University of Jaffna

Sir Pon Ramanathan
Memorial Lecture – 2024

“Monsoon Steel': Serandib's Contribution to Global History of Science and Technology”

by

Prof. Gillian Juleff,
Department of Archeology,
University of Exeter

on

Wednesday 20th March, 2024 at 3.00 p.m.

at

Kailasapathy Auditorium,
University of Jaffna.

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20.03.2024

Sir Pon Ramanathan

Message from the Vice Chancellor

Sir Ponnampalam Ramanathan Memorial Lecture along with the Lady Leelawathy Ramanathan Memorial is a cherished annual event of our University. University of Jaffna was inaugurated in 1974 and the Golden Jubilee celebrations are celebrated throughout the 2024 year with all sphere of events. In this respect, Sir Ponnampalam Ramanathan memorial lecture-2024 becomes highly significant.

This memorial lecture series is a prestigious event organized annually by our University aligned with the Annual General Convocation to commemorate the legacy of Sir Ponnampalam Ramanathan, who was a leading Hindu Educationalist, Great Scholar, Nationally acclaimed statesman and Philanthropist. His immense contribution to education was the establishment of two schools, the Ramanathan College for girls established at Maruthanarmadam, Chunnakam in 1913, and the Parameswara College for boys, eight years later. The latter has since become the Jaffna University.

This Ramanathan memorial lecture is funded by an Endowment instituted by the Board of Directors of Parameswara College in 1980. The memory of Sir Ponnampalam Ramanathan is very near and dear to us, every premises and buildings which form the nucleus of our University are closely associated with him. We are indeed thankful to those who instituted this endowment for giving us the opportunity to cherish Sir Ponnampalam Ramanathan's memory in a fitting manner.

This year, the Ramanathan memorial lecture is being delivered by Prof.Gillian Juleff, Professor in Archeology, Department of Archeology, University of Exeter on the topic "Monsoon Steel': Serandib's Contribution to Global History of Science and Technology". Prof. Juleff is a distinguished archeologist who has passionate interest in our heritage and culture. His lecture would recall the historical contributions of our nation to Science and Technology.

We are very much thankful to Prof. Gillian Juleff for accepting our kind invitation and to deliver this memorial lecture and we welcome the guest speaker on behalf of the University of Jaffna.

All glories to God.

Prof. S. Srisatkunarajah,
Vice - Chancellor,
University of Jaffna.

Monsoon Steel: Sarandib's Contribution to Global History of Science and Technology

When we consider the history of science and technology in relation to the production of metals, particularly of iron and steel, it is inevitable that our thoughts turn instinctively to the powerful nations and empires of the recent and distant past. Britain in the Industrial Revolution, the industrialisation of America, Russia and Japan in the early 20th century, the dominance of India and China in more recent times, for example, but also the explosion of iron production in the Roman Empire and Han China of ancient times. These were strong political entities with the wealth and administrative infrastructure to support the development of complex technologies and sustain the creation of industries. Even those places where iron ore, the raw material for iron and steel production, is in greatest abundance, such as Australia and Africa, cannot compete. Against this background, the contribution made by Sri Lanka's metallurgists in the first millennium AD to the development of technologies for the creation of high-quality, high-carbon steel is all the more remarkable.

The production of raw iron from iron ore is a complex task that requires considerable social investment in surface collecting or mining of iron ores, preparation of large quantities of charcoal fuel and the construction of purpose-designed furnaces capable of withstanding high temperatures and separating metallic iron from unwanted waste products. This smelting process is more than a simple case melting the metal from the rock, it involves creating gaseous reducing conditions within the furnace that allows chemical conversion of mineral to metal. Achieving this is the work of a master smelter (usually a man) who has perfected his practice through his own experience and transferred knowledge through generations. It is rarely knowledge recorded in writing. In the western world the raw iron produced was known as bloomery iron and would be a mixture of soft pure iron and slag waste. In ancient China the raw metal produced would be hard and brittle cast iron. Both soft bloomery iron and brittle cast iron have limited functionality and each needs further refinement to produce steel, i.e. alloys of iron and carbon that are both hard and strong. Producing steel alloys, particularly high-carbon steels that are free from contamination, is again technologically challenging requiring both technical knowhow and social (and economic) investment. High-carbon steels are able to hold a cutting edge and are used for making tools, including those that cut rock. They are also used to make bladed weapons, especially swords. In the 9th century the Islamic writer, al-Kindi, in his authoritative contemporary treatise on swords, repeatedly emphasized the availability and quality of 'Sarandibi' steel (Hoyland and Gilmour 2006). We know Sarandib as the early Islamic name for Sri Lanka and this reference to swords, that were later mythologised as Damascus swords, being manufactured from steel produced in Sri Lanka gives us the starting point for a new chapter in the history of science and technology.

In this lecture I will describe the archaeological fieldwork that led to the discovery of an iron smelting industry in the hills of Samanalawewa and the experimental reconstruction of the technology which demonstrated the use of monsoon wind power to produce high carbon steel at the time that Sarandibi steel was prized in the Early Islamic world for the making of swords. I will also overview some of the evidence indicating that elements of the wind-powered smelting technology of Samanalawewa was transmitted eastwards to other parts of Asia, reaching as far as Japan. A more detailed discussion is contained in the appended paper, published in World Archaeology in 2009 (Juleff 2009)

World Archaeology, (2009) 41: 4, 557 — 577

Technology and evolution: a root and branch view of Asian iron from first-millennium BC Sri Lanka to Japanese steel

Abstract

Evidence for a previously unrecognized pan-Asian metallurgical tradition of linear configuration iron-smelting furnaces is reviewed. The foundation of this technological lineage lies in an evolutionary series of excavated furnaces in Sri Lanka dating from the fourth century BC to the eleventh century AD. Further archaeological, ethnographic and documentary evidence from Burma, Cambodia, Sarawak and Japan demonstrates the spread of linear furnace technology and its association with the production of high-carbon steels, often associated with weapons manufacture. An evolutionary approach is used to argue that a process of memetic inheritance explains a major divergence in Eastern and Western metallurgical development and furnace design.

Keywords

Sri Lanka; monsoon steel; iron smelting furnaces; Asian metallurgy; Tatara; cultural evolution; memetic inheritance.

Introduction

The aim of this paper is to open a debate on the nature of technological development and the viability of applying an evolutionary approach to the early development of iron production. While the concept of cultural evolution is finding growing advocacy and application in many fields of archaeology (Shennan 2002), archaeometallurgy and the complex technical prerequisites of primary metal production remain firmly rooted in the realms of functional determinism. Here, evidence from Asia is reassessed, along with new evidence from Sri Lanka, to explore the possibility that processes of memetic cultural inheritance can explain a major divergence in Eastern and Western metallurgical development. The debate is also extended to include a consideration of the manner in which present-day Western perceptions of technological ascendancy can inhibit and skew interpretation of other evolutionary pathways. The starting point for this debate is the evidence for a 'unique' wind-powered iron-smelting technology in Sri Lanka.

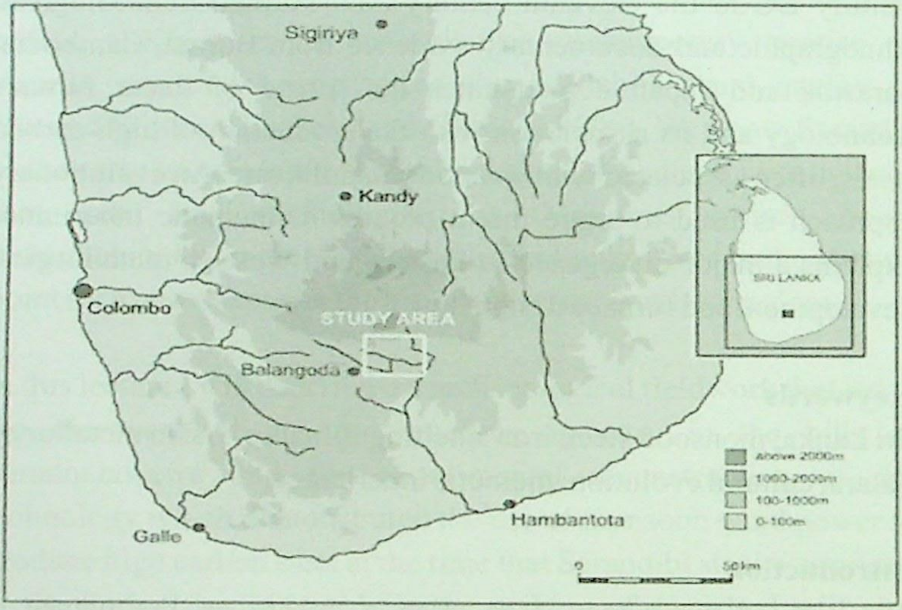

Figure 1 Map of Sri Lanka marking the Samanalawewa project area and also Sigiriya.

Monsoon steel: the wind-powered furnaces of Samanalawewa

In 1996 the science journal Nature published the results of an archaeological survey and excavation project in Sri Lanka that culminated in a series of experimental iron-smelting field trials which reconstructed a late-first-millennium AD wind-powered furnace (Juleff 1996). At the time the article attracted considerable attention for the fact that it demonstrated a previously unknown and novel technology which, strikingly, appeared to have no parallels. Subsequent publication of the full results of the Samanalawewa project described in detail the archaeological evidence that underpinned the experimental reconstructions and suggested possible local antecedents of the highly evolved furnace design (Juleff 1998).

The area investigated by the Samanalawewa archaeological project lies in the foothills of southern central highlands of Sri Lanka to the east of the provincial town of Balangoda (Fig. 1). The landscape comprises forested hilly terrain bisected by fast-flowing rivers that are the source of water for small tracts of irrigated paddy-land that sustain dispersed village settlements. Climatically, Samanalawewa lies in a zone intermediate between the wet zone to the west and the dry zone to the east and experiences heavy rainfall during inter-monsoon periods and high-velocity, desiccating winds from the west during the months of the south-west monsoon (June–September).

Archaeology

The project originated as an archaeological survey of an area affected by the development of a major hydro-electric scheme. Lying on an elevated peneplain, Samanalawewa does not share the typical ‘tank and temple’ (man-made irrigation reservoirs and

Buddhist temple) settlement pattern that characterizes the lowland dry zone civilization of the first millennium AD. Thus, the archaeology of the area was not considered significant and had not been examined previously. However, it was known for two important iron-working technologies described in eye-witness accounts of the first decade of the twentieth century (Coomaraswamy 1956: 189–92). Field survey from 1988–90 identified and recorded c. 250 sites, ranging from evidence of prehistoric activity to historic period settlements (Juleff 1998: 40–99). The published record is dominated by sites associated with iron working and, while both the technologies described by Coomaraswamy were identified, by far the largest component of this group (now more than eighty records in an area of c. 70km2) is a series of sites that became known as the west-facing iron-smelting sites. The technology evidenced on these sites had not been recorded previously from Sri Lanka or elsewhere in Asia.

As with most sites of metallurgical activity, the predominant identifier was the presence of discarded slag waste. In this case, slag was consistently and thickly deposited on the western leading edges of hills and ridges with uninterrupted aspects in that direction, hence the early association with monsoon winds. Morphologically, the slag assemblages again had no obvious parallels. They comprised, in addition to recognizable runs of fluid tap slag, large sub-rectangular slag blocks, preserving pseudomorphic impressions of bundles of rice straw (paddy), that had solidified against a line of reused tapering tuyeres, telescoped one into another to form a barrier (Fig. 2). The resulting distinctive forms, with fragments of tuyeres filled with slag, were consistent across all the sites of this type. At the upslope boundary of the slag deposits pairs of upright stones protruding no more than 0.4m above the surface and positioned c.1.5–2.0m apart, occasionally with remnants of a connecting clay wall, were recognized as evidence for furnace structures (Juleff 1998: 66). Pottery finds from survey dated these west-facing sites to the Middle Historic period (300– 1100 AD) (Deraniyagala 1992: 713; Juleff 1998: 94).

The interpretations drawn from the survey, that the west-facing sites represented industrial-scale production of iron based on a technology that utilized strong monsoon winds, were further resolved by excavation of one of the larger west-facing sites in 1990–1. An estimated 20 per cent of the deposits on the site (SM88) were excavated and within this sample forty-one individual furnace structures were identified, many of which showed evidence of successive rebuilding, demonstrating the intensity of activity. The stratigraphic sequence resolved two major phases of production, the first dated by radiocarbon to the seventh to ninth centuries and the second to the ninth to eleventh centuries AD. The absence of evidence for domestic habitation reinforced the argument for seasonal activity associated with monsoon winds. The furnaces themselves conformed to a persistent design that comprised a two-part structure consisting of a permanent curving back wall of clay constructed into a shallow cut and a temporary, single smelt, front wall connecting the two upright stones (Fig. 2 and Plate 1). The front wall did not survive in situ but was reconstructed from the fragmentary slags and refractories discarded in front of each structure. Survival of back wall 'rims' clearly established that the structures were no more than 0.5m in height and heat damage distribution patterns on the back walls indicated maximum temperatures at the point where the back wall abutted the upright stone and the front wall (Juleff 1998: 141).

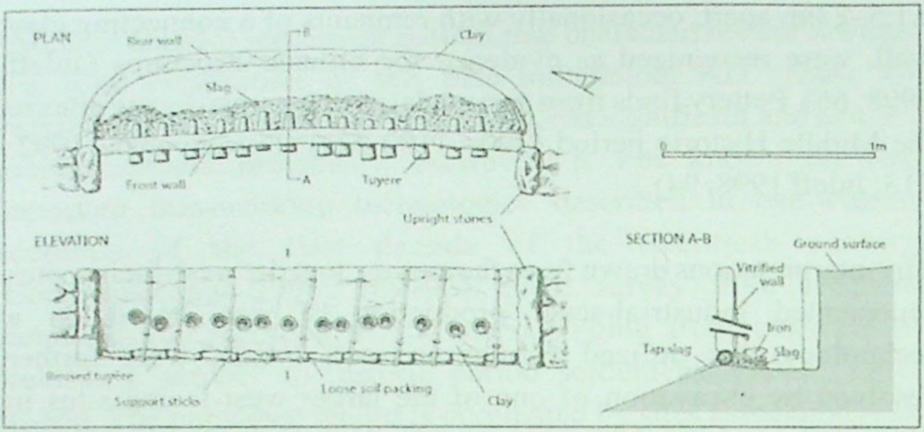

Figure 2 Reconstructed wind-powered furnace used in the smelting trials of 1994 at Samanalawewa, Sri Lanka (Juleff 1996).

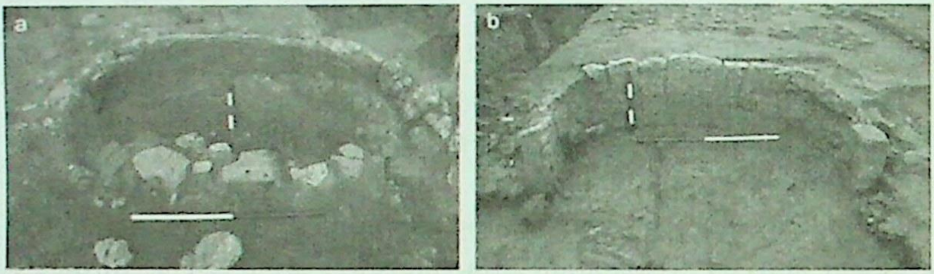

Plate 1 Two of the forty-one excavated furnaces at the west-facing site of SM88, Samanalawewa, Sri Lanka. a) During excavation with debris from dismantled front wall in foreground. The central section of the back wall in this example preserves a smoothed rim. b) After excavation with upright stones terminating the back wall and heat damage concentrated at either end of the wall.

While a very high level of consistency was apparent, there was also evidence for technological development and optimization from the first phase of activity to the second. This is discernible in a number of features but is most apparent in the width of the furnaces (the distance between the upright stones). In the first phase the range of furnace widths is 1.35m–1.76m and in the second phase it increases to 1.70m–2.10m (ibid.: 142).

Objections and reconstruction experiments

The substantial body of data amassed through both survey and excavation clearly demonstrated the existence of a successful late-first-millennium industry based on a smelting technology that made use of strong monsoon winds to drive a low, linear-form furnace. Despite the convincing nature of the evidence, its interpretation was greeted with considerable scepticism by the archaeometallurgical community. Objections focused on the two central elements of the technology: the use of wind and the postulated furnace design. No records existed for any furnace being driven exclusively by the wind. It seemed implausible that a natural wind, liable to gusting, could emulate the controlled blast of a bellows over the period of time of a smelt (in the region of four to five hours). The use of 'natural draught', whereby the buoyancy of low-pressure combustion gases rising up an enclosed shaft induces a draught sufficient to drive the smelting process, was well known, particularly from African ethnographic examples, and accepted as the alternative to the more preferable forced draught created by the use of bellows. The lack of chimney-like shaft or superstructure above the large, low, west-facing furnaces made natural or induced draught impossible.

Putting to one side the issue of wind power, the overall configuration of the west-facing furnaces was equally unpalatable. On the basis that successful iron smelting requires an enclosed environment in which gas and temperature conditions can be controlled, the bellows-driven shaft furnace postulated from archaeological and experimental evidence by such pioneers as Tylecote et al. (1971) epitomizes optimum conditions and has assumed ascendancy as the primary 'model' for pre-industrial iron smelting. The west-facing furnaces departed radically from this model, being large structures, apparently freely open to atmospheric gases and also very low, only 0.35m between tuyere nozzle and furnace rim, offering apparently no extended reaction column or 'residence time' (the time needed for a reacting ore particle to sink through a charcoal bed). That this evidence derived from distant, tropical island Sri Lanka only increased its implausibility, and, if accepted, it could find a place only as a marginalized or exotic outlier of mainstream metallurgical development.

Plate 2 Experimental smelting in reconstructed furnace, Samanalawewa, Sri Lanka, during series of trials in 2007.

To address these understandable objections a series of reconstruction experiments were carried out in the field in 1994 (Juleff 1996, 1998: 174–212). Furnaces were constructed from the archaeological evidence on a west-facing site, at locations used in the past as furnace settings, and were fired during the height of the monsoon when winds reached an average velocity of 45km/h. Using local ores, comprising 79–87 per cent Fe2O3, and locally procured charcoal of the Syzygium species identified in the archaeological record, three smelts, each lasting five to six hours, were carried out with increasing success (Plate 2). All produced free-flowing slag, and the final smelt achieved c. 17kg of metal from a charge of c. 120kg ore and recorded combustion zone temperatures of >1400°C, despite experiencing below average wind speeds, including a 1.5-hour near lull (Juleff 1998: 210).

While the success of the field experiments led to widespread recognition of the evidence, the veracity of the exercise lay in the close correlation between the archaeological and the experimental data in terms, for example, of the patterns of heat damage on the furnace walls and the morphology of the slags and other debris produced. Subsequent analysis of incident wind speeds and airflow patterns, with the help of specialist expertise in fluid dynamics, also conclusively established that the furnace operated not by wind blowing directly down the tuyeres into the core of the combustion zone as had been assumed but by it blowing up and over the straight front wall of the furnace. This created a dramatic pressure gradient between the top of the front wall and the external mouth of the tuyeres, equivalent to that created in a natural (induced) draft furnace of several metres in height (Juleff 1996: 61, 1998: 202; Tabor et al. 2005).

Sarandibi steel and Early Islam

Analysis of the metal products from the smelt provided a further unexpected result. The metal retrieved as discreet lumps or 'blooms' at the end of the smelt when the front wall of the furnace was broken down while still hot (to re-enact what was interpreted from the archaeological record) could be readily forged by local blacksmiths and showed typical low-carbon bloomery-type microstructures when analysed (Juleff 1996, 1998: 196). In addition to this material a further layer of metal was found still attached to the upper surface of the large slag block that had formed against the front wall, just as seen in the archaeological record. When analysed, this material proved to be slag-free high-carbon steel (ibid.). The significance of this discovery is an adjunct to the central focus of this paper but nonetheless is included here for completeness.

The Samanalawewa evidence, for a robust, large-scale industry capable of producing substantial quantities of high-quality, high-carbon steel during the latter half of the first millennium, coincides with rapidly growing demand for such weapons-grade metal in the emerging Islamic power block to the west of Sri Lanka. Perhaps the most authoritative contemporary treatise on sword-making is that by al-Kindi (Hoyland and Gilmour 2006) in which the availability and quality of Sarandibi steel is repeatedly emphasized. Sarandib is the early Islamic name of Sri Lanka and the strong inference is that the west-facing monsoon-driven furnaces were ultimately the source of the raw material used in Early Islamic weapons (the Damascus swords of legend).

Sri Lanka: an evolutionary series

Returning to the smelting technology, the euphoria and local pride that accompanied the first publication of the results of the

Samanalawewa smelting trials and the claims for a 'unique' Sri Lankan process masked the inevitable and obvious question of how such a novel technology arose and from where. While the terms 'innovation' and 'invention' are often associated with technology, never more so than in this instance, true invention is rare. Technology and technological change are much more likely to be the result of processes of adaptation and development, processes which have cultural foundation and thus should leave an archaeological footprint. The obvious first place to look for that footprint is at Samanalawewa itself.

During the same surveys that first identified the west-facing sites, a lone smelting site that did not appear to conform to any of the then recognized technologies was recorded in the village of Kosgama. Assigned the site code SM200, the remains at Kosgama comprised the horseshoe-shape outline of a thick-walled clay structure protruding through the swept floor of the courtyard of a village house lying on the lower slopes of a wide valley. Excavation revealed the well-preserved, truncated base of a furnace (Fig. 3) which comprised a number of familiar elements. The curving in situ furnace wall was constructed to be permanent and was terminated at either end by stone blocks, one of which had been removed. Within the slag and furnace debris filling the shallow clay-lined basin in front of the main structure were fragments of straight wall showing multiple imprints (up to three together) of tuyeres embedded in the front wall. Many of the slags retrieved from the same fill preserved pseudomorphic impressions of bundles of rice straw. Radiocarbon dating of charcoal samples from the debris places the use of this furnace in the lower to mid-Early Historic period (Deraniyagala 1992: 733) between the fourth century BC and the first century AD (Juleff 1998: 153).

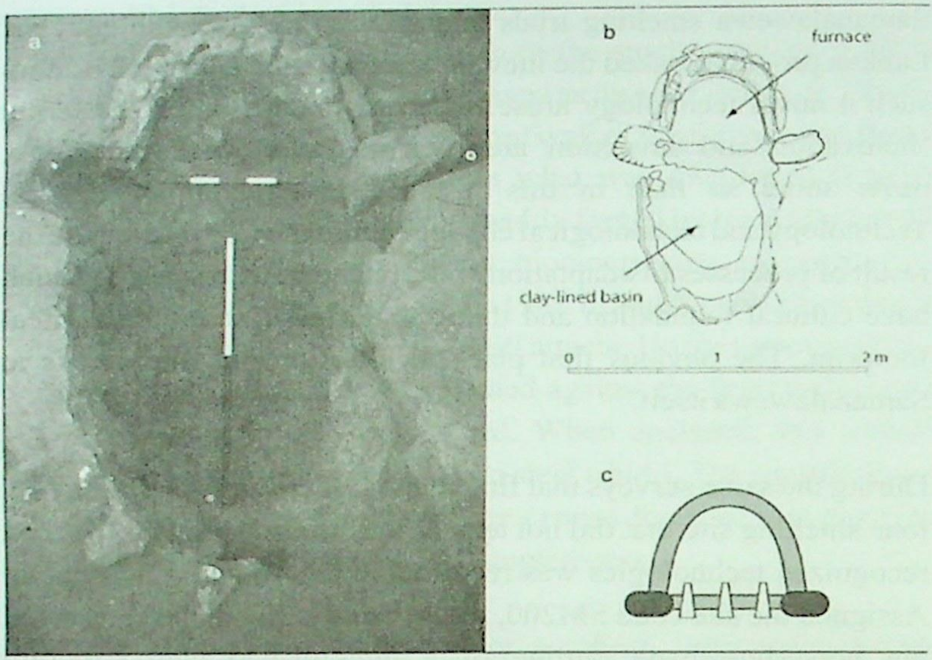

Figure 3 SM200, fourth century BC-first century AD furnace at Kosgama, Samanalwewa, Sri Lanka: a) after excavation; b) in plan (Juleff 1998: 156); c) schematic representation of the furnace footprint.

As no superstructure survives it is not possible to predict whether this was a tall shaft-like furnace or a shallower structure. The furnace is oriented with its open front to the south west and, although the valley is windy during the monsoon season, it is unlikely to have experienced the exceptionally strong directional winds that are so apparent on the west-facing hilltops. Thus, it is possible that this is a natural (induced) draught furnace which may or may not have been assisted by wind power in the same manner as the west-facing furnaces. It is also possible that it could have been blown using bellows, although there is little field evidence to support this. What is clear, however, are the similarities in furnace design between this and the west-facing furnaces of over half a millennium later. In this instance the overall structure is smaller, with the width of the open front (blocked during smelting with a straight front wall containing multiple tuyeres) being 0.5m and the distance from the centre of the postulated front-wall foundation to the interior surface of the back wall being 0.6m (Juleff 1998: 154).

The dimensions of the furnace give the impression of a relatively equi-axed or subcircular smelting chamber and the archaeological plan of its footprint (Fig. 3) bears many resemblances to the footprints of furnaces excavated across Europe. This same plan would be entirely plausible if published for a European metal smelting site and in interpretative reconstruction would be portrayed as a circular-plan shaft-like structure (for examples, see the numerous illustrations and reconstructions in Pleiner 2000: 164, 167, 184-5, 199).

While the footprints left by the elongated wind-powered furnaces of SM88 and the subcircular furnace of SM200 appear quite different, they share constructional details that suggest strongly that they belong to the same technological lineage. A third furnace can also be added to this lineage, fitting the chronological gap between SM200 and SM88. The iron-smelting site of Dehigaha-ala-kanda, in the vicinity of the World Heritage site of Sigiriya, lies to the north of the central highlands of Sri Lanka (Fig. 1). Although at a lower elevation than Samanalawewa, the area experiences a similar climate with strong, dry, directional winds during the months of the south-west monsoon. The site was first identified and then excavated by a joint Sri Lankan-Swedish archaeological team in the early 1990s (Bandaranayake et al. 1990; Forenius and Solangaarachchi 1994).

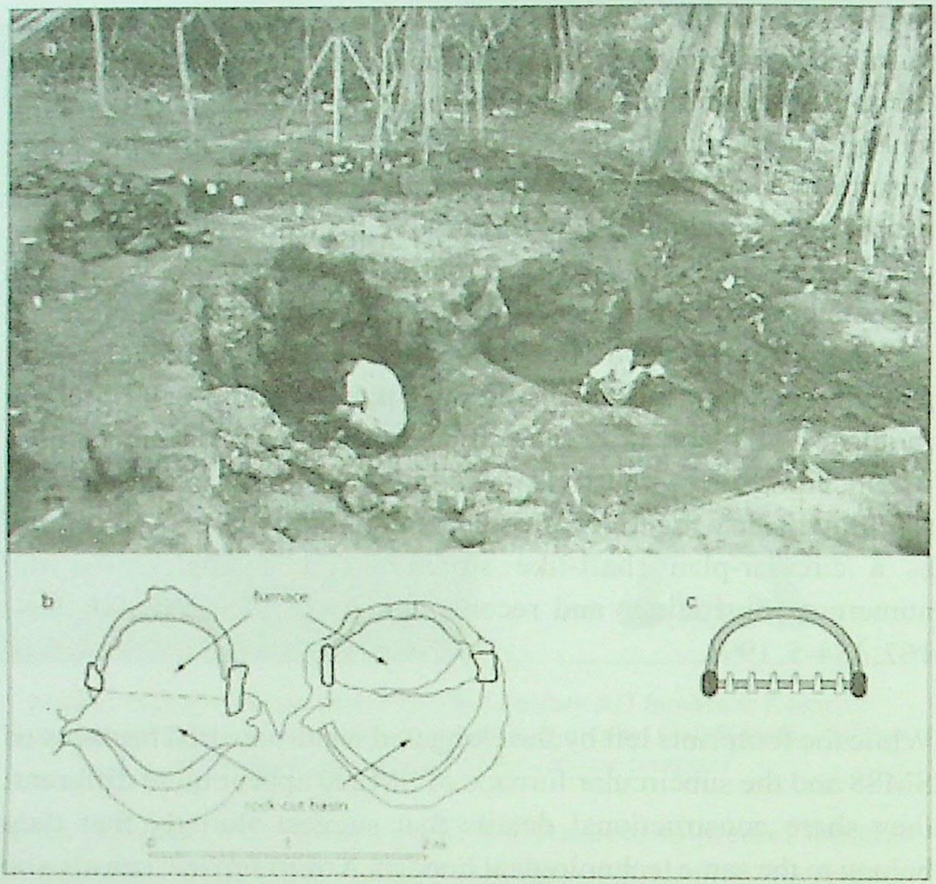

Figure 4 Dehigaha-ala-kanda, Sigirya, Sri Lanka, a) during excavation (photo: G. Juleff), b) in plan (after Forenius and Solangaarchchi 1994) and c) schematic representation of furnace footprint.

In this case four furnaces were excavated of a group of five situated in a line with a strong preferred orientation. All the structures examined were sited within individual, shallow, unlined basins cut into bedrock and built into a supporting bank. These furnaces, like SM200 and SM88, comprised a permanent curving C-shaped back wall, terminating in large stone slabs between which the temporary, single smelt, straight front wall was constructed (Fig. 4). Nothing remained in situ of the front walls but associated debris included wall fragments showing the imprints of multiple tuyeres allowing a line of up to eight tuyeres to be reconstructed. The associated debris also includes both tap slag and slag that preserved pseudomorphed impressions of straw. Radiocarbon dating and pottery evidence place the activity on this site between the upper Early Historic and the Middle Historic period (Deraniyagala 1992: 712), from the second century BC to the fourth century AD, with the most concentrated activity towards the end of this range (Forenius and Solangaarchchi 1994).

Dimensionally, using the convention of width and depth-in-plan adopted for SM88, the Dehigaha-ala-kanda furnaces range from 0.8m to 0.95m wide (between the stone slabs terminating the back wall) and 0.4m to 0.6m in depth-in-plan (from the centre of the back wall to the position of the front wall. Thus, in plan they are no longer equi-axed or sub-circular in the manner of SM200 (Fig. 3). Importantly, good evidence survived for superstructures on these furnaces with the best example standing to a height of 1.6m and indicating a shaft tapering to 0.5m in width (Fig. 4). It is therefore quite possible to postulate that these furnaces were driven by a natural (induced) draught effect, probably enhanced by the use of strong incident winds during monsoon months. Interestingly, the excavators of Dehigaha-ala-kanda argued strongly that the intensity of smelting at the site, seen in the volume and quality of the slag and the patterns of heat damage on the furnaces, could have been achieved only using bellows-driven forced draught (Forenius and Solangaarchchi 1994). This interpretation was arrived at before the experimental reconstruction of the Samanalawewa furnaces established the viability, and indeed efficiency, of wind power. It is also telling that the reconstruction of the Dehigaha-ala-kanda furnace (Plate 3) valiantly attempts to meld together the Sri Lankan field evidence with a circular-plan shaft furnace – the predominant expression of a Euro-centric model of early iron-smelting furnaces. Rather like the reverse of trying to put a square peg into a round hole.

Plate 3 Sri Lankan postage stamp depicting the Sigiriya (Dehigaha-ala-kanda) furnace, showing the excavated furnace and a reconstruction of a circular-plan structure (by kind permission of Anura Manatunga).

To the evolutionary series that emerges from the discussion of the three furnaces above can be added the distinction between the furnaces of the first phase of activity at SM88 and the second phase. From the seventh to the ninth centuries AD, the furnaces of the first phase range in width from 1.3m to 1.76m, while the ninth-to-eleventh-century furnaces of the second phase range from 1.7m to 2.1m in width. Thus, over a period of 400 years the furnaces increase significantly in width while their depth-in-plan remains largely unchanged at c. 0.35–0.45m (Fig. 5).

The evolutionary process and inheriting success

Having established that the Samanalawewa wind-powered technology, far from being 'unique', stands at the head of long line of

Sri Lankan iron-smelting furnaces, there are now sufficient data to consider what it is that evolved through the span of almost a millennium and a half. While it is the dramatic use of monsoon wind power that has gained the Samanalawewa furnaces their international reputation, the use of wind power is not the common thread that connects all the examples described here. It is, in fact, the furnace design, in particular its design in plan, or its footprint, that is both the common trait and the trait which changes, or evolves. SM200, at the base of the series, although undoubtedly not the first furnace as it represents an already successfully functioning technology, if treated in isolation can be described as having a roughly equi-axed or subcircular footprint. It would not be out of place in either a European or an African archaeological context and would most probably be reconstructed with a cylindrical shaft-like superstructure of indeterminate height. Sufficient material remains to deduce that the air enters the SM200 furnace through a number of tuyeres placed side by side in a temporary furnace front. Again, this interpretation would not be especially out of place anywhere in the world. Our assumption is that this configuration creates a high-temperature combustion zone which fills the cross-sectional interior of the enclosed clay structure.

The creation of a high-temperature combustion zone is the foundation of all pyrotechnologies and we can perhaps hypothetically trace this further back to its origins embodied in the campfire. The campfire is our earliest universal encounter with controlled combustion. It can be manipulated, intensified and most significantly encircled, especially by people. As an aside but reinforcing this point, the simple exercise of entering 'fires' into an internet search engine will demonstrate that images of campfires, large and small, invariably include people encircling, controlling and observing, while images of fires which take other forms, e.g.

waves, fronts, horizontal or vertical lines, rarely include people. Encircling a fire with a fire-resistant structure and manipulating the intensity of the fire within by controlling the air supply to it is the first step towards creating a successful furnace (Fig. 5). The combustion zone created by a given pressure of air can therefore be regarded as the indivisible basic building block or 'effective unit area' of a furnace.

The success imperative cannot be underestimated in the development of metallurgy. Given the energy investment in the procurement and preparation of raw materials, and designing and building a furnace, then running it until mineral rock is converted to useable metal, success, or more precisely the successful creation of a combustion zone, is the meme (the cultural 'gene') which drives development and change, the converse, failure, being unequivocal and unacceptable.

The case for treating human culture as an inheritance system analogous with Darwinian biological evolution is debated in depth by Shennan (2002). While Shennan adds complexity to the system by incorporating rates and modes of transmission to the processes of inheritance, the underlying unit of inheritance, the meme, as first proposed by Richard Dawkins (Shennan 2002: 46), provides us here with a usable tool for understanding replicating behaviour that functional determinism lacks. Dawkins, famous for the 'selfish gene' (1976), sees memes as replicators, analogous to genes (Shennan 2002). Here, we can perhaps treat the success imperative of smelting as being the 'selfish' driver within an inheritance system.

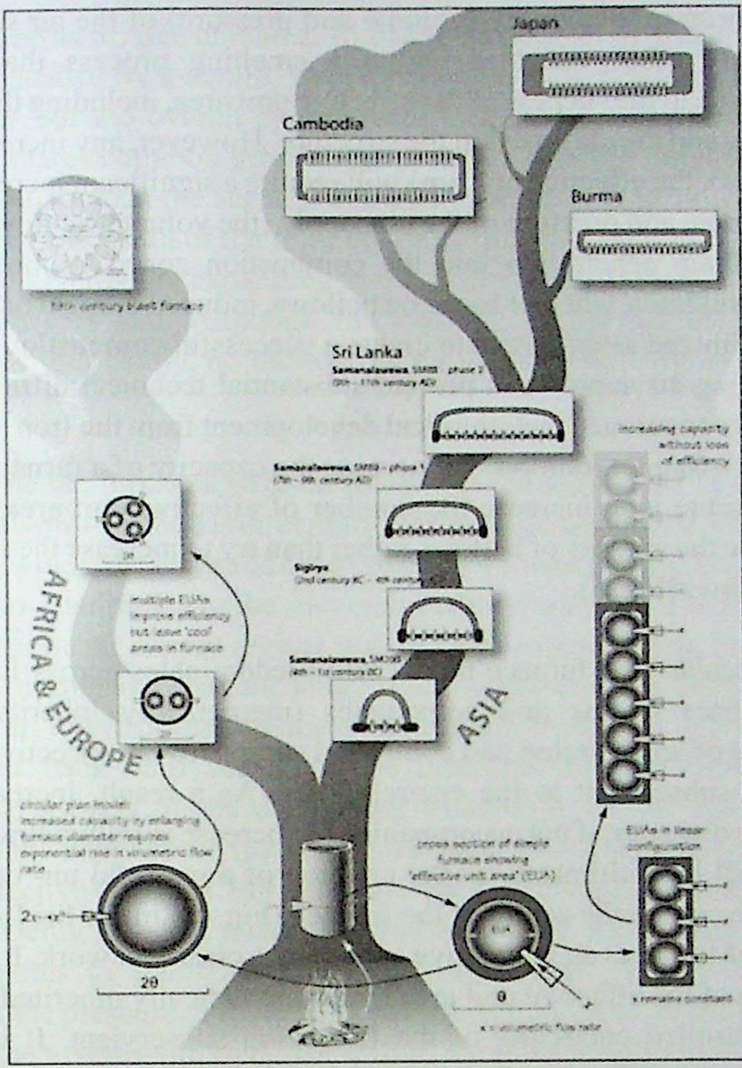

Figure 5 Hypothetical representation of the divergent east-west evolution of furnace designs emerging from a common origin and based on the concept of an effective unit area. The western, circular-plan designs are not given resolution here while the Asian linear furnace tradition arises out of the well-defined Sri Lankan evolutionary series. The schematic diagram of the furnace, the 'footprint', represents a simplified cross-section plan at tuyere height. The size, shape and placement of the tuyeres is, in some cases, a best guess.

In addition to the quality (volume and pressure) of the air supply, there are other variables within a smelting process that will contribute to the success of the effective unit area, including the fuel and ore, and the clay used in the structure. However, any increase in the size of the effective unit area will require a significant increase in the volume and pressure of the air supply (the volumetric flow rate) to maintain penetration into the combustion zone. As most air-supply regimes, whether based on bellows, induced draught or wind, are optimized at the outset to create a successful combustion zone, increasing air supply can present substantial technical difficulties and has constrained metallurgical development from the Iron Age to the Industrial Revolution. To increase the capacity of a furnace, the easier route is to increase the number of effective unit areas, e.g. increase the number of bellows rather than try to increase the size of the bellows (Fig. 5).

The circular-plan furnace model that predominates across Europe and Africa retains and perpetuates (memetically inherits) the concept of an encircled and controlled campfire. The effective unit area is subservient to the encircled fire. As a result, increase in furnace diameter, if not accompanied by increase in volumetric flow rate, will lead ultimately to the creation of a wasteful un- or sub-reactive core in the centre of the furnace (Fig. 5). In the Sri Lankan series of furnaces an alternative approach is clearly at work. It is the success of the effective unit area that is memetically inherited, with the controlled encircling of the fire being subservient. It is this behavioural difference that has produced the divergent east-west evolutionary paths expressed in Figure 5.

By repeating or copying the success of the first unit area with a second and then a third, side by side, the capacity of the furnace can be increased while the air supply regime remains unchanged. Thereby, optimum conditions with three or five, or more, unit areas are the same as for one unit area. At SM200 a number of unit areas, each represented by a tuyere, have already been aligned alongside each other but the overall approximate symmetry of the furnace structure shares common ground with a more 'Western' model. At Dehigaha-ala-kanda the success of the aligned tuyeres is extended by doubling the width of the front of the furnace and increasing the number of tuyeres. By expanding in one dimension only, any sense of symmetry is lost. Although the capacity of the furnace has increased significantly, no increase in air pressure per unit area is required.

By the time the furnaces have been taken to the tops of the hills of Samanalawewa in the sixth century AD to take advantage of the monsoon winds, the length of the front of the furnace has tripled, and goes on to quadruple by the eleventh century with no associated increase in the air supply regime per unit area required (Fig. 5). As the depth-in-plan remains unchanged the combustion zone becomes truly linear; in effect the furnace is the straight front wall, with the permanent back wall acting as the container for the furnace. Functional aspects of the developing technology can be seen to follow in the wake of the memetic inheritance of the success of the single effective unit area. For example, there is an important change between Dehigaha-ala-kanda and SM88 from thick-walled parallel-sided tuyeres to thinner walled, tapering tuyeres. This change increases the pressure of the air into the furnace and also, in the later reuse of the tuyeres, improves the efficiency of the construction and functioning of the front wall. However, while this is an innovative development, it is a response to, rather than a driver of, the underlying evolutionary process.

Exploring the process of memetic inheritance further to consider the rate of evolution, it is telling that the development of the linear furnaces in Sri Lanka proceeds at a relatively constant pace and spans 1500 years. If the efficacy of repeating effective unit areas in lines rather than within circles was consciously recognized, as an innovation, it could be argued that there should be no barrier to the rate of development and a significant acceleration might be predicted. The move from three, to five, to eight, to twelve tuyeres, and so on need not span more than a few generations. That this is not the case invites deeper debate on the nature of memetic transmission.

South and Southeast Asia: a technological tradition

The foregoing discussions have focused on the core evidence for an unbroken technological lineage from the lower Early Historic to the Middle Historic periods of Sri Lanka. Other evidence in the form of sites, slags and tuyere finds from across much of the country (from the North Central Province to the southern coast) demonstrate widespread occurrence of the technology. This extensive distribution is an indicator of the cultural and socio-political unity and stability that prevailed from the protohistoric to the end of the first millennium AD (de Silva 1981: 35). The eleventh century then sees major political and demographic change with Cholan invasions from the South India bringing to an end the long-established political stability. At Samanalawewa the west-facing smelting technology disappears from the archaeological record. By then the industry had been producing high-carbon steels for export out of the area for several centuries. Production was probably overseen by middlemen and entrepreneurs who also controlled the movement of the products from the hills, across the lowland plains, to coastal ports under the patronage of the Royal court of Ruhuna (the southern kingdom of Lanka) based in the capital, Magama, present-day Tissamaharama (Weisshaar et al. 2001). With the collapse of the court, the control of the trade also collapsed and the iron smelters and steel makers of Samanalawewa lost their principal outlet. As their high-carbon steel product was difficult to forge it was better suited to specialist sword manufacture than agricultural and domestic tools, and as the limited local population they served could not absorb the additional supply, so the industry also collapsed.

Thus far the evidence discussed derives from Sri Lanka alone. Given the dominance of the linear furnace technology within Sri Lanka and the pivotal position of the island within the trade and exchange network of the Indian Ocean, and also the influence of the Sri Lankan Buddhist polity in the wider South and Southeast Asian cultural sphere during the first millennium AD (Ray 1994), it is not unreasonable to ask whether any elements of the Sri Lankan technological tradition were transmitted to other regions of southern Asia.

Burma

The nearest description of an iron-smelting furnace with a linear footprint comes from the Mount Popa region of central Burma in the hinterland of the great medieval Buddhist city of Pagan (Fig. 9 below). Still operational in the nineteenth century, the furnaces were observed by W. Blanford, whose account is quoted by Percy in his seminal four-volume work on metallurgy (1864: 270–3), and further studied by Chhibber (1926) after they became obsolete. In this instance the furnace is unequivocally driven by induced draught, having an extended shaft superstructure (Fig. 6). The furnace is built into an earth bank and at its base is rectangular in plan, being 1.5m wide and 0.3m deep (in plan). The c. 3mtall shaft above the smelting zone narrows to become trapezoidal in plan. A row of twenty tuyeres was embedded into the temporary closure of an elongated opening at the base of the front of the furnace. More recent fieldwork in the same area by Hudson (2004: 199– 206, pers. comm.) has identified at least twelve smelting sites with large numbers of furnaces which he dates to at least to the eleventh-to-thirteenth-century Pagan era, if not possibly earlier. An excavation of one of these furnaces revealed many of the features described in the nineteenth-century accounts. The bank construction and the shaft-like superstructure suggest parallels with the Dehigaha-ala-kanda furnaces of Sigiriya, Sri Lanka.

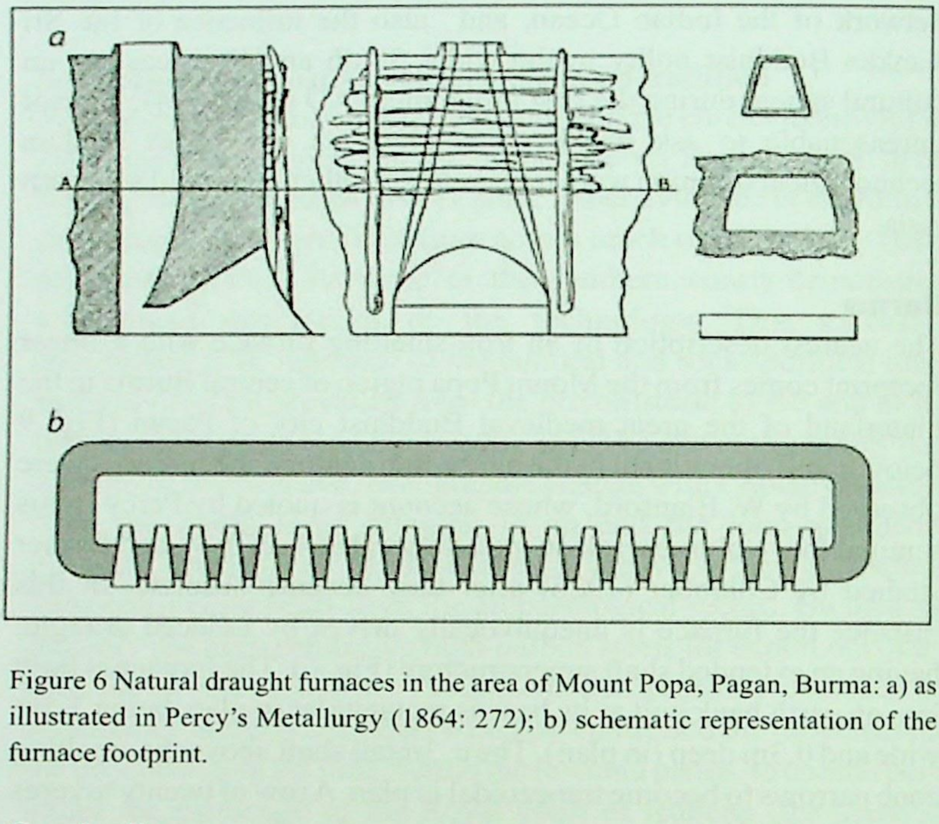

Figure 6 Natural draught furnaces in the area of Mount Popa, Pagan, Burma: a) as illustrated in Percy's Metallurgy (1864: 272); b) schematic representation of the furnace footprint.

Cambodia

Further east in the Compong Soai province of Cambodia (Fig. 9 below), another nineteenth-century eye-witness account (Moura 1883; Bronson and Charoenwongsa 1986) describes the traditional smelting furnaces of the Kui (Cuoi) ethnic group. In this case the furnace is blown from two long sides using two 0.5m-diameter drum bellows. The footprint of this furnace is once again rectangular, with a linear combustion zone. Its structure is 2.5m long and 0.9m wide with twenty-six tuyeres set into each long side (Fig. 7). Interestingly, the accounts describe the furnace as 0.4m deep (high), making it a low structure unlike the Burmese furnace but similar to the Samanalawewa furnaces.

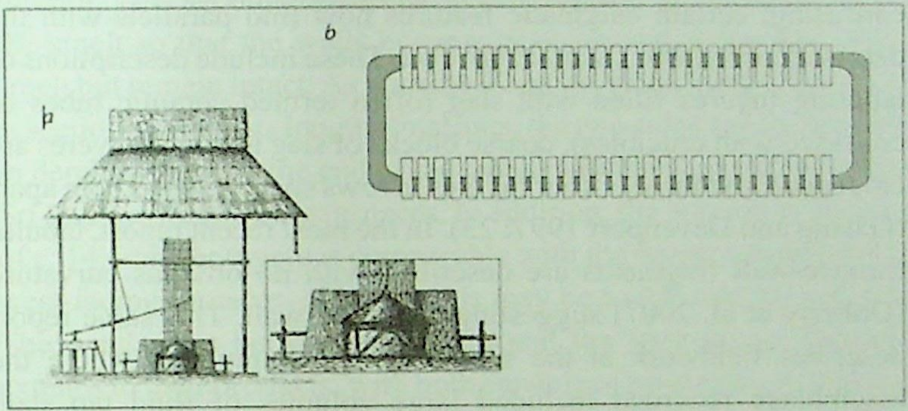

Figure 7 Low, rectangular, bellows-driven furnace of the Compong Soai region of Cambodia: a) as illustrated in the nineteenth century by Moura (1883); b) schematic representation of furnace footprint. The tight tuyere spacing here is based on the necessity of accommodating twenty-six tuyeres.

Despite being bellows driven and two-sided, if a line is drawn through the central long axis of this structure, the separate halves are dimensionally very similar to the Sri Lankan furnaces, having a depth-in-plan of c. 0.45m. Reputedly, this furnace produced iron and steel of high purity that was highly prized and traded across Cambodia and Thailand. While there is no dating for the archaeology of this technology, in their commentary Bronson and Charoenwongsa (1986: 11) suggest a relatively early introduction.

Sarawak

The evidence from Sarawak derives not from furnace structures but from smelting debris found during field survey in the Santubong peninsula (Fig. 9 below). Since the 1960s researchers have described significant numbers of smelting sites in the region and an abundance of slag on these sites (Gasing and Davenport 1997; Doherty et al. 2007). While many of the descriptions of the debris are confusing, certain enigmatic features now find parallels with the debris recorded from Samanalawewa. These include descriptions of tapering tuyeres filled with slag (often termed ceramic tubes or confused with crucibles), coarse blocks of slag in which tuyeres are embedded and three or four tuyeres in rows spaced 10 to 15cm apart (Gasing and Davenport 1997: 23). In the most recent report, tabular furnace-wall fragments are described with no obvious curvature (Doherty et al. 2007) suggesting a straight wall. This same report describes fieldwork at the site of Sungai Santubong where the assemblage recorded included large volumes of fluid tap slag, Chinese ceramics, waisted hammer stones and shallow rectangular troughs and smaller hollows or cups cut into the tops of in situ boulders (ibid.). The latter feature is one that was also recorded as conical cups in the outcropping boulders at Dehigaha-ala-kanda, Sri Lanka (Forenius and Solangaarchchi 1994: 140).

Japan

The final and most striking example of a linear furnace is the tatara of Japan. Unlike others above, the tatara is well known and still in operation today, although only in specialist workshops. It is the source of steel for the manufacture of Japanese samurai swords.

There have been numerous descriptions of the tatara, the name of which derives from the large, double-chambered, foot-operated blowing machines used to power the furnace, with Rostoker et al. (1989) offering a useful summary of the process. What concerns the discussion here is the design of the furnace and its footprint. Like the Cambodian example, the tatara is a double-sided rectangular furnace. Lyman (1879, in Rostoker and Bronson 1990) gives the dimensions of the furnace as 2.9m long, 0.9m wide and 1.13m high, with nineteen or twenty tuyeres per long side (Fig. 8). The walls of the furnace taper to give a narrow-based, V-shaped profile to the interior. This accommodates the severe erosion of the walls during the smelt so that the walls become near vertical at the end of the smelt but remain intact. As with the Cambodian furnace, if the tatara is sectioned along its longitudinal axis, the two sides are comparable in depth-in-plan, at the end of the smelt, with the dimensions of the Sri Lankan west-facing furnaces. In addition, the horizontal spacing of c. 14.5cm per tuyere is comparable with the tuyere spacing of the west-facing furnaces, although this may be a coincidental statistic. The similarities between the tatara and the west-facing furnaces extends to their products, with both capable of producing within one smelt a range of ferrous alloys from low-carbon bloomery-type iron to homogeneous, slag-free, high-carbon steels intended for weapons manufacture. On present evidence, the origins of the tatara in Japan are no earlier than the mid-sixth century AD, when the appearance of the first box-shaped furnaces mark the beginning of iron smelting in the Japanese archipelago (Anazawa 1998). It is believed that the technology was adopted from Korea.

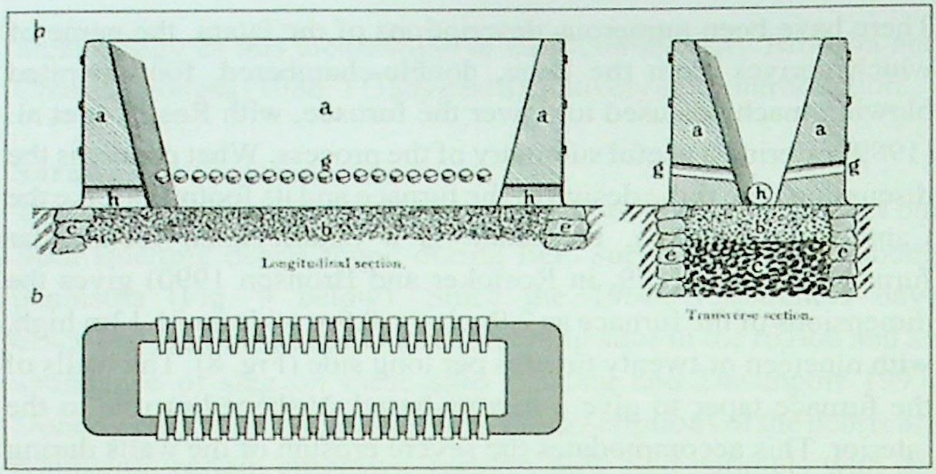

Figure 8 The tatara furnace of Japan: a) as illustrated by Gowland (1899); and b) schematic representation of furnace footprint.

Technology transfer

Like the wind-powered west-facing furnaces of Samanalawewa, the tatara process has been frequently described as 'unique' and has as a result occupied a marginal position, albeit exalted, as an exotic outlier of mainstream metallurgical development. In the light of the evidence discussed here it is possible to see the tatara not as unique but as one manifestation of a much larger pan-Asian tradition of linear furnaces. The geographical spread of this technological tradition is truly extensive, stretching from Sri Lanka in the west to Japan in the east (Fig. 9). Only further fieldwork and close examination of documentary records will determine the density of coverage this tradition achieved and whether it coexisted alongside other traditions.

In Sri Lanka the archaeology indicates possible universal adoption of the linear furnace concept from at least the fourth century BC.

Chronologically, as it stands, the evidence suggests that the tradition has its origins in Sri Lanka and was transmitted eastwards across Southeast Asia. Although an extended discussion of the mode of technology transfer is beyond the scope of this paper, two mechanisms can be postulated for future consideration. The first is the obvious, long-established, sea trade routes crossing the Indian Ocean to the Malaysian archipelago and South China Sea. The flow of commodities along these routes in both directions is well attested and undoubtedly metals, particularly highly desirable steels, would have counted among the cargoes. However, it is important to distinguish here between the transmission of commodities and the transmission of ideas and practitioners and memetic behaviour patterns. For example, looking westwards from Sri Lanka during the height of the steel-making industry of Samanalawewa, while it is clear that there existed a robust traffic of raw steel to the swordsmiths of the Islamic world, there is no evidence that experienced smelters or smiths travelled the same route, taking their knowledge with them. Thus, no element of the Sri Lankan technology has been identified to the west, despite familiarity with the material and the existence of well-established routes. Therefore, looking eastwards again, we may assume that transmission of the linear furnace tradition was by a second mechanism, through individuals, groups of people and communities that physically moved from one area to another, taking their cultural and technological baggage with them. Perhaps the one movement from west to east during the first millennium AD that could have provided the vehicle for transmission was the spread of Buddhism from the Indian sub-continent, including importantly the Buddhist stronghold of Sri Lanka, across Southeast Asia (Ray 1994) as far as Japan.

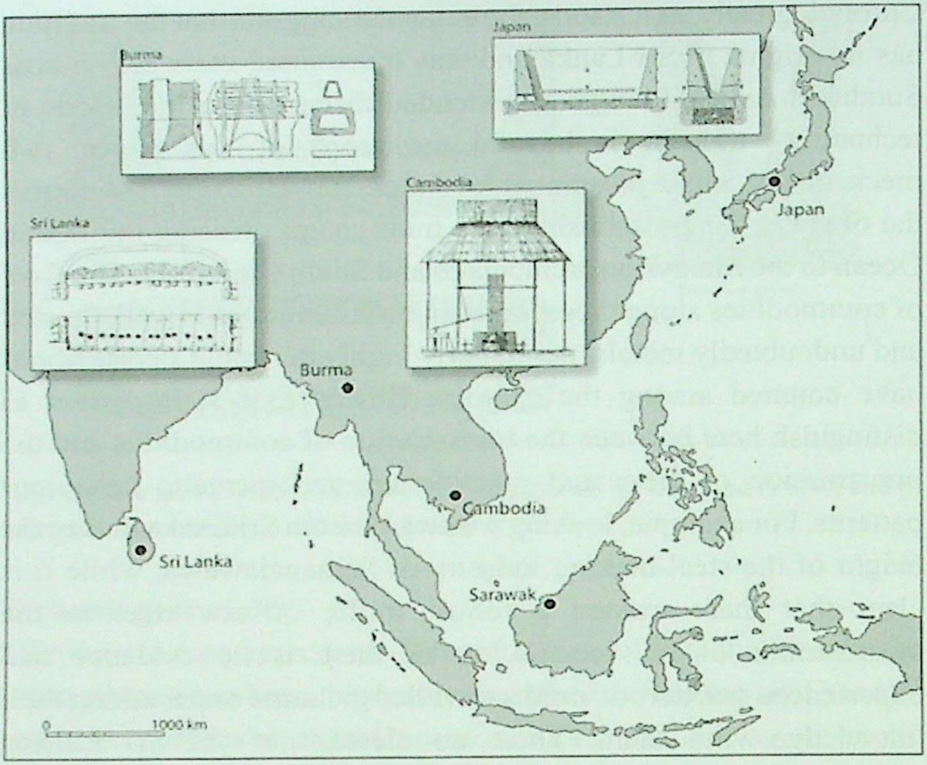

Figure 9 Map of South and Southeast Asia with locations of linear furnaces discussed in the text.

Conclusions

Through a reassessment of archaeological evidene for iron smelting in Sri Lanka it has been shown that far from being unique, the wind-powered furnaces of Samanalawewa stand at the head of a well-defined 1500-year evolutionary lineage. By deconstructing the furnaces that comprise this lineage, the combustion zone, or effective unit area, has been identified as the indivisible building block forming the foundation of the development of these furnaces. By recognizing the successful effective unit area as a cultural meme, the memetic action of aligning and repeating the unit areas side by side to form a line, rather than arranging them within a circle, as in the predominant western model, a divergent branch of metallurgical evolution has been identified (Fig. 5).

The well-defined evolutionary series of linear furnaces in Sri Lanka are characterized by the use of a single smelt, straight wall into which is embedded a row of tuyeres, each representing an effective unit area. A permanent setting or container for the straight wall is formed by a parallel back wall, set at an optimized distance from the furnace wall, curved at the ends to enclose the structure and terminated with upright stones. The presence of a superstructure above the rectangular base formed by these two elements is an indicator of the use of natural or induced draught while the use of monsoon winds to drive a low version of the same linear structure represents an advanced functional adaptation to advantageous local conditions.

This lineage dies out in Sri Lanka in the eleventh century AD but review of evidence from across Southeast Asia suggests that a linear furnace tradition, based on the same memetic behavioural pattern, extended significantly beyond Sri Lanka. All the furnaces described are rectangular or linear in plan and are characterized by the use of multiple tuyeres embedded into a straight, single use, furnace wall. A number of the technologies examined were also associated with the production of high-quality high-carbon steels for use in the manufacture of swords and weapons.

Finally, the debate opened here on the value of using cultural evolution, as an alternative to functional determinism, to approach an understanding of technological development should be considered in the cold light of the twenty-first century. Industrialera European colonial ascendancy in the economic production and mass distribution of iron eclipsed both the existence and significantly the recognition of an Asian branch of metallurgical development. This has allowed the 'Western' model of the circular-plan shaft furnace to dominate as a universal model and has led to inhibited and distorted interpretations of evidence that does not readily fit this model. This is manifested in the marginalization of key technologies such as the Japanese tatara and in the Westerninfluenced interpretation of the Dehigaha-ala-kanda furnace of Sri Lanka (Plate 3). A memetic inheritance approach to cultural evolution provides an opportunity to transcend this legacy and build models that are more representative of the field data.

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Gill is an archaeometallurgi[illegible]ork on previously unknown first millennium AD wind[illegible]ed furnaces for the mass production of iron and steel i[illegible]ka (Monsoon Steel) resulted in a fundamental paradigm-si[illegible]er field and established her international reputation. Fr[illegible] featured on the front cover of Nature, a rare single-auth[illegible]per by a female postgraduate researcher, the work has [illegible] test of time and continues to inspire research across Asi[illegible] led to further projects in India (Pioneering Metallurgy) to [illegible] the origins of wootz steel, the raw material of Damascus swords, and collabor[illegible]ith early iron-working research groups in China and Japan. In Sri Lanka, the wor[illegible]ntered popular culture, with the story of her discoveries being told as a comic book in three languages, and continues to be used to showcase national initiatives in sustainable technologies and renewable resources.

Monsoon Steel characterises her approach, combining assiduous fieldwork and methodological precision within her own field with cross- and multi-disciplinary collaborations to develop understanding beyond archaeology and ultimately beyond academic communities. This is seen, for example, in the first use of CFD (computational fluid dynamics) to model an ancient furnace and, more recently, in work with geologists and mining specialists to contextualise the past, present and future of critical mining and resource exploitation.

The thesis that underpins her work is that metallurgy and the possession of metallurgical knowhow is one of the central drivers of cultural change and that understanding the development of metallurgy is a route to elucidating complex cultural dynamics. It has led her to examine the long-range transmission of technology across Asia (World Archaeology, 2009) and the distorting impact of dominant western scholarship on non-western knowledge systems. Away from Asia, it has led her to study landscapes of production in the UK, spanning the metallurgical process, both ferrous and non-ferrous, from mining to manufacturing outputs on Exmoor and in Cornwall. This work is interwoven with community engagement in archaeology and heritage, as in the Time and Tide and Heritage on the Beach collaboration with Perranzabuloe Museum to raise public awareness of the mining heritage of a much-loved but poorly understood local cliffscape. In contrast, Gill's long-standing connections with Sri Lanka have taken her back in recent years to work with colleagues at the University of Jaffna in a new collaboration that explores the meaning of identity, place and heritage in post-war communities.

Gill's research journey has taken her from objective, evidenced-based archaeology, through multiple international collaborations, to a more reflexive and discursive examination of the past as an agent in shaping the present and future.

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