafah ibn al-'Abd (Danecki 1981: 47–67), evoked the deathly effectiveness and resilience of blades made of Indian steel, and its white shining or exceptional pattern on those made of *wootz* (Smith 1960: 14). One of the most famous poet-warriors of the period, Amr bin-Madikarib owned a sword made of the best quality steel produced in northern India (Hoyland and Gilmour 2006: 60, 154, 170). The weapon with etched or carved images on the blade was as famous as its owner, but outlasted him, becoming after 300 years the pride of the arms collection of the Abbasid caliph Harun al-Rashid (Hoyland and Gilmour 2006: 154, 254). Another sword of this kind was used by the prophet Muhammad (Hoyland and Gilmour 2006: 154, 170).

The first truly technical characteristic of *wootz*, centers of production and the weapons made in them was made by Arabic scholars. In the 9th century AD, the caliph Al-Mu'tassim commissioned a great scholar of the age, Ya'qūb ibn 'Ishāq as-Sabbāh al-Kindī, scion of the pre-Islamic royal family of the south Arabic kingdom of Kinda, to write a complete and precise compendium of knowledge on swords and the steel they were made of (Hoyland and Gilmour 2006). Al-Kindi included also data on metallurgical centers of the Islamic world and their products. According to him, iron was either "exploited" or "natural", meaning smelted and classified as soft *narmāhan*-iron which was not to be tempered and hard, tempered *shaburkan*-steel and "unnatural" or "cleaned" (*massafa*) which was crucible steel in fact. *Fulad* was a special form of unnatural steel characterized by a complex pattern on the polished and etched surface. These patterns were supposed to be typical of specific production places and Al-Kindi devoted much space in his work to recognizing particular types, their properties and quality. His detailed work, entitled *Risala fi gavahir al Sujuf*, can be considered the first fully scientific study of *fulad*. In Al-Kindi's time thousands of swords were produced of this steel every year and its highest quality, exceeding all other types of steel, was treated as commonplace. Thanks to Al-Kindi, we now know that in the 9th century *fulad* was being produced not only in India and Sri Lanka, but also near Qalai in the neighborhood of the port of Kalang on the Malay Peninsula (Fatimi 1964: 211–215), in Khurasan in Central Asia, Iranian Fars, Basra in southern Iraq, but still the best iron (and swords made of it) was supposed to come from Yemen (Hoyland and Gilmour 2006: 27–82).

TRADE ROUTES

Analyzing the location of metallurgical centers with regard to the network of great trade routes one can see that they emerged along the roads by which Indian *wootz* had been transported to customers for ages. The Malay peninsula came under the influence of southern India already in the 4th century AD (Power 2012: 56–59) and possibly also earlier. In the 1st century AD a marine route to China may have passed along the peninsula to Malakka (Schoff 1915: 226–227); it was down this route that goods from Southeastern Asia, and silk, too, possibly, were imported to India (Leslie and Gardiner 1996: 13, note 28; Sidebotham 2011: 190–193, 223–224, 240). South Arabia and especially Yemen had been intermediaries since time immemorial in the Indian–Mediterranean trade via the maritime Spice Route (Sidebotham 2011: 13–16, 32–38, etc.). In Al-Kindi's times, Basra had become one of the most important stages on the maritime route from India to the capital of the Caliphs in Baghdad, while another port, Siraf, was the sea gate to southern Persia (Priestman 2005). Khurasan in central Asia remained at the center of the Silk Road, a crossroads with the ancient Southern Trail leading off to India.

Archaeological data from recent excavations have confirmed the information gleaned from written sources. A large metallurgical center with remains of furnaces for melting crucible steel was discovered near Merv in modern Turkmenistan (Griffiths and Feuerbach 1999: 36–38; Feuerbach, Griffiths, and Merkel 2003; Simpson 2001: 14–15) and Akhsiket in Uzbekistan which is the ancient metallurgical center of Khurasan (Rehren and Papakhristu 2000). Despite the manufacturing autonomy of each of the production centers of this extensive network extending all over the Islamic world (each had, for example, its own mines of an appropriate kind of ore called "ondanique" in the Middle Ages from the Arabic word *hinduani*, "Indian" [Polo 1.35]). Al-Kindi clearly states that practically all of these centers were using to some extent iron from either India or Sri Lanka (Hoyland and Gilmour 2006: 54–55). The number of *wootz* ingots produced in and exported from India must have been huge and the quality still highly appreciated.

Improvement of *wootz* production technologies took place along the trade routes, which served first to spread the product and then to propagate the technique. Archaeological excavation of metallurgical centers in Central Asia demonstrated the use of a different type of crucible, two or even three times bigger than those in southern India and made of a completely different clay than the Indian ones (Rehren 2002: 38). The southern Indian crucibles were more massive, produced of a ferruginous clay tempered with rice husks, which after firing created a heavily porous structure. Crucibles of such primitive make reached the limits of their endurance during melting and therefore the batch could not be too big. They were also sealed tightly and could not contain too much of the iron and carburizer in order to keep the gasses generated in the production process at manageable levels (Rehren 2002: 37). The central Asian crucibles were completely different in these respects: thin-walled, very high, made of thick, light-colored and well levigated clay resembling the material used in faience or china production. The clay presumably contained a large amount of aluminum oxide, which is still used today to make highly durable metallurgical crucibles. The durability of Central Asian crucibles permitted them to be much bigger than the southern Indian ones, thus letting ingots exceeding 1 kg in weight to be produced in them. Moreover, the openings in the lids made it easy to observe the content and let off gasses from inside; it had a favorable effect on the durability of the furnace and the possibility of making larger ingots (Rehren and Papakhristu 2000: 57–58;

Rehren 2002: 38–39). This was important because *fulad* pieces could not be welded together for technical reasons.[11]

There were also considerable differences between the technologies of the two regions. In southern India an older method of carburizing iron with charred wooden chips was used with green leaves as an accelerant. The method in Central Asia was fusion of melted iron and white cast iron. Both the clay type and excellent working of properties and principles of processing pig-iron with high levels of cementite could point to China as a source of innovations in the crucible process (Rehren 2002: 39). Crucible steel was not produced in China, but the achievements of Chinese metallurgists and pottery specialists, brought from Central Asia by way of the Silk Road, gave local makers the impetus to develop an entirely new method of producing excellent *fulad* steel. This technique would remain in use in Khurasan until the 19th century, making the famous local "black *fuladh*" (Kara Khurasan).

CONCLUSIONS

Archaeological research in the past 20 years has supplemented the information coming from written sources on the development of iron metallurgy in the Near East. It is now confirmed that as early as the end of the 5th century BC the inhabitants of India invented a crucible technology for producing steel. The know-how came most likely from the technical expertise of highly developed Indian bronze-making, which had long used crucibles for cleaning and preparing a homogenous quality metal. Intensive carburization applied in the process for the first time made it possible to liquefy the alloy completely in the crucible, but it also made possible a carburized steel that was much more uniform than using any other technique. The resultant crucible steel could be very pure and feature a high carbon content translated into exceptional hardness of the new material,[12] conditioning the commendable sharpness. *Wootz*, steel that combined great hardness with a greater resilience than most crucible steel, was invented in India sometime between the 3rd century BC and the 1st century AD. It was characterized by an extraordinary pattern on a polished and etched surface. The production process is so specific that the first ingots could have been made by accident, when a crucible with melted high carbon steel was left overnight. But the development of the highly complicated process of thermal treatment for this type of steel required extensive blacksmithing know-how and practice. The results had key

[11] When heating *fulad* to a temperature permitting fusion (about 1100–1200°C depending on the carbon content) one had to exceed the maximum allowable temperature of steel thermal processing. After 850°C was exceeded (especially if substantially) for steel with a 1.2% carbon content and about 970°C for steel with 1.5% carbon, hypereutectoid cementite forming light-colored bands that create the Damascene pattern is dissolved in austenite and pattern disappears irreversibly. After cooling such overheated *fulad*, the cementite is crystallized in the form of tiny needles at the edges of minor perlite grains, making this entire material extremely friable.

[12] Metal containing from 1.2 to even 1.7–1.8% carbon (Ranganathan and Srinivasan 2006: 76) would be exceptionally hard but also brittle. New metallurgical research has demonstrated, however, that appropriate thermal processing can bring an alloy with such carbon content to a state of superelasticity that allows easy and precise mechanical working while raising substantially its capability to withstand damage after cooling (Sherby and Wadsworth 1985: 120).

impact on the history of Eastern and world metallurgy and sword-making.

Their inventions in this respect put the inhabitants of India in a monopolist position for long ages, supplying half the "Old World" via land and sea routes. Clients included first of all the peoples of the Achaemenid empire (the Bactrians and neighbors), who were the first to trade with India, the Arabs of Southern Arabia, presumably also the people of southeastern Asia (Kalang district in the Malay Peninsula near modern Kuala Lumpur [Fatimi 1964: 211–215; Hoyland and Gilmour 2006: 53]) and the Aksumites. In view of the exceptionally complex preliminary thermal treatment of ingots of crucible steel and *wootz*, ready products and partly processed half-products (ingots cast into bars or rods) must have long been the mainstay of the Indian trade. About the 3rd century AD crucible steel started being produced also outside India (possibly in northeastern Persia), but Indian crucible steel and *wootz* continued to be unmatched until the early Islamic period (hence presumably the admiration of swords made of Indian steel expressed by Arabic poets and the value of the swords presented to Hosrow Anoširvan).

From the 4th century AD customers who had learned the processes of production and processing of crucible steel started to buy larger amounts of *wootz* ingots (which would explain finds of such ingots ready for shipment in Indian ports of the Islamic period, Hoyland and Gilmour 2006: 55, Fig. 12). From the 6th to the 9th century AD, local *wootz* production outside India reached an excellence comparable to the Indian centers (even surpassing them according to Al-Kindi), but ingots continued to be imported from India and Sri Lanka (Hoyland and Gilmour 2006: 54–55). Some authors (like Idrisi [1.65–66] still thought of Indian swords as unsurpassed in quality. The use of local sources of iron ore and locally developed production methods (such as the Persian method which mixed and melted iron with pig-iron instead of carburizing it with wood, perhaps under the influence of Chinese metallurgical and pottery production techniques) led in time to the development of many different local types of *wootz/fulad* characterized by a specific appearance and physical properties known and widely described through the 19th century.

The presented reconstruction of the process of development of crucible steel production is hypothetical and should be confirmed, especially in the course of new archaeological excavations. Assuming that it is correct to any extent, greater attention should be turned to finds of ingots on ancient sites from the period of the emergence of trade in crucible steel, but not the cakes and eggs of steel usually seen on Islamic-period sites. Identification and archaeometric studies of ingots formed as bars, rods, cubes, etc. from these earlier sites will extend the scope of this early trade as well as broaden our knowledge of the composition, structure and properties of the famous "iron of the Seres".

Marek Woźniak
PhD candidate, Institute of Archaeology and Ethnology, Polish Academy of Sciences
00-140 Warsaw, Poland, Al. Solidarności 105
wozniakarcheo@gmail.com

REFERENCES

Bhatia, S. K. (1994). Carburisation of iron in ancient India. *Indian Journal of History of Science*, 29(3), 353–360.

Bronson, B. (1986). The making and selling of wootz, a crucible steel of India. *Archeomaterials*, 1(1), 13–51.

Buchanan, F. (1988). *A journey from Madras through the countries of Mysore, Canara, and Malabar: For the express purpose of investigating the state of agriculture, arts and commerce, the religion, manners, and customs, the history natural and civil, and antiquities*. New Delhi: Asian Educational Services.

Burrow, T., and Emeneau, M. B. (1961). *A Dravidian etymological dictionary*. Oxford: Clarendon Press.

Campbell, J. (1842). Report upon the manufacture of steel in southern India. *Journal of the Asiatic Society of Bengal*, 11, 217–218.

Casson, L. (1989). *The Periplus Maris Erythraei: Text with introduction, translation, and commentary.* Princeton, NJ: University Press.

Craddock, P. T. (2003). Cast iron, fined iron, crucible steel: Liquid iron in the ancient world. In P. T. Craddock and J.Lang (Eds.), *Mining and metal production through the ages* (pp. 231–257). London: British Museum Press.

Danecki, J. (Ed.). (1981). *Siedem kasyd staroarabskich: (mu'allaki)* [*Old Arab qasidas*]. Warsaw: Państwowy Instytut Wydawniczy [in Polish].

Fatimi, S. Q. (1964). Malaysian weapons in Arabic literature: A glimpse of early trade in the Indian Ocean. *Islamic Studies*, 3(2), 199–228.

Feuerbach, A. (2002). The glitter of the sword: The fabrication of the legendary Damascus steel blades. *Minerva*, 13(4), 45–48.

Feuerbach, A. (2006). Crucible steel: Production and identification. In R.D. Smith (Ed.), *Make all sure: The conservation and restoration of arms and armour* (pp. 12–17). Leeds: Basiliscoe Press.

Feuerbach, A., Griffiths, D. R., and Merkel, J. F. (2003). Early Islamic crucible steel production at Merv, Turkmenistan. In P. T. Craddock and J. Lang (Eds.), *Mining and metal production through the ages* (pp. 258–266). London: British Museum Press.

Granet, M. (1995). *Cywilizacja chińska* [*Chinese civilization*]. (M. J. Künstler, Trans.) (2nd ed.). Warsaw: Państwowy Instytut Wydawniczy [in Polish].

Griffiths, D. R., and Feuerbach, A. (1999). Early Islamic manufacture of crucible steel at Merv, Turkmenistan. *Archaeology International*, 3, 36–38.

Harmatta, J. (Ed.). (1994). *History of civilizations of Central Asia* II. *The development of sedentary and nomadic civilizations, 700 BC to AD 250*. Paris: UNESCO Publishing.

Heath, J. M. (1840). On Indian iron and steel. *The Madras Journal of Science and Literature*, 11, 184–191.

Hill, J. E. (2009). *Through the jade gate to Rome: A study of the silk routes during the Later Han Dynasty 1st to 2nd centuries CE. An annotated translation of the chronicle on the "Western Regions" from the Hou Hanshu*. Charleston, SC: BookSurge.

Hourani, G. F. (1995). *Arab seafaring in the Indian Ocean in ancient and early medieval times*. (J. Carswell, Ed.) (expanded ed.). Princeton, NJ: Princeton University Press.

Hoyland, R. G., and Gilmour, B. J. J. (2006). *Medieval Islamic swords and swordmaking: Kindi's treatise "On swords and their kinds"* .Warminster: Gibb Memorial Trust.

Juleff, G. (1996). An ancient wind-powered iron smelting technology in Sri Lanka. *Nature*, 379(6560), 60–63.

Juleff, G. (1998). *Early iron and steel in Sri Lanka: A study of the Samanalawewa area* [=*Materialien zur allgemeinen und vergleichenden Archäologie* 54]. Mainz am Rhein: Philipp von Zabern.

Juleff, G., Srinivasan, S., and Ranganathan, S. (2011). *Pioneering metallurgy: The origins of iron and steel making in the Southern Indian subcontinent. Telangana field survey interim report 2011*. Bangalore: National Institute of Advanced Studies.

Kalita, S. (2009). *Grecy w Baktrii i w Indiach: wybrane problemy ich historii* [*The Greeks in Bactria and India*]. Kraków: Historia Iagellonica [in Polish].

Lang, J., Craddock, P. T., and Simpson, S. J. (1998). New evidence for early crucible steel. *The Journal of the Historical Metallurgy Society*, 32(1), 7–14.

Le Coze, J. (2003). About the signification of wootz and other names given to steel. *Indian Journal of History of Science*, 38(2), 117–127.

Leslie, D., and Gardiner, K. H. J. (1996). *The Roman Empire in Chinese sources* [=*Studi orientali* 15]. Rome: Bardi.

Loewe, M. (2000). *A biographical dictionary of the Qin, former Han and Xin periods, 221 BC–AD 24* [=*Handbuch der Orientalistik* 16]. Leiden: Brill.

Lowe, T. L. (1989). Refractories in high-carbon iron processing: A preliminary study of the Deccani wootz-making crucibles. In P. E. McGovern and M. D. Notis (Eds.), *Cross-craft and cross-cultural interactions in ceramics* [=*Ceramics and Civilization* 4] (pp. 237–251). Westerville, OH: American Ceramic Society.

Marshall, J. (1951). *Taxila* II. *Minor antiquities*. Cambridge: Cambridge University Press.

Nagaraja Rao, M. S. (1985). *Indian archaeology, 1982–83: A review*. New Delhi: Archaeological Survey of India, Government of India.

Narain, A. K. (1957). *The Indo-Greeks*. Oxford: Clarendon Press.

Narain, A. K. (1989). The Greeks of Bactria and India. In A. E. Astin, F. W. Walbank, M. Frederiksen, and R. M. Ogilvie (Eds.), *Rome and the Mediterranean to 133 B.C.* [=*Cambridge Ancient History* 8] (pp. 388–421). Cambridge: Cambridge University Press.

Piaskowski, J. (1974). *O stali damasceńskiej* [*Of Damascus steel*]. Wrocław: Zakład Narodowy im. Ossolińskich [in Polish].

Power, T. (2012). *The Red Sea from Byzantium to the Caliphate: AD 500–1000*. Cairo: American University in Cairo Press.

Prakash, B. (1991). Metallurgy of iron and steel making and blacksmithy in ancient India. *Indian Journal of History of Science*, 26(4), 351–371.

Priestman, S. (2005). The rise of Siraf: Long-term development of trade emporia within the Persian Gulf. In *Proceedings of the International Congress of Siraf Port: November 14–16, 2005, Bushehr-Iran* (pp. 137–156). Bushehr: Iranology Foundation.

Rabb, K. M. (1896). *National epics*. Chicago: A.C. McClurg.

Rajan, K. (1994). *Archaeology of Tamilnadu (Kongu country)*. Noida: Book India Publishing Co.

Rajan, K. (1997). *Archaeological gazetteer of Tamil Nadu*. Thanjavur: Manoo Pathippakam.

Ranganathan, S., and Srinivasan, S. (2006). A tale of wootz steel. *Resonance*, 11(6), 67–77.

Rao, K. N. P., Mukherjee, J. K., and Lahiri, A. K. (1970). Some observations on the structure of ancient steel from South India and its mode of production. *Bulletin of Historical Metallurgy*, 4(1), 12–17.

Ray, H. P. (2003). *The archaeology of seafaring in ancient South Asia*. Cambridge: Cambridge University Press.

Rehren, T. (2002). As similar as black and white: Steelmaking crucibles from South and Central Asia. *Archaeology International*, 6, 37–39.
Rehren, T., and Papakhristu, O. (2000). Cutting edge technology — the Ferghana Process of medieval crucible steel smelting. *Metalla (Bochum)*, 7(2), 55–69.
Sandford, J. R. (1895). Notes on the recent opening of some Pre-historic burials in the Coimbatore District, Madras Presidency. *Journal of the Anthropological Society of Bombay*, 3, 461–471.
Sasisekaran, B. (2002). Metallurgy and metal industry in ancient Tamil Nadu — An archaeological study. *Indian Journal of History of Science*, 37(1), 17–29.
Sasisekaran, B., and Raghunatha Rao, B. (1999). Technology of iron and steel in Kodumanal – An ancient industrial centre in Tamil Nadu. *Indian Journal of History of Science*, 34(4), 263–272.
Schoff, W. H. (1912). *The periplus of the Erythræan sea: Travel and trade in the Indian Ocean*. New York: Longmans, Green, and Co.
Schoff, W. H. (1915). The eastern iron trade of the Roman Empire. *Journal of the American Oriental Society*, 35, 224–239.
Scott, D. A. (1991). *Metallography and microstructure of ancient and historic metals*. Marina del Rey, CA: Getty Conservation Institute.
Sherby, O. D., and Wadsworth, J. (1985). Damascus steels. *Scientific American*, 252(2), 112–120.
Sidebotham, S. E. (2007). Coins. In S. E. Sidebotham and W. Z. Wendrich (Eds.), *Berenike 1999/2000. Report on the excavations at Berenike, including excavations in Wadi Kalalat and Siket, and survey of the Mons Smaragdus Region*. Los Angeles, CA: Costen Institute of Archaeology, University of California
Sidebotham, S. E. (2011). *Berenike and the ancient maritime spice route*. Berkeley: University of California Press.
Sidebotham, S. E., and Wendrich, W. (2002). Berenike: Archaeological fieldwork at a Ptolemaic-Roman port on the Red Sea coast of Egypt 1999–2001. *Sahara*, 13, 31–44.
Simpson, S. J. (2001). The Early Islamic crucible steel industry at Merv. *IAMS*, 21, 14–15.
Smith, C. S. (1960). *A history of metallography: The development of ideas on the structure of metals before 1890*. Chicago: University of Chicago Press.
Srinivasan, S. (1994). Wootz crucible steel: A newly discovered production site in South India. *Papers from the Institute of Archaeology*, 5, 49–61.
Stein, A. (1903). *Sand-buried ruins of Khotan: Personal narrative of a journey of archaeological & geographical exploration in Chinese Turkestan*. London: T.F. Unwin.
Talbert, R. J. A. (2010). *Rome's world: The Peutinger map reconsidered*. Cambridge: Cambridge University Press.
Tylecote, R. F. (1962). *Metallurgy in archaeology: A prehistory of metallurgy in the British Isles*. London: E. Arnold.
Verhoeven, J. D. (1987). Damascus steel, part I: Indian wootz steel. *Metallography*, 20(2), 145–151.
Verhoeven, J. D. and Jones, L.L. (1987). Damascus steel, part II: Origin of the damask pattern. *Metallography* 20(2), 153-180.
Voysey, H. W. (1832). Description of the manufacture of steel in Southern India. *Journal of Asiatic Society of Bengal*, 1, 245–247.
Walhouse, M. J. (1875). Notes on the Megalithic monuments of the Coimbatore District. *Journal of the Royal Asiatic Society of Great Britain and Ireland*, 7, 17–34.
Wulff, H. E. (1966). *The traditional crafts of Persia: Their development, technology, and influence on Eastern and Western civilizations*. Cambridge, MA: M.I.T. Press.