Invention, innovation and inspiration: optimisation and resolving technological change in the Sri Lankan archaeological record

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Dirty, heavy, intractable, dependent on the muscle and tenacity of people most often situated on the physical and cultural fringes of society, iron has nonetheless gravitated towards the centre of human development since its first known appearance over three millennia ago.

The aim of this session of World of Iron was to examine evidence in the archaeological record that allows us to explore the interface between technology and culture dynamics and the circumstances of technological change. What emerged was a disparate collection of perspectives, each insightful in their own right but which, when combined, are demonstrative of the infancy in our collective study of the drivers of innovation in this field, whether individual, societal, technological or evolutionary. While other sessions of World of Iron showcased the wealth and maturity of our understanding of the nature of iron as a material, its production through the smelting of ore minerals and its optimisation through alloying and heat treatment, far less apparent was our understanding of the nature of the relationships between the people and societies who contextualised its use.

Over some five decades or more of research the discipline of archaeometallurgy has progressed from a focus on the material itself in the form of artefacts. Detailed, laboratory-based metallographic studies of individual and assemblages of objects have brought to light the range of iron-carbon alloys and heat treatments utilised. The place of a metallurgical tradition within the development of iron was largely based on a linear scale of increasing technological repertoire and competency.

The need to understand how and where the raw materials of artefacts were produced soon followed and, with this, field studies of smelting and refining sites and processes gained importance. By their nature such studies are location specific, leading to claims evidenced by major concentrations of technological waste (slag) to 'centres of production'. This 'dots on maps' approach can have the effect of isolating the evidence from both its physical (topographical and environmental) and human (cultural) landscapes. Technological characterisation, through the analysis of site-level data and micro-structural and compositional evidence from collected samples has become the core task of the archaeometallurgist, where standardisation of projected production figures through the use of mass-balance calculations is the measure of technological success.

As data has accumulated in more recent years, however, there has been a growing appreciation that – given the ubiquitous use of iron within most past societies – a more continuous landscape of production, contoured by the physical topography of raw material distribution and the cultural topography of human settlement and economy, would be a more realistic model for understanding the development of iron in both spatial and temporal dimensions. With a broader canvas to view and data drawn from the field as well as the laboratory, detecting where and when changes happen and the pathways by which they are transmitted should become more visible. Importantly, it also gives the opportunity to recognise the impetus behind change and to consider whether that change is technologically or culturally determined, or indeed driven by evolutionary processes. Conversely, looking at broad socio-cultural landscapes may also help explain why technological change may be slow to occur or, when it does happen, what impact it has on local or regional cultural dynamics.

Thus, to address an expanded set of objectives that incorporates cultural archaeology as a vehicle for explaining invention, innovation and inspiration in metallurgy, it seems that, as a discipline, there is a need to share trajectories with archaeology, in all its forms, with material culture and with the history of science and technology. In summarising the papers presented in this session of the conference I frivolously commented how refreshing it was to hear so much about iron and see so few phase diagrams. Instead of the expected quick in-breath of opprobrium, there were mutterings of approval, suggesting the possibility that we have all now arrived at this realisation.

Invention, innovation and inspiration, in the context of archaeology in general and the development of iron technology in particular, are terms that have invited important debate in recent years (Fitzhugh, 2001, Shennan, 2002, Killick, 2004, Rehren et al, 2007, Charlton et al, 2012) and their definition offers considerable potential for understanding the nature of technology. However, rather than attempt to distinguish between them at a theoretical level or in the archaeological record, a more constructive approach with practical application may be to simplify the task by examining evidence of technological change to determine what drives or motivates change and from that define what processes are in action – innovation, invention, adoption, adaptation, optimisation – if this indeed is a useful conclusion to draw. More useful may be what can be inferred from the rate or pace of change. Archaeology abounds with examples of technological change. What constrains our chances of determining with any precision the drivers of change will be the resolution of available data. Here I will consider instances from the Samanalawewa Archaeological Project in Sri Lanka, now perhaps better known as Monsoon Steel (Juleff 1996, 1998).

Tracing technological optimisation

Setting

Samanalawewa lies in the southern foothills of the Central Highlands of Sri Lanka (Fig. 1) in an area traditionally regarded as of low archaeological interest. During the first millennium AD the broad lowland plains of the north and southeast of Lanka were densely settled with affluent agricultural communities, based on irrigated rice cultivation and two strong, stable, regional kingdoms, each closely aligned with the established Buddhist priesthood (De Silva 1981). The Samanalawewa area occupied a physiographic and culturally marginal position, remote from the heartland of the polity. It saw only small scattered valley-bottom settlements in otherwise wild, jungle-clad hilly terrain. The ethnic make-up of the local population is uncertain but traditions and early chronicles suggest that they were in part pulindas, a semi-vedda (aboriginal) tribal group (Perera 1959).

Climate

Sri Lanka's climate is dominated by the tropical monsoonal system and the seasonal weather pattern of Samanalawewa

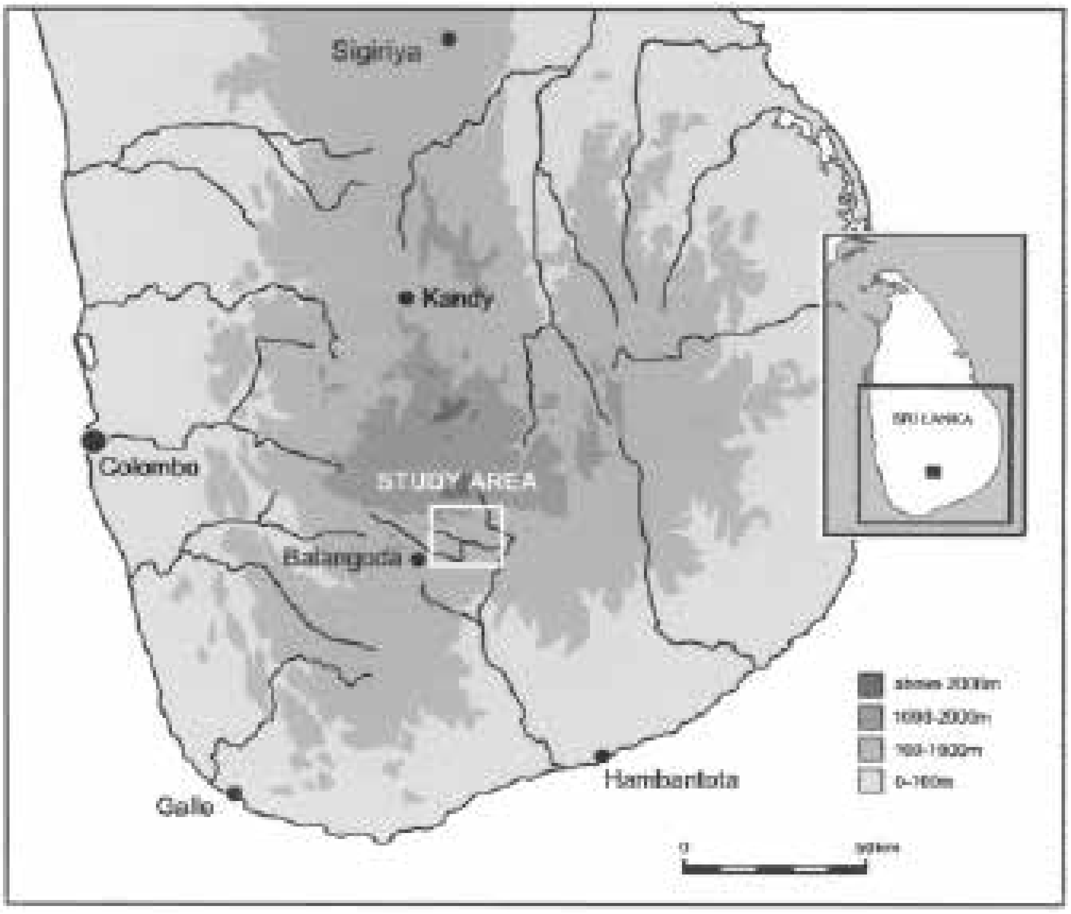

Figure 1: Map of Sri Lanka marking the Samanalawewa project area.

is transitional between the south-western Wet Zone and the northern and eastern Dry Zone, with constant, desiccating winds emerging from the Wet Zone to the west, where the burden of rain is dropped during the monsoon months of June to September. Orographic uplift, caused by the highlands, increases wind velocities in the area to an average of ~35km/h, rising frequently to 50+km/h and occasionally above 100km/h (Somasekaram et al, 1988, Juleff, 1998).

Survey

In the 1980's Samanalawewa became the focus of a major hydro-electric scheme that necessitated environmental and cultural impact studies, including an archaeological survey. Despite the lack of settlement during the first millennium Early and Middle Historic periods of the Island (for periodisation see Deraniyagala 1992), the area was closely associated with iron smelting and blacksmithing traditions and, significantly, crucible steel-making during the Late Historic Kandyan and colonial periods. Eye-witness accounts of smelting and steel-making by Ananda Coomaraswamy (1956) in the first decade of the twentieth century located these processes within specific named villages (Ondaatje, 1854, Wayman and Juleff, 1999, Juleff et al 2009). Hence, the initial priority for the Samanalawewa archaeological survey was to identify field evidence relating to these processes. From the outset of fieldwork, however, a previously unknown group of smelting sites dominated the archaeological record. These sites quickly became known as west-facing sites because of the consistent location of slag waste deposits on the west-facing slopes at the summits of exposed hilltops with uninterrupted aspects in that same direction. Correlation between smelting and strong directional, seasonal winds was clearly apparent from the first recognition of these sites. Slag morphologies across the seventy-seven sites of this type, recorded during the first survey (a number that continues to rise with every return visit to the area), demonstrated a similar high level of consistency, with forms that suggested a large furnace of unusual design and shape.

Excavation

On the strength of the data from field survey, in 1991 the Archaeological Survey of Sri Lanka initiated the excavation of one west-facing smelting site on a ridge known as Galewalahinna (site code SM88) (Fig. 2). The strategy was to open a series of 10x10m excavation areas to reveal the lateral extent of the site and to excavate two long, metre-wide trenches through the full depth of the deposits, to quantify output and examine the development of the site over time. In addition, attention focussed on the detailed investigation of individual furnace structures. Despite six months of digging, quantitative sampling of 17 tonnes of technological debris and exposure of 41 furnace structures it was estimated that only 20% of the site had been excavated and that the potential number of furnaces on this site alone was in the region of two hundred (Malim et al, 1995, Juleff, 1998).

Furnace design

The furnace design comprises a semi-permanent elongated C-shaped clay structure, reaching no more than ~0.5m in height, terraced into the leading westerly edge of the ridge. Evidence shows that the wall was terminated at each end with a large stone set in the ground and that a straight clay wall extended across the open front of the furnace, between the stones – although the evidence suggests that this was a single-smelt construction, deliberately broken down as the final act of each smelt. Embedded in the front wall were a line of pre-fired clay tuyérès, for the purpose of channelling air into the furnace (Figs. 4 and 5).

Furnace function

The manner in which the furnaces functioned was deduced from careful study of the archaeological evidence and, most valuably, the experimental reconstruction of the process, combined with the application of CFD (computational fluid dynamics), and has been described in a number of papers (Juleff, 1996, 1998, Tabor et al, 2005). Low-level incident wind, travelling up the contour of the hill-slope in front of the furnace, reaches its maximum velocity at the leading edge of the summit where it encounters the front wall of the furnace. It is forced upwards off the outer lip of the top of the wall, causing boundary layer separation and creating an area of extreme low pressure along the top of the wall. The pressure difference between the top of the wall and the external mouth of the tuyérè then generates a powerful air flow through the tuyérès embedded in the front wall (Tabor et al, 2005).

Phasing and chronology

Analysis and interpretation of the excavation record resolved 32 stratigraphic groups, each comprising multiple contexts, which in turn formed a sequence of five major phases in the development and use of the site (Juleff 1998). Of these, Phase 1 refers to circumstantial evidence for prehistoric occupation unrelated to the smelting site. Phase 2 sees the initial use of

Figure 2: View of excavation area from north after removal of topsoil. The upper levels of structures at furnace locations L and J, in foreground, and G, in background, are visible.

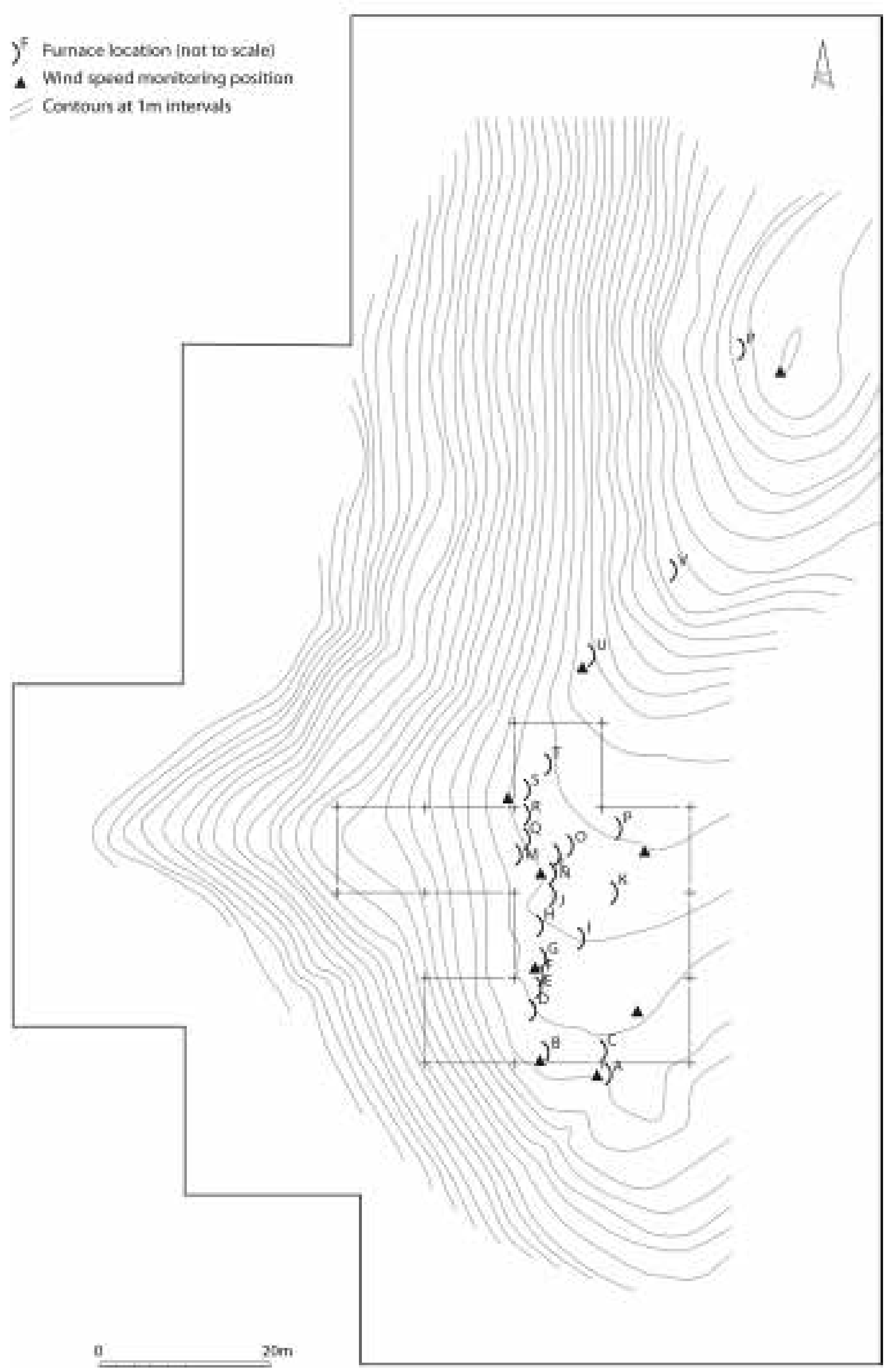

Figure 3: Site plan showing excavation areas and trenches, furnace locations and wind monitoring positions.

the site for smelting and a series of radiocarbon dates indicates activity from a start in the mid-7th century AD through to the early 9th century. Phase 3 represents a break in the smelting sequence and site-wide colluvial deposition of soil, suggesting abandonment. The duration of this abandonment is uncertain but a single radiocarbon date places it in the 9th century. Phase 4 sees a return to full scale smelting activity from the mid-9th to the early 11th century. Two radiocarbon dates from the first evaluation excavation at the site record the termination of smelting activity at the end of this phase. From then until the present the site remained abandoned and Phase 5 is assigned to the build up of topsoil over time. Reinforcing the series of radiocarbon dates, 350 rim sherds were recovered from the site, conforming to known Middle Historic types and dating broadly to the period 300 to 1100AD. Pottery finds from a number of west-facing sites, recorded during field survey, comprised the same dominant Middle Historic storage jar forms, suggesting that the dating of SM88 holds true across Samanalawewa. Using a combination of radiocarbon, pottery finds and consistency of morphologies, there is no evidence at present to extend the dating of what is clearly an industry earlier or later than the mid-7th to early 11th century AD (Juleff 1998).

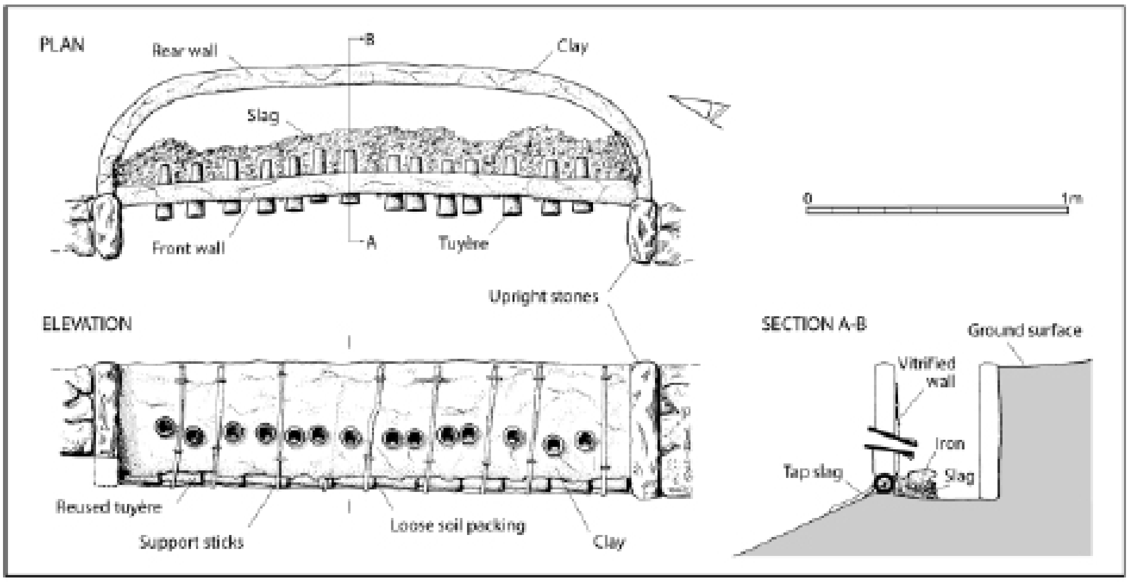

Figure 4: Reconstruction drawing of west-facing, wind-powered furnace with front wall in position.

Figure 5: Experimental smelting in reconstructed furnace, Samanalawewa 2007.

Synchronic and diachronic variations

Against this general background we are now able to examine in more detail the technological changes that took place during the working life of the site and to begin to tease out the character of technological change.

Evidence from the excavation identified three distinct smelting campaigns during phase 2, alternating with brief episodes of localised disuse. The number of furnaces in use during any one campaign varies from three to seven, and in total fourteen furnaces at ten locations operated during the phase (within the area excavated). It is important here to distinguish between furnaces and furnace locations. Furnace indicates a single structure in which a series of smelts took place while a furnace location records a position on the site where a succession of furnaces were constructed, one on top of another. For example, furnace location B on the southern edge of the excavated area (Fig. 3) saw a succession of at least seven furnaces (labelled B1-B7).

The resumption of smelting in phase 4 saw at least six smelting campaigns, with 28 furnaces at fifteen locations. Again the smelting campaigns appear to alternate with localised episodes of disuse. The data allows us to chart the movement of activity across the site in terms of combinations of furnace locations going in and out of use and re-use but no distinct pattern of usage was discernible. For example, furnace location B is used during four of the campaigns but not in succession and in random combination with other locations.

Correlation of wind and furnace

The major changes from Phase 2 to Phase 4 are shown in Figs. 6 and 7, with the most distinct change being in furnace position. During Phase 2 furnaces are constructed both on the leading edge of the ridge and on the marginally flatter summit of the ridge, less than 10m from the leading edge. Their positioning also places some furnaces directly behind others, as in those at locations J and K and B and C. Our understanding of fluid dynamics and CFD analysis enables us to surmise that boundary layer separation off the front wall of the furnace, on the leading edge, would create a lee-eddy effect for some meters behind the furnace (Juleff, 1998, Tabor et al, 2005). With a gap of no more than 5m between J and K, B and C, the airflow over furnaces at K and C would be significantly reduced and turbulent. We know from stratigraphic evidence that furnaces at B and C did operate during the same smelting campaign and we can only imagine that smelting in C would have been sub-optimal at the least.

Whether shielded by another furnace or not, we also know that the winds incident on the flatter area along the summit of the ridge are substantially lower than those at the leading edge. During the monsoon season of 1990, a week-long wind monitoring exercise was conducted on the site and ~450 half-hourly velocity and direction readings were collected from positions along the ridge (see Fig. 3, positions marked with

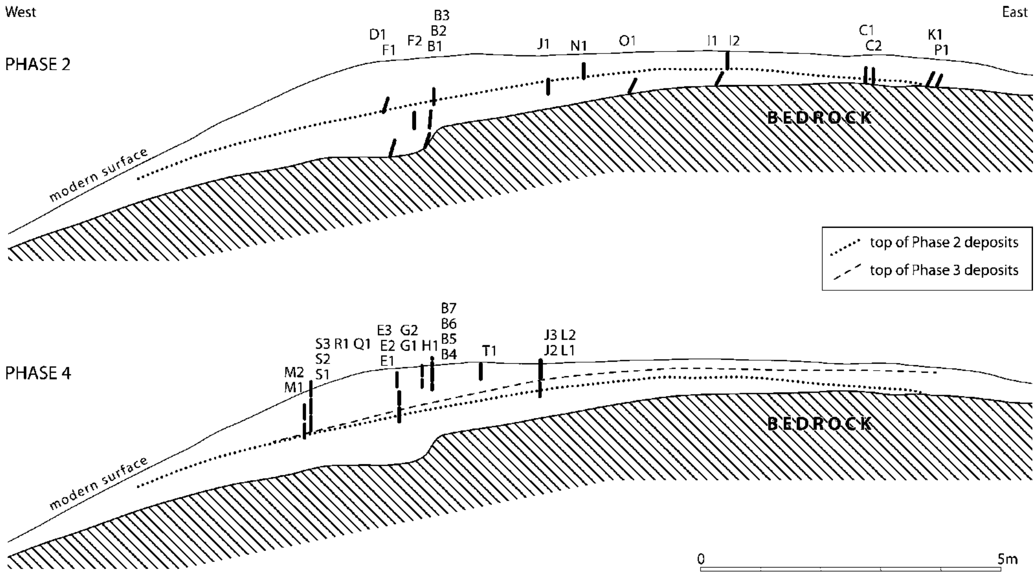

Figure 6: Schematic view of site phasing in section with all furnace wall positions.

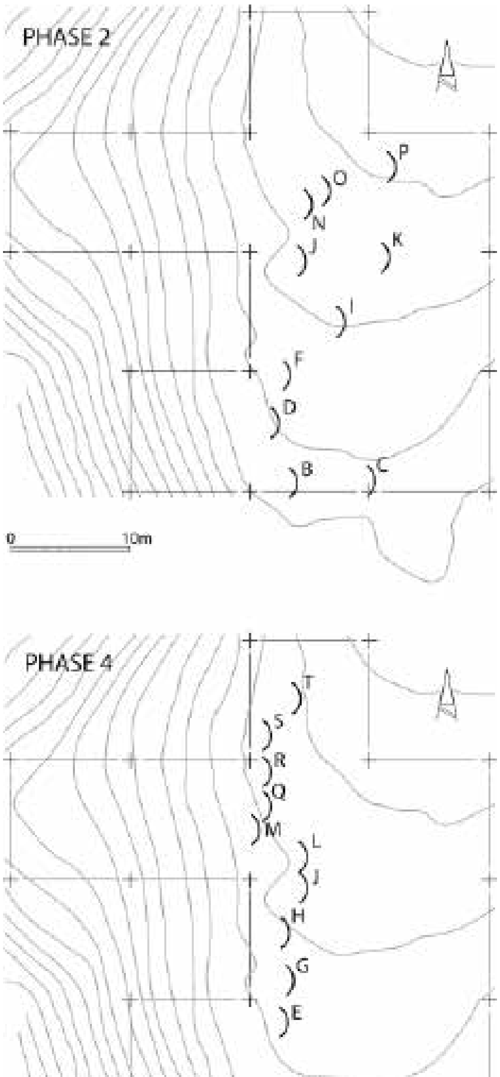

Figure 7: Schematic view of site phasing in plan showing main excavation area and furnace locations.

triangles). At the time the wind data was collected excavations had not taken place and furnace positions were unknown. Thus any correlation between wind records and furnace position only became apparent later, when data sets were compared. The records clearly show that winds recorded at the two positions to the east of the smelting debris on the flat of the ridge have average velocities of 10 and 12km/h, while positions along the leading edge average between 26 and 35km/h (Juleff, 1998). In consequence the furnaces of Phase 2 would have varied in their performance, with those at the leading edge probably being noticeably hotter and more stable.

The response to these observations in Phase 4 is dramatic, with furnaces lining up along the leading edge with no overlap or shielding of positions (Figs. 6 and 7). This principle is adhered to regardless of which of the locations are used during any one campaign. Only location A does not strictly line up with other Phase 4 furnaces within the main excavation area, although its position at the southernmost tip of the ridge (Fig. 3) suggests it would have experienced uninterrupted winds. Three other furnace locations are shown in Fig. 3 outside of the main excavation area, at U, V and W. Interestingly, the 1990 wind data shows that location U recorded the highest average wind speeds at 35.3km/h while at location W, the highest part of the ridge, wind speeds averaged only 26.3km/h. Overall the wind data from SM88 and other sites recorded in the course of the project, demonstrates a high degree of localised velocity variation, undoubtedly determined by local topographies. What is striking is that these phenomena were empirically observed, learned and exploited in the technological development of the site. The micro-level correlation between wind conditions and furnace location is seen at location B, which coincides with one of the 1990 wind monitoring positions. Winds at this position were the second highest of the dataset, with an average of 34.4km/h. Excavation data shows that the first furnace constructed at B was at the outset of smelting on the site in the first campaign of Phase 2. A succession of at least six more furnaces were built at this position spanning both Phase 2 and 4, each furnace being constructed on top of the previous as the surrounding slag and debris accumulated.

The fine-tuning of furnace with the wind can be discerned in a further change from Phase 2 to 4, with a gradual and almost imperceptible shift in orientation from west-facing to west-northwest (Fig. 8). Again, the close correlation between wind and furnace was not recognised until the data sets from two strands of research, wind monitoring and excavation, were finally compared later on in the project analysis. It was mentioned above that the 1990 wind-monitoring exercise included recording wind direction. Of 215 readings, the major component (64.5%) records the wind direction as WNW, with W making up most of the remainder at 33%, N comprising only 1.3% and WSW just 0.9% (Juleff 1998). It was also noticeable that the most sustained periods of velocities above the averages coincide with the wind veering to WNW. The subtlety of this observation, recorded through relatively sophisticated instrumentation, appeared unimportant until the footprint plans of the most complete furnaces were seen together (Fig. 8) and the shift in orientation of the Phase 4 furnaces towards WNW became apparent. The act of re-aligning the furnace structure towards WNW would ensure that the straight front wall of the furnace was presented broadside to the strongest and most constant winds, thereby optimising furnace performance.

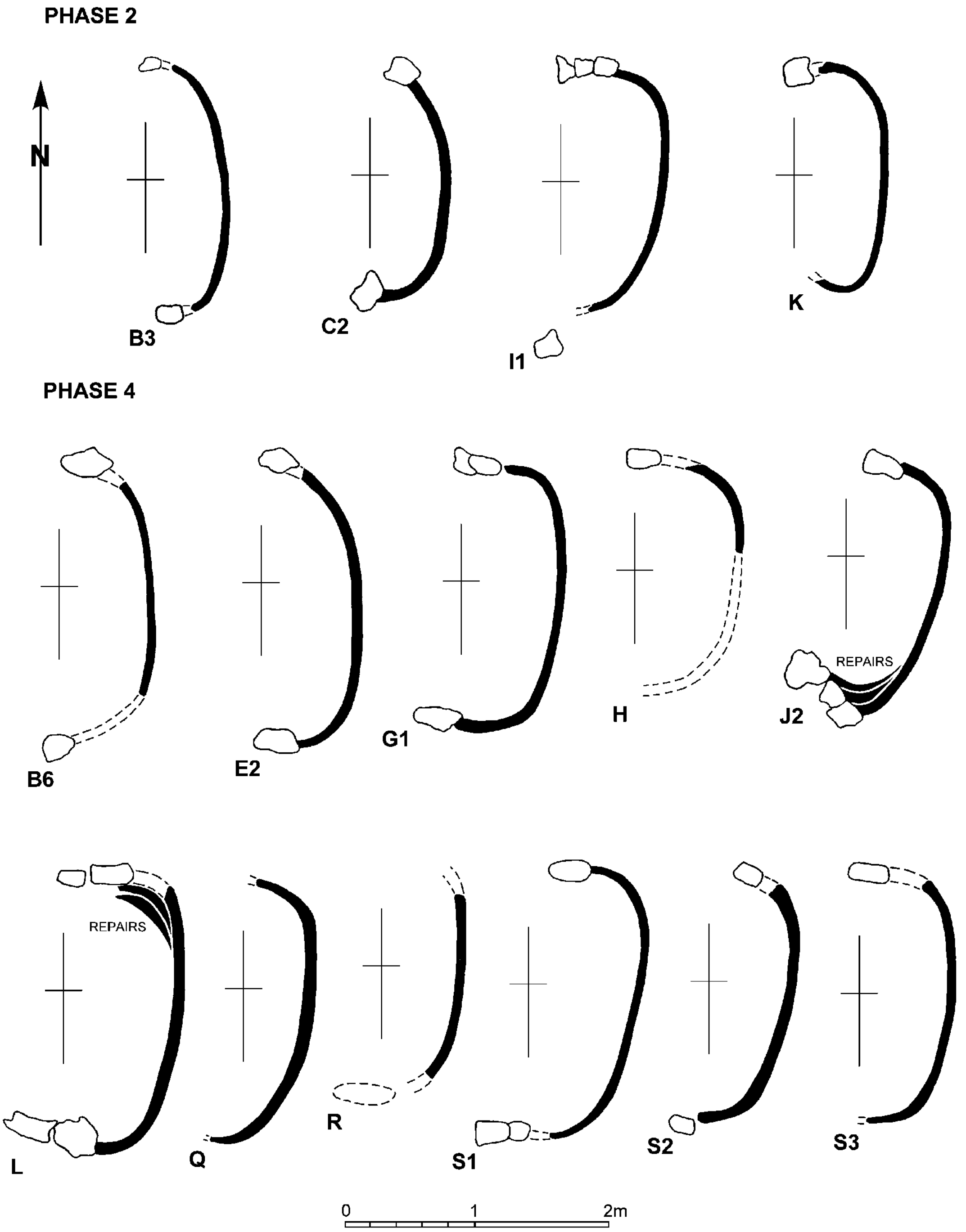

Figure 8: Plans of most complete furnace walls for phase 2 and 4. Note west-northwest orientation and increase in length in phase 4.

Furnace size and construction

Changes are also seen in furnace size and construction between the two phases. Fig. 8 also shows the increase in furnace length from Phase 2 to Phase 4 for the most complete examples. Furnace length is the internal N-S measurement and seven examples were captured for phase 2, ranging between 1.35m and 1.76m, with the mean falling at 1.60m. For phase 4 the range starts at 1.60m and extends to the longest examples at 2.10m, with the mean falling at 1.85m. While furnace length increases over time, depth-in-plan, the distance from the centre of the back wall to the line of the straight front wall, although problematic to record accurately, shows little variation between the two phases. It remains within a range from 0.3m to 0.5m with 0.4m being the mean, and with only one anomalous outlier at 0.8m (Malim et al, 1995, Juleff, 1998). Using both length and depth-in-plan to calculate furnace volume (on the basis that the two curved ends form 90° quadrants of radius 0.4m, leaving a rectangular central section), the overall increase in furnace length from 1.35m to 2.10m represents a 39% increase in furnace capacity.

In the early stages of Phase 2 furnaces were constructed with finesse and careful attention to detail. The clay used was of uniform texture, with few visible inclusions. Back walls were carefully modelled to angle backwards (to the east) and extended into a thin but equally carefully-modelled base to take on a scoop-like form. The angled walls of B1, D1, F1, O1, I1, K1 and P1 are shown in Fig. 6. The wall of B1 is set into a purpose-dug scoop, cut into the bedrock, as was the base of F1. By Phase 4 furnace building is stripped of any unnecessary effort and reduced to uniform functionality, with back walls being universally vertical and crudely constructed from coarse clay, loaded with massive inclusions of readily available garnetiferous granulite bedrock. The walls are poorly finished, displaying uneven plastering marks, and the idea of a clay furnace base is entirely dispensed with. Despite the apparent lack of attention to detail, the furnace walls of Phase 4 are clearly functionally robust and survive as well as those of Phase 2.

Characterising change

The technological developments between the two phases of smelting at SM88 all point to processes of optimisation, with changes made to maximise the interaction between smelting furnace and the most constant and powerful wind conditions. These changes would thereby improve furnace performance and increase output, coupled with changes to eliminate the unnecessary expenditure of energy. The changes observed are tightly proscribed by geographical, environmental, chronological and archaeological means and allow a high-resolution view of events. What is powerfully conveyed is the conscious nature of the changes enacted between the inception of smelting in the 7th century and the abandonment of the site in the early 11th century. This is not a process of random copying-error or diffusion of innovation as described in recent studies of technological evolution, but conforms more closely to conscious and directed invention as creative human behaviour (Fitzhugh, 2002, and see also Rehren et al, 2007, Charlton et al, 2010). The subtle re-orientation of the furnace from west to west-northwest could only have resulted from empirical and scientific observance of regional and local wind and weather patterns, combined with micro-level observation of the furnace in action.

When weighing the case for invention versus innovation, the rate or pace of change may provide useful insight. The changes seen at SM88 took place over a period of 300 to 400 years, perhaps the span of ten or twelve generations. Given the nature of radiocarbon date ranges and the lack of additional precisely datable material, this is the best chronological resolution we can expect. Within this span, the archaeology suggests a steady rate of seasonal site use punctuated by fallow episodes, perhaps when charcoal fuel trees were allowed to regenerate and smelting continued at other nearby west-facing sites. With the changes to furnace design, size, location and orientation comes an increase in activity, with more furnaces constructed and more debris generated (with corresponding increase in metal produced) (Juleff, 1998). Experimental reconstructions of the smelting process have demonstrated the possibility of achieving consistent furnace temperatures of 1450°C and above and of smelting directly to slag-free, high-carbon steels. The rate of optimisation conjures a scenario of cumulative knowledge consciously transmitted from one generation to the next, as well as a kinship between generations that requires custodial preservation of knowledge, as might be expected in craft/caste specialisation.

Interestingly, the dynamic picture of optimisation and increasing focus on maximising efficiency argues strongly for an underlying economic motivation. However, the archaeology provides us with insights that suggest otherwise. As mentioned, Samanalawewa lay at the fringe of mainstream society during the Middle Historic period and there are strong hints that its inhabitants were ethnically distinct from the core Sinhalese society of the lowland plains. There is no evidence in the archaeological record of any material or social gain, in the form of built structures, religious endowments, increased settlement size or material culture, from the development of the highly productive and sophisticated iron and steel industry. The likely interpretation, that the high-carbon steel produced in the wind-driven furnaces of Samanalwewa was one and the same as the sarandibi steel described by the Early Islamic writer, al-Kindi, as highly prized for the making of swords in the Islamic world, has been hypothesized elsewhere (Juleff, 1996, 1998). For the valuable products of the west-facing furnaces to reach end-users in the Near East, a trade network connecting the remote hills of Samanalawewa with coastal ports via the lowland plains must be envisaged, with state officials or entrepreneurs to maintain the link. The lack of evidence for local economic or material gain from this trade suggests that smelting and the production of steel was carried out as tribute to the state or as a contractual obligation. In which case, it becomes more difficult to identify the driving force behind technological change and the process of optimisation. Perhaps what we see here is ultimately innovation and invention inspired by curiosity, natural learning combined with ownership of, and identification with, the technology.

Discussion

The arguments for conscious processes of optimisation based on empirical learning embedded within a specialist craft society developed here, appear to run counter to the overview presented in a recent paper (Juleff, 2009) that examined the development of the west-facing furnace type from its earliest appearance in the 4th century BC in the Samanalawewa area, through other manifestations of long, low furnaces both within Sri Lanka and further afield, across Southeast and East Asia. In this broad sweep the linear configuration of the furnace was traced as a distinct, long-range evolutionary development independent of the means of air supply used to drive the furnaces, e.g. monsoonal wind or bellows, and processes of memetic inheritance were postulated for a divergence in technological evolution which distinguished circular plan furnaces from an Asian tradition of linear furnaces. The data discussed here, however, describes localised, meso- and micro-level processes of adaptation, innovation and optimisation. In conclusion, the potential for detecting and characterising processes of technological change and development exist at a variety of levels. Evidence from field survey and excavation can prove a valuable source of insight into the cultural dynamics of technology.

Acknowledgements

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