Doctoral Thesis

Early Iron Production in Sri Lanka: An Archaeological and Geochemical Approach to the *Yodhawewa* Metallurgical Settlement

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By

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DEDICATION

This thesis is dedicated

to

My Wife Chameera, Daughter Randeepa, and Son Pawara

for enduring the time snatched from them.

CONTENTS

ABSTRACT

Sri Lanka is a South Asian country where ancient metalwork was done using unique methods adapting to the prevailing natural conditions. Very few scientific studies of metallurgy have been conducted in Sri Lanka, and until 2018, no such research was carried out in the northern part of the country. The *Yodhawewa* site is located in the Mannar District of Northern Province and the northern plains of Sri Lanka. Physically, the artifacts pool reflected that it was a historic metallurgical site. This thesis aims to provide multi-disciplinary interpretations of this newly discovered metallurgical site based on the artifacts and nature-facts collected from the *Yodhawewa* research in 2018.

The *Yodhawewa* metallurgical site is close to *Mannar* (12 km), the main port city of *Anuradhapura*, the first and foremost kingdom of Sri Lanka, for over 1500 years. After the historical and geomorphological overview of the study area, research was conducted on a field survey, and vertical excavation at two localities was carried out in March – April 2018. The total survey area was 201,600 m^2 based on the canal and the right bank starting from the *Yodhawewa* reservoir. The collected artifacts (n=14,017) were classified based on the source material, and selected artifacts and nature-facts were used for multi-disciplinary analysis.

The research analyses were mainly based on archaeology and geochemistry disciplines. The constant relative probability was considered in interpreting the archaeological context based on slag, crucible fragments, and furnace factors. The slag had the highest artifact density (n=6,814 of 48.5 kg) on the premises, significantly contributing to the definition of a metallurgical site. Slags represented several production conditions through physical factors such as color configuration, high or low vascularity, oxidation, and glassy or non-glassy texture. According to the archaeological analysis, two types of crucibles were identified; elongated tube-shaped crucibles from the second excavation (Ex-2) area were used to make

crucible steel through the carburization process, and the other crucibles (found in the first excavation area) were used for copper works. The crucible-shaped (lower half-spherical typed) furnace (activated by the 'Bellow method') discovered in the *Yodhawewa* excavations was used for ancient crucible steel production.

Selected soil (n=33) and slag (n=46) samples were analyzed by X-ray fluorescence spectroscopy (XRF) in the Earth Science laboratory of Shimane University. Through soil chemistry, the vertical soil distribution of the study area revealed that copper residues were abundantly mixed with the soil in the first excavation area (Profiles 1 and 2). The iron (Fe_2O_3) average abundance of cultural layers (6.97 wt%) and natural layers (6.55 wt%) of the soil gives clues that the ore was not procured from the premises. However, analyzing the elements of cultural and natural layers through vertical soil profiles and correlations (against TiO_2) evidence that metalworking affected Earth's soil chemistry. With the geochemical analysis of slags, heavy slags converted to HIS *(High Iron Slag*, content of 10-50 wt%), and light slags became LIS *(Low Iron Slag*, 1-10 wt%). The discrepancies in the elemental correlations between HIS and LIS against TiO_2 suggest that they are not the result of the same metallurgical activities.

Significantly LIS shows luster and is transparent by observation of thin section through EPMA analysis. The colors of these samples are highly variable, ranging from light green to dark gray, some with hues of red. Further, some glassy slags have a flowing texture. Noteworthy is an occurrence of olivine in the slags with higher iron contents. Olivine crystals show various morphologies, namely, almost euhedral (0.5-1.0 mm in size), fletching, and acicular, which might be related to cooling mode. Electron probe microanalysis of olivine demonstrates that they are fayalite in composition. Fayalite in the slags is associated with glass, leucite and wüstite. The phase equilibrium examination of olivine and glass in the crystal showed that the crystallization temperature of olivine was estimated to be over 1100 ℃. Leucite forms fine-scale intergrowth with fayalite, suggesting its crystallization at the fayalite-leucite eutectic temperature of ~1128 ℃.

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LIST OF ABBREVIATIONS

BRW – Black and Red Ware

C^{14} Dating – Radiocarbon dating

HFSE – High Field Strength Elements

HIS – High Iron Slag

KOB – Kiri Oya Basin

LIS – Low Iron Slag

LMBA – Lower Malwathu-Oya Basin Archaeology

MSL – Mean Sea Level

Mv - Mahavamsa

RW – Rauletted Ware

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Sincerely,

Wijepala Mudiyanselage Tikiri Bandara Wijepala

July 2022

CHAPTER ONE

INTRODUCTION

1.1 Thesis background, aim, and objectives

There are considerable discussions of the historical and archaeological significance of *Mannar*, a major international port city located 12 km west of the *Yodhawewa* site, from the first century BC to the $13^{th}/14^{th}$ centuries AD (Prickett-Fernando, 2003; Carswell, Deraniyagala and Graham, 2013; Bohingamuwa, 2017). The *Yodhawewa* area has historically been significant due to the agricultural economy associated with one of the largest irrigation reservoirs of Sri Lanka. In October 2017, a reconnaissance survey of ancient settlements near the *Yodhawewa* reservoir revealed the first information about the metalworking site, and formal archaeological field studies were carried out in March-April 2018. This is the first formal archeological observation of historical metalwork in the Northern Province of Sri Lanka.

This thesis was based on the results of archeological and geochemical analysis of the *Yodhawewa* ancient metallurgical site of Sri Lanka. The thesis aimed "to provide archaeological and scientific interpretations of the time and space of ancient metallurgical activities by examining the material culture and natural factors collected by *Yodhawewa* archaeological observations." The aim was approached through several objectives:

(a) Providing chronological interpretations for the *Yodhawewa* historical metalworks in the South Asian context

(b) Explaining the authenticities of resource utilization, technical parameters, and metal usage by analyzing the artifacts and the nature-facts of the site

(c) Presenting the microstructure and phase compositions of the constituent minerals and bulk chemical compositions of iron smelting slags of the study area, and

(d) Defining the technical parameters of ancient metalworking and the supportive environmental conditions by the geochemical signatures of the slags and soil obtained from the *Yodhawewa* archaeological site.

1.2 Thesis structure

This is based on an archaeological study; it also integrates scientific explanations of the artifacts and nature facts uncovered by the *Yodhawewa* archaeological research in 2018. The thesis is composed of four parts;

(a) Part one focuses on the development of the archaeometallurgy discipline and its application with geochemistry in the research approach, an overview of material and technology-based ancient metallurgical practices (focussing on copper, iron, and crucible steel), and the research history in South Asia and Sri Lanka *(in chapter 1)*. A brief discussion is provided regarding the historical and archeological background, significance, and identities of Sri Lanka in the South Asian context, including the macro-environmental setting of Sri Lanka and the geo-environmental setting of the study area *(see chapter 2)*.

(b) The second part provides an overview of the research methodology. Data collection, recording, sample collection, classification, archaeological analysis, and geochemical analysis (XRF, EPMA, C14 dating) methods are discussed in chapter 3.

(c) The third part presents the overall results of the research. The first attention focused on the stratigraphy (in Ex-1 and Ex-2 areas) and material culture discovered through the comprehensive exploration and excavations *(chapter 4)*. A total of 14017 artifacts

were discovered from the *Yodhawewa* site, but discussions were only held regarding selected objects to represent the whole in the thematic context. Furthermore, Chapter 5 describes the results of geochemical analysis of soils and slag and the C^{14} dating obtained from charcoal samples.

(d) Part four of the thesis consists of a discussion of the overall research. This part begins with a detailed discussion of the archaeological discoveries, such as furnaces, crucible steel production, copper work, and iron extraction at the *Yodhawewa* site *(see chapter 6)*. The rest of this section contains a detailed discussion of the geochemical consequences (related to soil, slag, and C^{14} dating) of the research *(chapter 7)*.

The combination of the above four parts collectively provides the structural formation of this thesis.

1.3 Geochemistry applied to Archaeometallurgical studies

Archaeometallurgy expresses an interdisciplinary relation in the investigations of archeology and metallurgy and has become a highly productive scientific field of study over the past 50 years (Killick and Fenn, 2012; Stöllner, 2014). Killick put a fundamental explanation in this regard as follows;

> *"Archaeometallurgy is one of the most interdisciplinary of all branches of historical inquiry. Disciplines that contribute essential insights into archaeometallurgy include archaeology, ethnoarchaeology, economic history, the history of technology, the history of philosophy (beliefs about transformations of matter), philology, social anthropology, mineralogy, petrology, geochemistry, economic geology, extractive metallurgy, physical metallurgy, foundry practice, blacksmithing and goldsmithing, ceramic technology, numismatics, forestry, and limnology"* (Killick, 2014:11p).

Archaeometallurgical studies were primarily based on the material culture of metal production, distribution, and consumption in a long period from prehistoric to pre-industrial times (Craddock, 1995; Killick and Fenn, 2012; Roberts and Thornton, 2014; Hauptmann, 2021). Gradually, archaeometallurgy focused on the process of transformation from raw materials to production from technological, economic, and environmental approaches; however, more recently, it has been recognized that sociocultural dimensions are also a fundamental approach (Chirikure, 2015; Hauptmann, 2021).

The production and use of metals in various parts of the world marked the beginning of 'proto-globalization' that connected regions and continents for millennia (Chirikure, 2015). In recent years, in addition to traditional archeological methods that describe past cultural contexts, the substitution of geochemical analysis has also been identified (Haslam and Tibbett, 2004; Walkington, 2010; Pastor *et al.*, 2016). Soil presents significant factors in the selection and utilization of land for earth-based production in the past (Middleton, 2004; Cook *et al.*, 2006). Soil geochemical analysis results significantly improve archaeological interpretations of old metalworking settlements (Middleton and Price, 1996; Aston, Martin and Jackson, 1998; Wilson, Davidson and Cresser, 2008; Oonk, Slomp and Huisman, 2009).

Among the many metals, copper, bronze, and iron were three revolutionary metal products in the past. The Danish museum curator, C.J. Thompson (1836), proposed the “Three age system,” which is the technical periods (stone, bronze, and iron) of ancient world prehistory using museum objects (Rowley-Conwy, 2004). Although there was insufficient archaeological evidence to prove this chronological order everywhere, iron age evidence has been found in many countries (Srinivasan and Ranganathan, 2004). Access to the production of iron by smelting iron ore was a tremendous technological achievement of pre-modern man. Further, the ancient iron makers developed their technological skills to separate "raw iron" from ores using the bloomery furnace at temperatures around 1200 ^{0}C through long-term experience (Pleiner, 2000). However, iron production is a very long process with three main stages: ore smelting (reduction), refining (bar ingot), and forging (secondary smithing) for the final product (Tylecote, 2002; Yahalom-Mack and Eliyahu-Behar, 2015).

Slag is a liquid by-product removed as waste components (gangs) from metal ores and reactants (fluxes) at high temperatures (Cooke and Aschenbrenner, 1975; Davenport *et al.*, 2002). The interplay of iron oxides and other impurities affects changes in these slags' morphological characteristics and chemical properties (Bachman, 1982; Tylecote, 2002; Blakelock *et al.*, 2009). Although slag emission is defined as a by-product of ore extraction, it should be interpreted broadly. In that, researchers should be understood that slag can result from high-temperature operations such as remelting slag or metal, refining, casting, or forging (Hauptmann, 2014; Johansen, 2014). Such different metal handling methods are reflected in the morphological diversity of the slags. Moreover, the quality of the raw materials used, the physical temperament of the furnace structure, and other environmental and operational parameters can also affect slag morphology (Humphris *et al.*, 2009). However, all these types of slag can be classified into two types; (a) reduction phase slags (tap slag, bottom-furnace slag, and adhering and entrapped bloom slags), and (b) purification phase (reheating) slags (Coustures *et al.*, 2003; Blakelock *et al.*, 2009). On the other hand, metal ore processing and slag waste usually lead to multi-elemental environmental contamination (Dudka and Adriano, 1997).

1.4 Ancient Iron, Copper, and Crucible Steel production in South Asia

Primitive hunting, agriculture, irrigation, architecture, and other aesthetic activities from the prehistoric period have inspired humans to find and use metals. Prehistoric people identified the properties of native metals (copper, gold) from the Chalcolithic period (6000 BC).

Subsequently, steel production was the highest technological stage of metal products that entered the Iron Age (1200 BC) after the Bronze Age (3000 BC) (Tylecote, 2002; Srinivasan and Ranganathan, 2004).

The earliest evidence of iron production in the North Indian region dates back to around c. 2000 BC, and the results of that technological migration from the South Indian region are evident from around c. 1800-1200 BC (Johansen, 2014; Tripathi, 2015). This primitive iron production has been revealed in proto-historic megalithic burial sites in South India and Sri Lanka (Begley, Lukace and Kennedy, 1981; Seneviratne, 1984; Srinivasan and Ranganathan, 2004). In South Asian metalworking, ironsmiths were not closely associated with copper and bronze works; however, it has been noted that traces of copper were not rare at many iron extraction sites (Seneviratne, 1995). Copper extraction was reported in 2000-1500 BC and from South India around 700 BC (Neogi, 1918).

Prakash provided a clear explanation of the fact that steel production has taken place in South India in three modes, namely, *(a)* carburization of wrought iron and melting, *(b)* decarburization of cast iron, and *(c)* process of cofusion (2014: 402-404). The crucible-steel method discussed here is the same carburization method used in the South Indian region. The primary function of crucible-steel production is to absorb a significant percentage of carbon on raw iron, and the result of this process hopes a carbon (high, medium, or low) steel ingot with slag less than the original bloom (Feuerbach, 2002).

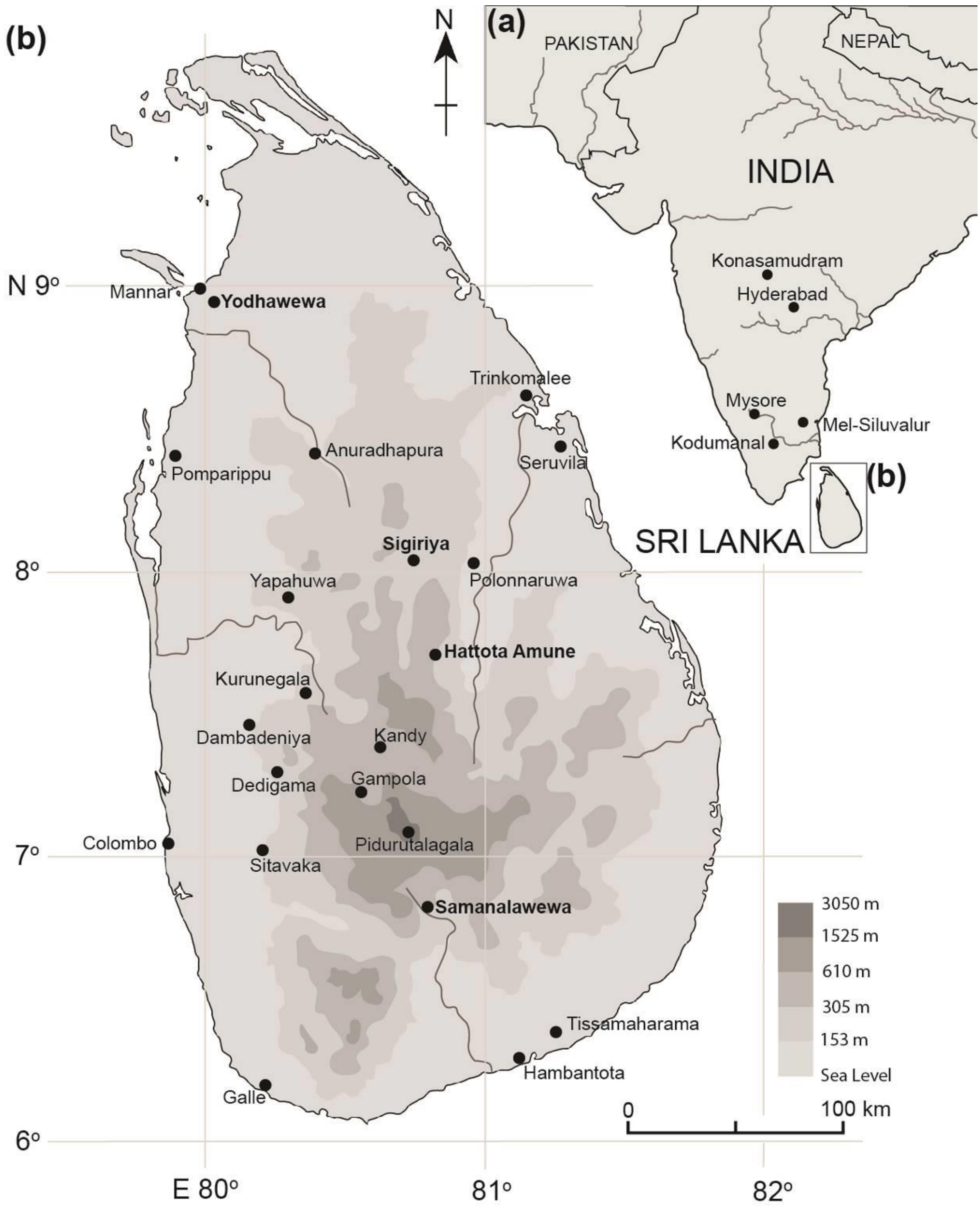

Fig. 1.1. Sri Lanka is located below peninsular India (a) South Indian places mentioned in the text (b) Map of Sri Lanka showing places mentioned in the text. The most significant metallurgical sites of Sri Lanka are mentioned with bolded fonts (after Juleff, 1996b).

The use of crucibles for ancient steel production was an advanced technological transformation in South Asian metal history. The solid state of carburized wrought iron was known as steel or wootz[1] in the historical records. Steels have been highly demanded to produce sharp cutting edges in tooling and flexibility during quenching and tempering (Srinivasan, 1994; Prakash, 2001; Feuerbach, 2002; Woźniak, 2011). The earliest semi-solid crucibles for steel production were dated from 300 BC, mainly from the *Kodumanal*

Fig. 1.1a) South Indian megalithic burial site in *Tamil Nadu* (Srinivasan, 1997, 2013; Sasisekaran and Raghunatha Rao, 2001; Feuerbach, 2002; Srinivasan and Ranganathan, 2004). Crucible technology has also been used for making world-famous Indian wootz steel in Hyderabad (Fig. 1.1a) and South India in the Early Historic Period. Prakash (2014) said only Indian blacksmiths knew the technical standards for producing these crucible steels in that period. Further, Juleff (1990) points out three hubs of Indian crucible-steel production: *Hyderabad, Mysore,* and *Tamil Nadu*.

The International Merv Project (1992-2000) conducted long-term research on crucible-steel production in the *Merv Oasis* region (Turkmenistan) in Central Asia. Researchers compared that the materials and techniques associated with the crucible-steel process in South Asia (Indian and Sri Lankan wootz) and those used in Central Asia[2] were significantly different (Feuerbach, 2002; Srinivasan and Ranganathan, 2004; Woźniak, 2011).

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[1] As mentioned by Hadfield in 1931, the term ‘wootz’ was first discussed in 1795 in a lecture by Pearson at the Royal Academy of Indian Steel (Feuerbach, 2002). After that, the term wootz was also used for crucible steel in parallel.

[2] Wootz was called as ‘pulad’ in the Persian region (Feuerbach, 2002; Alipour, Rehren and Martinón-Torres, 2021; Jaikishan, Desai and Rehren, 2021).

A clear picture of ancient metalworks can be obtained by focusing on the technical production environment used in the metalworking process, especially furnaces, crucibles, molds, lithic, tools, and fuel sources geological and environmental criteria (Hegde, 1973). Ancient metalworkers' workplaces for producing bloomery iron, cast iron, and crucible steel (wootz) are more challenging to identify separately considering refractories, surrounding smelting debris, and other artifacts of metalworking settlements (Gullapalli, 2009). Significant assumptions can be provided regarding the site's use context through the material culture of such a workplace. Researchers categorized the furnaces types from time to time, considering the morphological characteristics; after Banerjee's (1965) and Mahmad's (1988) typologies, Srivastava (1999) proposed the general classification for South Asian metal furnaces; Bowl-shaped, Dome-shaped, and Shaft-shaped (Gururaja Rao, 1970; Prakash, 2001; Saravanan, 2017).

Iron slag cakes are prominent when considering other extraction debris around the iron extraction sites. In the *Banahalli* (c. 400-300 BC) site in *Karnataka*, iron slag cake was found at the bottom of the bowl-shaped furnace. Besides, stone slabs near such a furnace indicate smeltings and forging at this site. One of the oldest iron extraction circular furnaces (c. 700 BC) found at *Naikund* in the *Vidarbha* region was constructed using curved bricks made of refractory clay (kaolin), and the base of the furnace chamber was also made of bricks (Prakash, 2001; Gullapalli, 2009).

Clear examples of circular furnaces in metalworking were found in the southern Indian region. Thus, excavations at the *Kodumanal* ancient metalwork site (1985-1996) revealed more than twelve (12) small circular furnaces associated with an oval furnace used for making crucible steel/wootz (Sasisekaran and Raghunatha Rao, 2001; Sasisekaran, 2002; Gullapalli, 2009). The primary evidence that these furnaces were used for steel production had been provided by crucible fragments discovered with furnace factors. However, until *Yodhawewa* discovered lower spherical (crucible-typed) furnaces used for metalworking had not been discovered in Sri Lanka.

An adequate supply of oxygen is essential to activate metal furnaces, and there is evidence that natural air and artificial methods have been used for this purpose. According to Banerjee (1965), the Ujjain excavations have uncovered evidence that metalworkers used the "bellow method" since c. 500 - 200 BC, and that method was reported to have been used in India until the 19th century for metal furnaces (Sasisekaran and Raghunatha Rao, 2001; Sasisekaran, 2002). Apart from this, the "tuyers" and "blowpipes" that supply air to the furnaces can also be considered the primary factors in identifying ancient metal furnaces in the world (Rehder, 1994; Juleff, 1996a, 1996b, 2015; Srinivasan and Ranganathan, 2004; Gullapalli, 2009; Solangaraarachchi, 2011; Johansen, 2014).

1.5 Historical and Archaeological overview of Metallurgy in Sri Lanka

The earliest evidence of iron use in Sri Lanka coincides with the evidence found in South Indian megalithic burials dating to the c. 8^{th} - 9^{th} centuries BC. Thus, the *Anuradhapura* Citadel excavation (dated c. 834-778 BC), *Aligala* excavation in *Sigiriya*, and *Pomparippu* megalithic burial excavations in *Vilpattu* wildlife reserve (c. 998-848 BC) have been recorded as the oldest evidence from Sri Lanka (Begley, Lukace and Kennedy, 1981; Deraniyagala, 1992; Karunaratne and Adikari, 1994). Juleff (1990, 1996b) and Solangarachchi (2011) provided detailed explanations of the previous research on iron and steel production in ancient Sri Lanka, citing the research and the historical reports of Knox (1681), Davy (1821), al-Kindi (the 1850s), Ondaatje (1854), Tennant (1859), Baker (1885), Coomaraswamy (1908), Parker (1909), Hadfield (1912), and Cooray (1967).

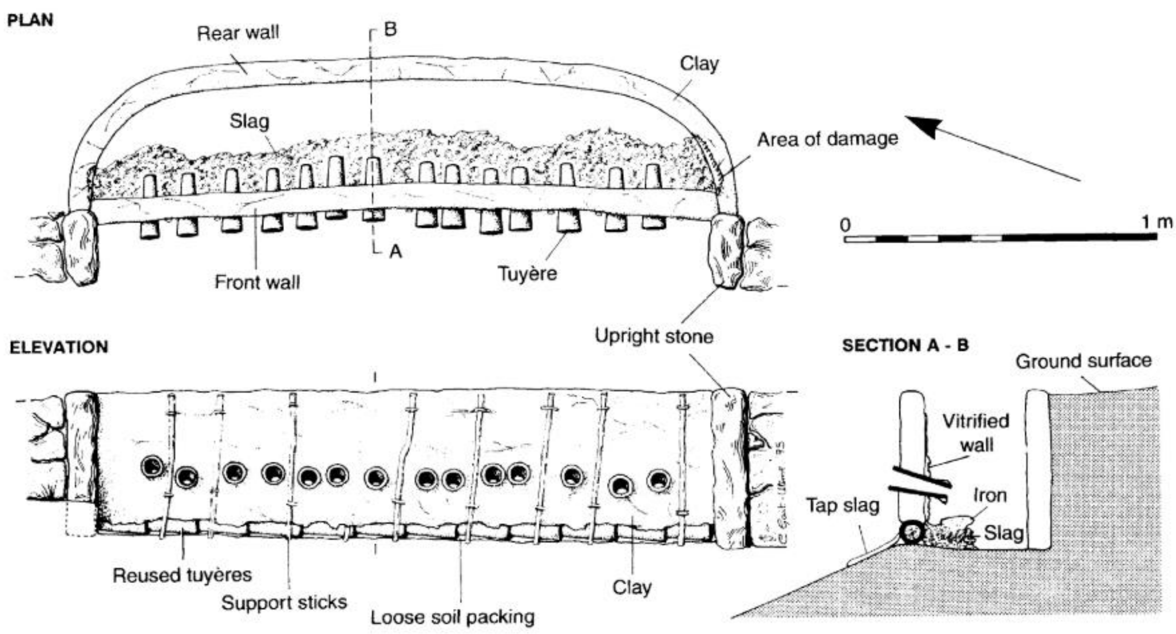


Fig. 1.2 The reconstruction drawing of the *Samanalawewa* furnace. Here the front wall was built abutting both the rear wall and upright stones whereas in archaeological examples it appears it abutted the upright stones only, thereby protecting the rear wall from unnecessary damage (Juleff, 1996b).

The study of ancient iron and steel (wootz) based on resource utilization and production technology by Seneviratne (1985) inspired metal research in Sri Lanka. He later conducted a significant archaeological review of the *Seruvila* copper ore deposit on the east coast of Sri Lanka, suggesting that its copper had even been used for South Asian metal needs (Seneviratne, 1995). Following the above studies, formal archaeological research of the ancient metalworks was carried out by Juleff (1996b, 1996a). She described the iron extraction in the *Samanalawewa* (Fig. 1.1b) area of the *Ratnapura* district as related to the metalworking evidence from the 5th century BC to the 12th century AD. Especially ancient metalworkers of this area used the seasonal monsoon wind power west-facing technology for iron smelting (Fig. 1.2).

Metallurgical evidence found at several sites near the old Kingdom of *Sigiriya* in the *Kiri-Oya* Basin (KOB) during 2004-2006 (Fig. 1.3) has been dated to the 3rd century BC to the 10th century AD (Forenius and Solangaarachchi, 1994; Solangaraarachchi, 2011). That research performed XRD and Electron Microscopic analyses on selected iron ore and slag samples (Solangaraarachchi, 2011). Thantilage's (2008) archaeometallurgical approach, based on historical metalwork (copper and copper alloys) in Sri Lanka, was vital in contemporary metal research. Further, EPMA and EDAX bulk chemical analysis has been used to study metal artifacts collected during the *Mannar* excavations in 1980-84 (Juleff, 2013).

Analyzing metal artifacts recovered from megalithic burials of the 6th/5th centuries BC, scholars point out that copper/bronze technology was used simultaneously with iron in Sri Lanka (Seneviratne, 1984). Thus, the dating of soil samples associated with a circular or semi-circular furnace found during the *Anuradhapura* Citadel excavations (1969 and 1984) has confirmed that it dates back to c. 200 BC. Although it has been suggested that the furnace may have been used for copper casting (perhaps for alloys), no further studies have been carried out in this regard (Deraniyagala, 1972, 1986). Iron slag has also been used as a flux for smelting copper in South and Southeast Asia (Seneviratne, 1995). Therefore, iron slag may be present even in places where copper was extracted. Juleff (2013) has speculated that the copper slag found during the Mannar excavations (1980-84) may have been the waste left over from making copper alloys. Since clear evidence of a copper deposit in Sri Lanka has been discovered in the *Seruvila* of eastern Sri Lanka, researchers have pointed out that copper may have been transported from that deposit to *Mannar* and South Indian copper neds (Seneviratne, 1995; Juleff, 2013; Srinivasan, 2016). This assumption is considerable because Sri Lanka does not have the tin (Sn) and zinc (Zn) metals required for bronze and brass alloying.

Sri Lankan crucible steel also had a significant identity in considering South Asian steel. Quoting Bronson (1986), Srinivasan (1994), and Juleff (1990) point out that Muslim writers such as Jabir-Ibn-Hayyar (8^{c} AD), al-Biruni (11^{c} AD), reported that Indian and Sri Lankan steel was used to make steel swords in many world regions. Especially al-Kindi (9^{th} century AD), in his "Qualities of Swords" book, pays great attention to the superior Sri Lankan *(Sarandibi)* Steel (Juleff, 1996b). Analyzing metal artifacts collected from *Samanalawewa*, *Hattota-Amune*, and *Mannar*, Juleff (1996b, 2013, 2015) pointed out that high-quality steel produced in Sri Lanka may have been exported to such Muslim countries through the ancient *Mannar* port. Ondaatje (1854) and Coomaraswamy (1908) provided eyewitness accounts of crucible steel production in Sri Lanka (Juleff, 1996b; Solangaarachi, 2011), and considerable archaeological attention was paid to crucible steel, concurrent with the *Samanalawewa* research (Juleff, 1996b). In addition to India, Sri Lanka contributed significantly to steel production to make sharp steel tools in the middle historic period.

Significant archaeological evidence of furnaces used in metalwork in Sri Lanka has been uncovered. Juleff (1996b) indicates that west-facing bowl or shaft furnaces of central highlands *(Samanalawewa)* of Sri Lanka were designed as elliptical, circular, or semi-elliptical types (Juleff, 1996b). However, the shaft or domed bloomery furnaces of Sigiriya (Dehigaha-ala-Kanda) were designed in circular shapes with circular or rectangular bases (Solangaraarachchi, 2011). In both types mentioned above of furnaces, the tuyeres are stacked horizontally on the vertical front clay wall, terminating in two vertical side stones. In extracting metal from such furnaces, it is common practice to break the front wall to remove the final product. However, these vertical stones are beneficial to protect the remaining parts when the same furnace is used repeatedly (Juleff, 1996b; Solangaraarachchi, 2011). Dave (1821) and Coomaraswamy (1908) indicate that iron extraction furnaces for regional or personal use in Sri Lanka were built rectangular (box) shaped at or slightly above ground level (using clay) during the pre-modern period (19th - 20th centuries) (Juleff, 1990b; Solangaraarachchi, 2011). The bellow system has also been used for the old metal furnaces in Sri Lanka to provide the oxygen required for combustion, and Knox (1681), Davy (1821), Coomaraswamy (1908), and Parker (1909) have provided more explanations on such furnaces (Juleff, 1996b, 1990; Solangaraarachchi, 2011).

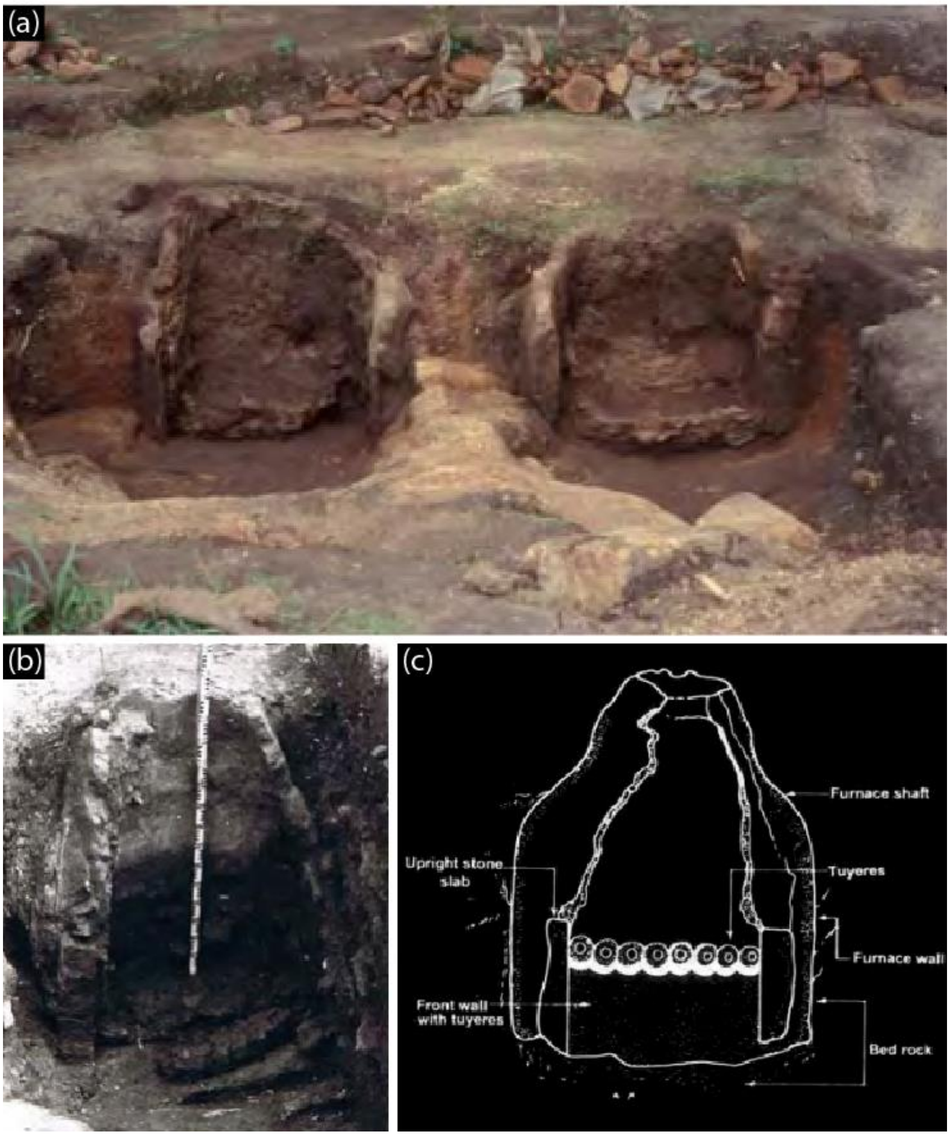


Fig. 1.3 Furnaces discovered from the Sigiriya Dehigaha-ala-kanda site (a) No. 06 and 06B furnaces (b) Excavated furnace No. 27 and presently exhibited at the Sigiriya archaeology museum (c) Reconstructed drawing of the furnace No. 27 (Solangaraarachchi, 2011: 279)

CHAPTER TWO

THE STUDY AREA: ENVIRONMENTAL AND CULTURAL OVERVIEW

2.1. Sri Lanka in the Indian Ocean: Geoenvironmental outline

Sri Lanka is located as an island at the southeastern point of India in the Indian Ocean (Fig. 2.1), centered at approximately 79^o 42' to 81^o 53' East longitude and 5^o 55' to 9^o 51' North Latitude (Fig. 2.2). Sri Lanka extends approximately 440 km from North to South and 220 km from East to West. The total land of the country is approximately 65,610 km^2 (Elliot *et al.*, 2003). Geographically Sri Lanka is divided mainly into three parts: coastal lowlands (up to 269 m above MSL); intermediate uplands (roughly between 269-1000 m above MSL); and mountain-rich highlands (about 1000-2420 m above MSL) found in the central regions of the country (Cooray, 1984). Furthermore, the central part of the central highlands comprises many complex topographies such as ridges, plateaus, valleys, basins, escarpments, and peaks. The highest mountain is Pidurutalagala, with a height of 2,524 meters, and the remaining land is flat except for a few small hills that suddenly rise in the lowlands.

Based on lithological and mineralogical criteria, major and minor structural processes, field relationships, and ages of crust formation, Sri Lanka is dominated by three striking tectonic provinces. Thus, the Highland Complex (3000-2200 Mya), Wanni Complex (2000-1000 Mya), and Vijayan Complexes (2000-1000 Mya) are the main ones, while the Kadugannava Complex (2000-1000 Mya) has been identified as a separate unit (Cooray, 1994; Mathavan, Prame and Cooray, 1999) (Fig. 2.2a).

Fig. 2.1. Sri Lanka in the south Indian Ocean: Satellite image (copyright Geology.com, 2022)

Sri Lanka belongs to the tropical climate zone. The nature of the country's location, topography, seasonal rainfall, winds, relative humidity, temperature, and other climatic conditions strongly influence spatial patterns. Further, The rainfall pattern in Sri Lanka varies depending on the monsoon wind behavior in the Indian Ocean and the Bay of Bengal. Southwest and northeast monsoon winds determine inter-regional climatic seasons in the country (Fig. 2.3);

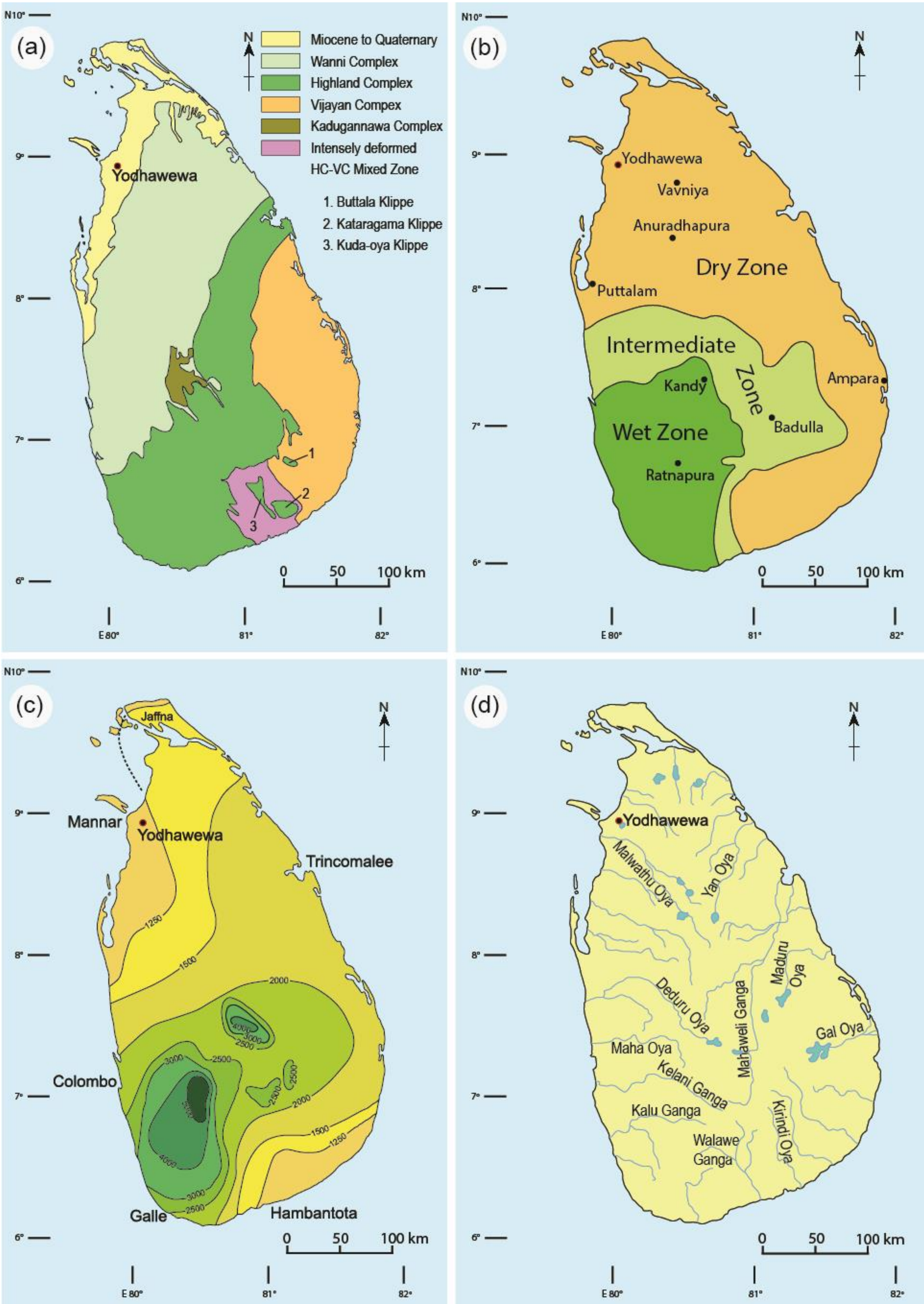


Fig. 2.2. Sri Lanka Maps (a) Lithotectonic units of the island (after Mathavan, Prame and Cooray, 1999). (b) Demarcation of Wet, Dry and Intermediate Zones (after Panabokke, 1996). (c) Mean Annual Rainfall (Isohyets in mm) (after Panabokke, 1996). (d) Rivers of Sri Lanka (after Abeywardana *et al.*, 2019).

- First Inter monsoon season — March to April
- Southwest monsoon season — May to September
- Second Inter monsoon season — October to November
- Northeast Monsoon season — December to February

The mean annual rainfall in Sri Lanka is divided into three geophysical zones – a dry zone, a wet zone, and an intermediate zone (Fig. 2.2b). Average annual rainfall varies from less than 900mm in the driest areas to over 5000mm in the wettest regions of the country (Fig. 2.2c). Further, a hundred and three rivers flowing from the central highlands and high lands of the plains flow towards the sea in a radial pattern (Fig. 2.2d). The average annual temperature in the country ranges from 26^{o} C to 28^{o} C (Panabokke, 1996).

2.2. Historical and Archaeological outline of Sri Lanka

Many scholarly works on Sri Lankan Prehistoric, Protohistoric and historical periods. "The Prehistory of Sri Lanka: an ecological perspective," the book by Siran Deraniyagala, presents a detailed picture of the Sri Lankan pre-written culture through archaeological evidence (Deraniyagala, 1992). Sri Lanka offers the oldest definitive evidence of Homo sapiens human fossils in South Asia, and regional research has provided insights into modern human adaptations and cultural practices over the past c. 45,000 years (Wedage, Amano, *et al.*, 2019). Much prehistoric research has uncovered important facts about the arrival of different ethnic groups in Sri Lanka, their inter-mingling, and their habitations in various regions of the country (Perera, 2010; Wedage, Picin, *et al.*, 2019; Wedage *et al.*, 2020). After the Mesolithic Age, no clear archaeological evidence of the Neolithic or Chalcolithic culture was found (Thantilage, 2008), and Daraniyagala (1992) stated that the absence may be due to the influence of environmental factors in Sri Lanka.

Table 2.1. Chronological representation of the ancient techno-cultural sequence of Sri Lanka

	Period	Age	Reference
I	Mesolithic	ca. 45000 BP - 18000 BC	Deraniyagala, 1992; Wedage, Amano, *et al.*, 2019
II	Mesolithic/Iron Age Transition ——— Post-mesolithic/Neolithic	The chronology of this period has not been identified yet	Deraniyagala, 1992 ——— Adikari and Thantilage, 2007
III	Protohistoric Iron Age*	ca. 900-600 BC	Deraniyagala, 1992; Liyanagamage and Gunawardhana, 1987
IV	Early Historic Age (basal)*	ca. 600-500 BC	
V	Early Historic Age (lower)*	ca. 500-250 BC	
VI	Early Historic Age (mid)*	ca. 250 BC-100 AD	
VII	Early Historic Age (upper)*	ca. 100-300 AD	
VIII	Middle Historic Age	ca. 300-1200 AD	
IX	Transitional Period	ca. 1200-1400 AD	Wijethunga, 2012
X	Late Historic Period	ca. 1400-1948 AD	Dewaraja, 1988
XI	Modern scenario (after the independence	After 1948 AD	Weligamage and Tisdell, 2000

*Proto and Early Historic sequences were presented by calibrated radiocarbon dating from the Citadel of *Anuradhapura* (Deraniyagala, 1992).

Although some research (Wijepala, 1997; Adikari and Thantilage, 2007) has attempted to fill the gap between the Mesolithic to Proto-history transition period (Neolithic/ Chalcolithic culture in Sri Lanka), they have not been able to uncover sufficient evidence to represent such a techno-cultural period. However, archaeological observations have uncovered much evidence of the Proto-historic Iron Age in Sri Lanka (Begley, Lukace and Kennedy, 1981; Seneviratne, 1985; Deraniyagala, 1992; Karunaratne and Adikari, 1994; Dissanayake, 2018; Mendis *et al.*, 2021). Then, the range of human cultural studies of the prehistoric period gradually expanded, and metal studies were also incorporated into technological studies (Bandaranayake and Mogren, 1994; Weisshaa, Roth and Wijeyapala, 2001; Coningham, 2006; Somadewa, 2006; Carswell, Deraniyagala and Graham, 2013). Metal factors have been discussed as one of the significant archaeological discoveries in many types of research based on the proto-historic or historical periods of Sri Lanka.

Deraniyagala (1992) presented a chronologically ancient techno-cultural sequence based on *Anuradhapura* Citadel excavation data. That classification was used in this study because it is most appropriate for studying the early phases in the history of Ceylon (Sri Lanka). However, the period after the Protohistoric Iron Age mentioned in the Deraniyagala classification (Table 2.1) is considered the historical period (mentioned in chronicles and literary sources) of Sri Lanka.

The history of Sri Lanka after the Proto-historic period was based on written sources, ancient chronicles (*Deepavamsa* and *Mahavamsa*[3]), and archaeological facts that provide some positive evidence. The C^{14} datings of context containing pottery included the early Brahmi script from Anuradhapura Citadel, which forwarded the Sri Lankan written history to 600-500 BC (Deraniyagala, 1992).

[3] Sri Lanka's second oldest historical chronicle, the *Mahavamsa* (meaning 'the great tradition'), was written by a Buddhist monk during the reign of King Moggallana-I (496-513 AD) and it was originally written in Pali. The second part of the *Mahavamsa* or extension is called the *Culavamsa*. This thesis draws upon the comprehensive English translations by Wilhelm Geiger (1912, 1925). Reffered both references here as (Mv. Chapter no: Text No.s).

Throughout the early and middle historic periods, a socio-cultural environment based on irrigated paddy cultivation and Buddhist culture was concentrated in the North Central Dry Zone, with Anuradhapura as the kingdom (Paranavitana, 1946; Nicholas, 1959). While the Middle Historic is regarded as the 'classical' period of Sinhalese culture and civilization, evidenced by vast manufactured reservoirs (tanks), irrigation schemes, and the religious monuments of *Anuradhapura* and elsewhere. Moreover, the kings of this era were reported to have maintained diplomatic relations with various world countries (Bandaranayake *et al.*, 2003). Until the end of the *Anuradhapura* Kingdom period, the Mantai port served as its main international port, which will be further elaborated on under the next subtitle. During the reign of the *Anuradhapura* Kingdom, Ruhuna had an administrative dominance centered on *Tissamaharama* in the south (Weisshaar, Roth and Wijeyapala, 2001). The kingdom, which lasted for over a thousand years, marked its end in the 10th century AD due to the influence of South Indian Cholas and the wrong administration of local rulers (Liyanagamage and Gunawardhana, 1987).

After the collapse of the Anuradhapura kingdom, the administrative unit centered on Polonnaruwa started in c. 1017 AD and lasted until c. 1235 AD, known as the Polonnaruwa kingdom period (Mendis, 1998). During this extended period, many historical monuments, religious complexes, colossal sculptures, architectural buildings, craft creations, and various irrigation works were developed in the new area. Kings Vijayabahu 1 (ca. 1055-1110 AD) and Parakramabahu 1 (ca. 1137-1186 AD) were prominent rulers of the *Polonnaruwa* period (Geiger, 1925; Ariyapala, 1997; Mendis, 1998). Since then, the political instability in Sri Lanka has forced the kingdom to move to several short-term locations;

- Dambadeniya (ca.1232-1270 AD)
- Yapahuwa (ca. 1271-1293 AD)

- Kurunegala (ca. 1293-1341 AD)
- Gampola (ca. 1341-1351 AD)
- Dedigama (ca. 1351- 1409 AD)
- Kotte (ca. 1410-1597 AD)
- Sitavaka (ca. 1521-1594 AD)
- Senkadagala-Kandy (ca. 1474-1815 AD)

(Liyanagamage, 1986; Strathern, 2009; Wijethunga, 2012).

Further, religious divisions, insurgencies, internal political turmoil, and the influence of the South Indian Tamil states continued to challenge these statehoods. Sri Lanka was gradually subjugated to the Europeans in such a political crisis.

- Portuguese intervention (ca. 1505-1658 AD)
- Dutch succession (ca. 1658-1766 AD)
- British occupation (ca. 1796-1948 AD)

(Dewaraja, 1988; Abeyasinghe, 1995; Strathern, 2009).

Although the Sinhalese kingdom lost its dominance in the coastal areas due to Portuguese and Dutch power, the Kandyan kingdom continued under Sinhalese rule until the British established a treaty dominion in the central highlands in c. 1815 AD (Dewaraja, 1988). However, Sri Lanka had to maintain one hundred and fifty years of colonial rule. Finally, in 1948, Sri Lanka re-established its independence, becoming the first of the British Commonwealth countries to accept a dominion status Westminster-type parliamentary government (Weligamage and Tisdell, 2000).

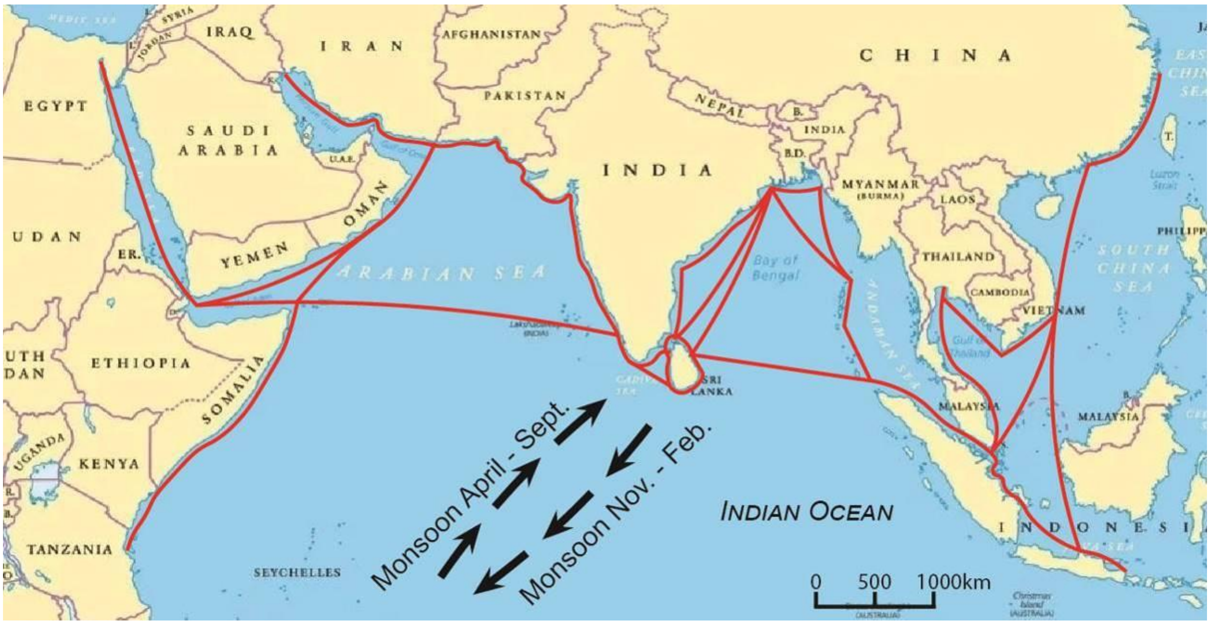


Fig. 2.3. Sri Lanka's connectivity with the Indian ocean trading (after Bohingamuwa, 2017)

2.3. Historical Overview of the *Manar* area

Mannar is the closest point between Sri Lanka and India. The two countries are separated by only eighteen miles between the tips of *Talaimannar* (Sri Lanka) and the *Dhanushkodi* (India). The chain of shoals and sandbanks stretching between, known as Adam's Bridge, has long formed the basis of significant themes in historical literature (Nicholas, 1963). It was the main active port in the western part of ancient Sri Lanka, located in the *Mannar* District of its Northern Province. The port was referred to in the literature and inscriptions; as Mahatittha, Mahātottha, Mahā Tirtha, Mahātota, Mantai, and Mahāvoti. The strategic location of this port has stimulated the use of high value in the past (Nicholas, 1963; Lokubandara, 2003; Carswell, Deraniyagala and Graham, 2013; Kiribamune, 2013; Bohingamuwa, 2017). Accordingly, it was the main trading port close to the ancient capital, Anuradhapura, and was conveniently located on the trade routes between India and the Indian Ocean.

According to the Mahavamsa, the Pandyan consort of Vijaya, the first historical ruler of Sri Lanka (6th century BC), came to the port of Mahatittha (Mv. VII: 58). Further, Panduvasadeva (500 BC), the nephew of King Vijaya, landed near the mouth of the *Mahakanadara* river and is believed to have arrived at the port of Mahathiththa (Mv. VIII: 10-12; Kiribamune, 2013). The Mahavamsa said that 60,000 troops arrived in the reinforcement army of King Elara (161 BC), an army with seven Tamil generals against King Vattagamani Abhaya (103 BC), and with political instability, King Ilanaga fled to Kerala from the port of Mahathittha (Kiribamune, 2013; Bohingamuwa, 2017). Further, Claudius Ptolemy (150-200 AD) referred to Mantai as "Modutti" in the East-West trade (Nicholas, 1963; Francis, 2013). These references show that Mahathittha played a pivotal role in various military endeavors as the main port of the *Anuradhapura* Kingdom at various times in history.

Significantly, King Dhatusena (459-477 AD) initiated large-scale irrigation projects such as the *Yodhawewa* (Manamatta Vapi) to develop the infrastructure facilities for the increasing local population in the *Mannar* port-city region and the periphery (Bohingamuwa, 2017). Cosmas's (6^{th} Century AD) records mentioned a port in Ceylon but not in the name, and scholars acknowledge that it must have been Mantai. He mentioned that the port was used for commercial navigation with countries such as India, Persia, Ethiopia, and Eritrea (Lokubandara, 2003; Bohingamuwa, 2017). An Indian monk named Vajrabodhi had seen 35 Persian ships at Mahatittha, and he traveled with these vessels from Mahathiththa to Canton along the east-west maritime trade routes connected to this excellent harbor (Kiribamune, 2013).

The Mahatittha port has become the main port for maintaining relations with the South Indian states during political instability in Sri Lanka. Thus, the Sinhala prince, who twice invaded Sri Lanka from the Mahathiththa port with the military support of the Pallava kings (Narasinghavarman I and II) during the Manavamma (684-718 AD), ascended the throne on the second attempt (Nicholas, 1959). During the period of King Aggabodhi VII (772-777 AD) of Sri Lanka, the security of the port of Mahatittha was strengthened against invasion by powerful contemporary Pandyas in southern India (Bohingamuwa, 2017). Further, it was reported that by the request of Prince Pandya Varguna, King Sena II (853-887 AD) sent military assistance to the Pandya Kingdom from Mahatittha port (Nicholas, 1959).

The rise of Cholas' power over the Pandyan among the South Indian kingdoms was a major historical event of the 10th century AD. Thus, during the King Kashyapa V (914-923 AD) period, the army left Mahatittha to join the Pandyan army (Bohingamuwa, 2017). King Rajasimghe Pandya, who escaped from the Chola army during the reign of King Udaya III (935-938 AD), came to Ceylon from this port seeking refuge (Mv. LII: 4-10). However, what is significant is that Mahatittha was the port of exit-entry point in both cordial and adversary relations with India.

Two inscriptions dated back to King Kassapa V (914-923 AD) found in the Mantai area have referred to the Mahatittha area as 'Mahaputu' (Nicholas, 1963). The Chola King Rajaraja I, who conquered Ceylon in the face of the weak rule of the last King Mahinda V of the *Anuradhapura* dynasty, had his general (Tali Kumaran) build a temple at Matottam (Mahatittha). Accordingly, it can be assumed that the attack from India targeting the last ruler of *Anuradhapura* must have been from the port of *Mannar* (Mv. LIV: 1-22). Bohingamuwa (2017) points out, quoting K. Indrapala (1971), that several Tamil inscriptions of Sri Lanka also confirmed the socio-economic facts related to the Manthai port city during this period. Furthermore, Nicholas (1963) points out that Sinhala inscriptions (9th and 10th centuries AD), which describe cattle slaughter as a very sinful act, were found in this region.

Even after Polonnaruwa became the new kingdom, the utility of the Port of Mannar did not diminish. Thus, upon learning that King Vijayabahu I (1055/56 AD) was preparing at Ruhuna for the invasion against Chola leaders at *Polonnaruwa*, the Chola king of South India sent two mighty armies twice through the port of Mahatittha and inflicted heavy losses on Vijayabahu (Mv. LVIII: 11-12). However, it is said that Vijayabahu sent a separate force to encamp around the Mahatittha during the last war against the Cholas at Polonnaruwa. Vijayabahu was victorious in this battle as the Cholas did not support additional forces from South India (Mv. LVIII: 25-28; Nicholas, 1963). Later, in 1085, Vijayabahu I (1065-1120 AD) sent two armies to Mahatittha and Matiwaltota (north) to invade the Chola kingdom, but they were unsuccessful.

The Mannar port is also mentioned on several occasions during the reign of King Parakramabahu I (1153-1186 AD), the second most powerful king of the Polonnaruwa Kingdom. Its first note is that Parakramabahu defeated a rebellion at Mahathiththa in the 11th year of his reign. The king prepared to invade the Pandyan kingdom in the same year, but it failed in Mahatiththa (Mv. LXXVI; 7-9). The Mahathiththa port was turned into a beautiful Buddhist city during Nissankamalla (1187-1196 AD) period in Polonnaruwa (Bohingamuwa, 2017). However, the Mannar port has played a significant role in India's economic and cultural interactions and other nations even in the aftermath (Fig. 2.3).

2.4. Archaeological Research of Mannar

Mainly eight archeological excavations have been carried out focusing on the ancient Mannar port city area (Fig. 2.4 and Fig. 2.5) during the last century and a half; as

- 1887 - W. J. S. Boake
- 1907 - John Still
- 1926-28 - A. M. Hocart
- 1950-51 - S. Sanmuganathan

- 1957 - S. M. Kaplan
- 1970 - R. H. de Silva
- 1980-84 - Carswell and colleagues
- 2009-10 - SEALINKS Project

and made publications (Carswell and Prickett, 1984; Prickett-Fernando, 2003; Carswell, Deraniyagala and Graham, 2013; Bohingamuwa, 2017). Boake has released a report with maps and plans, including the geo-environmental location of the old port city of Mannar. It also contains information on the historical period's urban features and religious conditions. It also contains information on slag, pieces of metal, and local and foreign coins. According to his report, most surface artifacts consisted of local and foreign pottery and porcelain (Carswell and Prickett, 1984).

Assistant Archaeological Commissioner John Still was the next person concerned about the Mannar in 1907. Although he spent two weeks there, he desperately noted that he could not find any ruins other than the "brick and mortar buildings ... and the simplest description." He has compiled a list of antiquities found at the end of his investigation to be housed in the Colombo Museum, including iron and copper artifacts (Carswell and Prickett, 1984; Graham, 2013). After, Hocart's excavations and explorations (1926-28) made every effort to obtain a clear picture of the ancient port city of Mannar. He included a series of photographs taken during the survey of the Mannar and a report in 1927 (Carswell and Prickett, 1984).

S. Shanmuganathan (1950), conservations assistant of the Archaeological Survey of Ceylon, undertook an excavation in Mannar. He noted an ancient road forty feet wide from the Eastern gate of the Fort city. Many artifacts were collected from this observation, including some objects of other religions, such as Hinduism. It is also stated that formal research has been done on the human bones and skulls collected in this research. Further, the archaeological records of the research of Kaplan (1957) and Raja de Silva (1970) have not yet been published.

Fig. 2.4. An areal photograph of Mantai by the Survey Department of Sri Lanka (after Carswell and Prickett, 1984)

Carswell, Deraniyagala, and Graham did high-value research on Mannar in the 1980s, and the book "Mantai: City by the Sea" (2013) provides detailed accounts. It can be described as the most detailed and essential publication ever published regarding the historic port city of Mannar. However, Julef's (2013) archaeological and scientific analysis regarding the slag (copper and iron), crucible fragments, tuyeres, refractory clays, non-metallurgical vitrifies, and waste metal droplets found in this research is fundamental. As she points out, the research also provides information on a small metal furnace dating back to 200 AD. Although the iron was being forged to make and repair tools on the spot, the essential function of the complex was to produce copper-based alloys suitable for casting high-value objects. Furthermore, this research reveals clear evidence of copper extraction, and Juleff hypothesizes that copper ore may have been transported from the Seruvila deposits on the east coast.

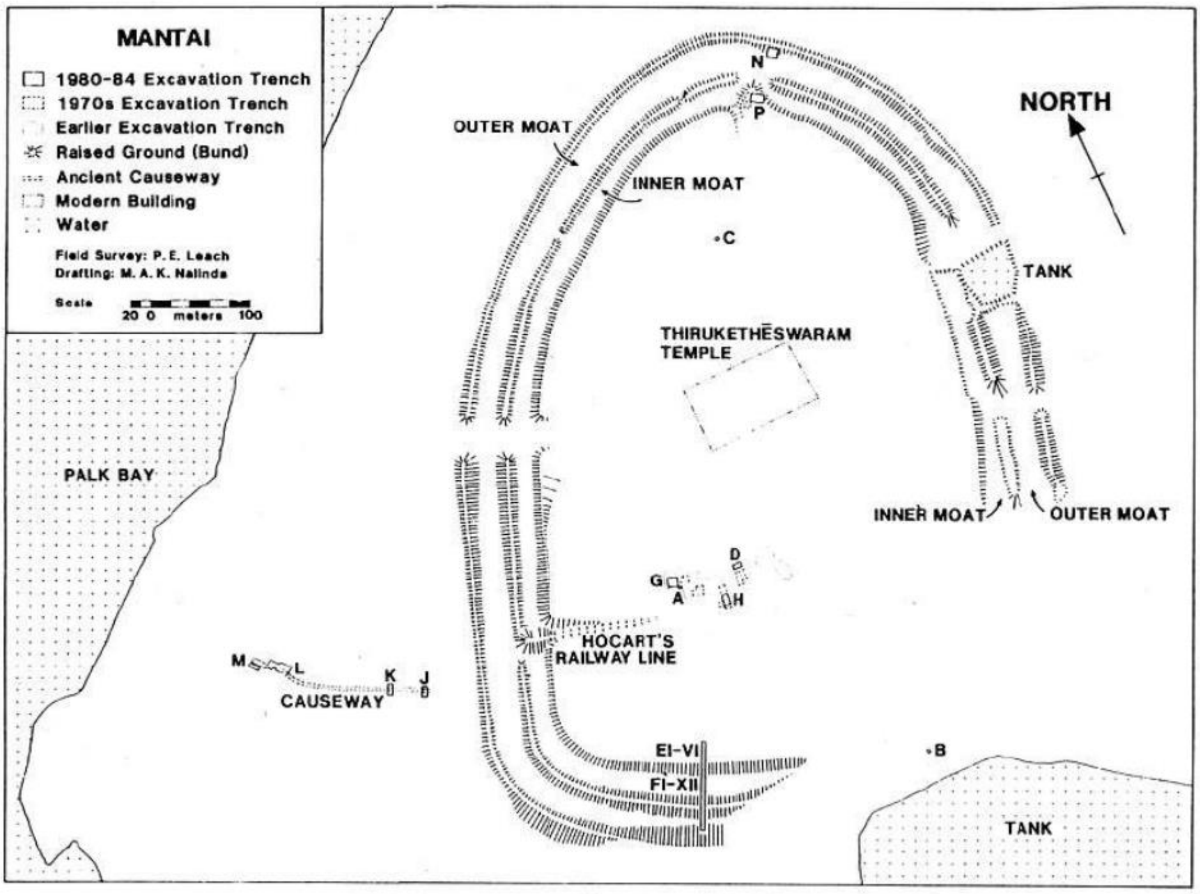


Fig. 2.5. Plan of Mantai showing excavation locations before the 1980s (after Prickett-Fernando, 2003)

The SEALINKS Project, based at the University of Oxford in 2009 and 2010, also excavated in Mannar and found significant archaeological materials. The study of pottery and bead reserves confirms foreign relations with China, Southeast Asia, India, Arabia, and Persia (Bohingamuwa, 2017).

Archaeological excavations in the vicinity of the Port City of Mannar at various stages highlight several key points; *(a)* Containing archaeological evidence of a continuous history from the 2^{nd} century BC to the $12^{th}/13^{th}$ centuries AD, and the earliest evidence uncovered so far dates back ca. 1800 BC. *(b)* Much evidence (earthenware/pottery, beads, pearl, and metal artifacts) has been found of massive trade across the Indian Ocean from China, the Pacific, Africa, and the Mediterranean (Fig. 2.3). *(c)* From the beginning of the Anuradhapura Kingdom to its end and various times after, the Port of Mannar profoundly impacted the political, social, cultural, and religious sectors of Sri Lanka.

2.5. The geo-environmental setting of the study region

The *Yodhawewa* study area is geologically located in the boundary that separates the Miocene limestone and the Vanni complex (Fig. 2.2a). The macro-environment represented the North-Western Dry-semi-arid zone (Pemadasa, 1984). The region consists of three soil distributions; The undulating terrain is spreading eastwardly from the *Yodhawewa* comprising Red Yellow Latosol (45-65%) horizon developed on the underlying Reddish Brown Earth, which has a higher (60-80 %) gravel content in subsoil (Alwis and Panabokke, 1972; Panabokke, 1996). The flat coastal terrain is mainly a composition of alluvial soils (with a high amount of Solodized Solonetz and Solonchaks), eroded surfaces (10%), and grumusols (10%) noticed within the region. The alluvial soil is deposed from the river and flood basins. Regosols on the recent beach and dune sands-flat terrain mainly could be identified in Mannar island (Pemadasa, 1984; Panabokke, 1996).

Although there is a long dry season from June to August, the region receives <1,200 mm of rain annually. The drought affecting this region has a significant impact on soil and vegetation. Temperatures are high throughout the year, resulting in high evaporation and relatively low humidity (65-82%). Dry climatic conditions are frequent; however, floods are reported occasionally. Grasslands and shrubs with thorny bushes are prominent in this region. In the drier parts of the Mannar area, the very dry or semi-arid fasciation consists of the thorny scrub jungle with stunted emergents (Pemadasa, 1984; Panabokke, 1996).

2.6. *Yodhawewa* Archaeological Site

The *Yodhawewa* (Giant's tank) reservoir is 12 km southeast of Mannar ancient port city (Fig. 1.1b). According to the territorial boundaries, the archaeological site is located in the *"Yodhawewa"* village of the Mannar District in the Northern Province of Sri Lanka. The archaeological site is bounded by the Sanctuary from the east, the *Yodhawewa* reservoir from the South, and excess water canal and agricultural lands from the north and west (Fig. 2.6). Archaeological field observations were carried out of the whole area, beginning from the outer spill of the *Yodhawewa* reservoir to the length of 1.6 km area, on the canal and right bank (Fig. 2.7). The GPS coordinates were 08°53'29.5"N and 080°02'53.0"E for the center of the site.

During the civil unrest for approximately the last three decades (1983 to 2009), the region was out of direct governmental administration and facilitated. Since 2009, large development projects have commenced, impacting the archaeological record and exposing the buried remains. The central part of the *Yodhawewa* site was also severely damaged by such impacts. Annual floods further exposed and transported the artifacts.

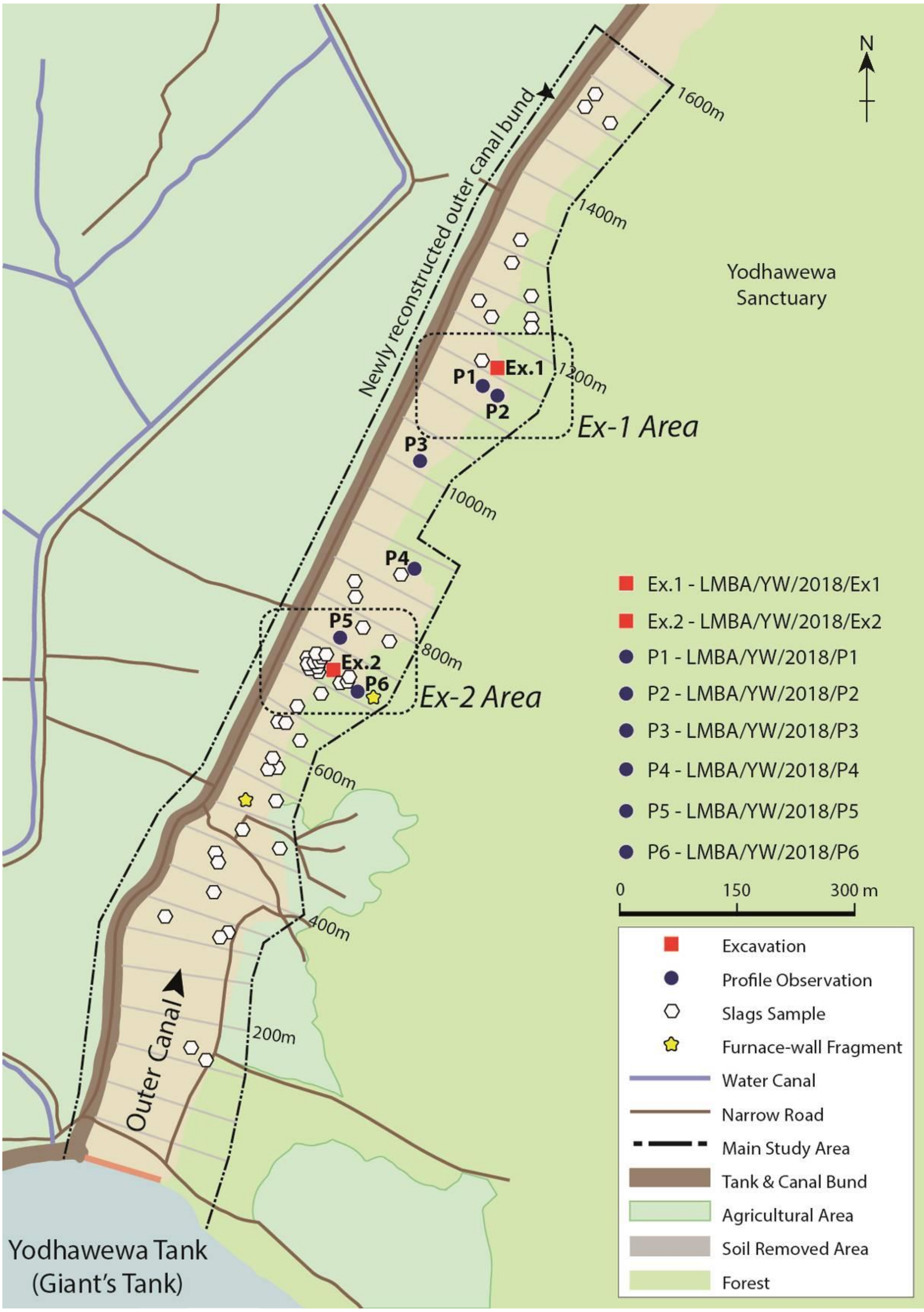


Fig. 2.6. The map shows the entire *Yodhawewa* study area, including two excavation locations, six locations of profile observation, Ex-1 area, Ex-2 area, and analyzed slag and FWF collected locations (after Wijepala, Young and Ishiga, 2021).

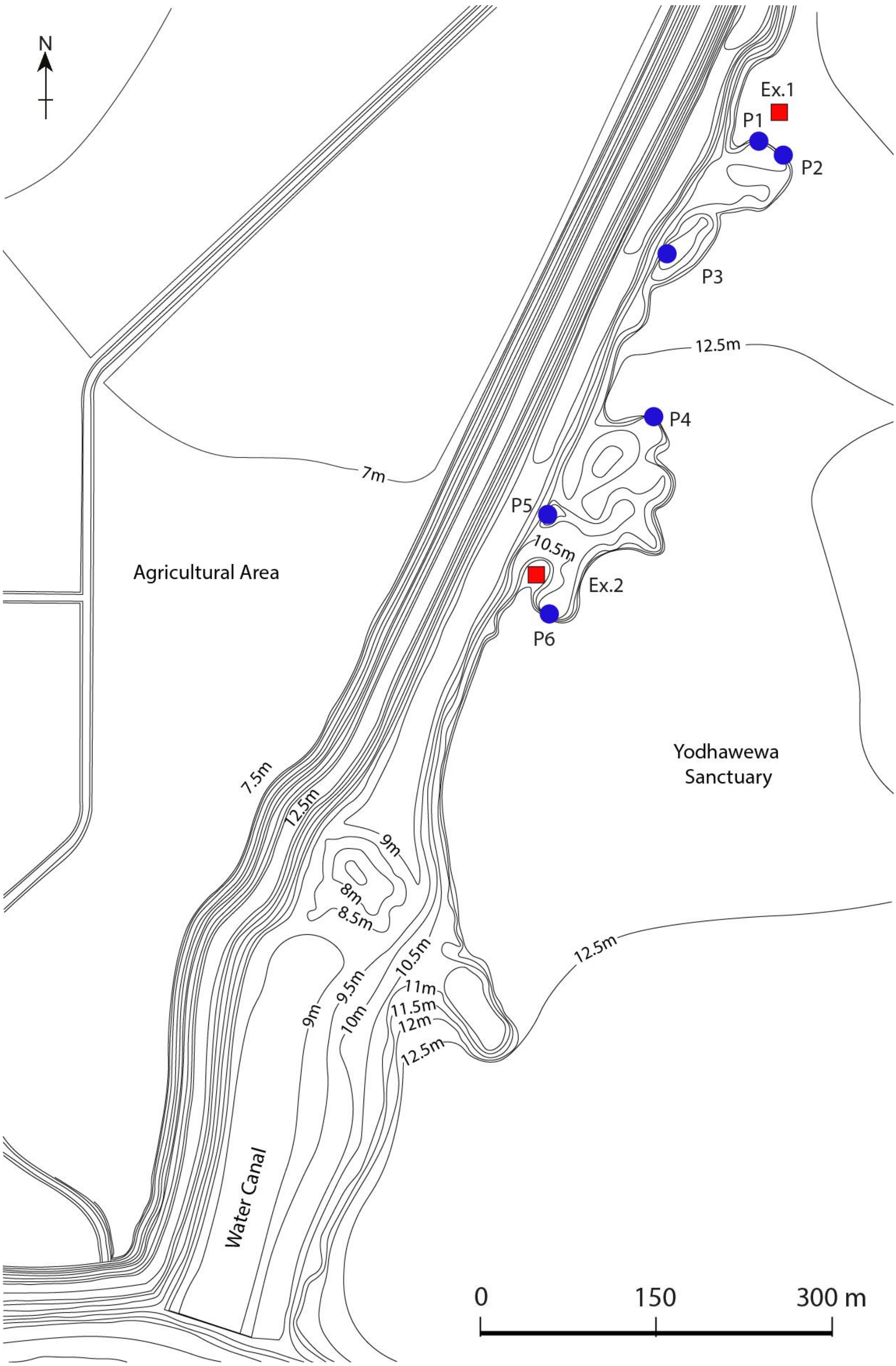


Fig. 2.7 Contour map of the *Yodhawewa* study area, including two excavation and six profile locations (Contour intervals were 0.5m).

CHAPTER THREE

RESEARCH METHODOLOGY

3.1. Data Collection

Accidental encounters with archaeological sites during development projects are common in Sri Lanka. Such is the archaeological site of *Yodhawewa*, which was discovered in 2009 during an irrigation project. Displaced artifacts were also found at the site in October 2017 to look for evidence of ancient settlements around the *Yodhawewa* reservoir (Giant's Tank). Accordingly, with the approval of the Director-General of Archeology of Sri Lanka, the research team of the Department of Archeology and Heritage Management of the Rajarata University of Sri Lanka conducted a field investigation in 2018 to uncover more information about the ancient settlements and related activities.

3.1.1. Archaeological Survey

During explorations in 2017, scatters on the surface of the archaeological site were identified as a metallurgical archaeological activity. Accordingly, in March-April 2018, planned excavations were conducted by our research team, and surface sampling was done along the right bank of the water canal length of the area of 1600 m. For formal exploration, the study area was divided into 32 sampling units in an interval of 50 m length (Fig. 2.6).

Detailed field notes were prepared according to the landscape changes, the artifacts distribution pattern specifics, and the cultural and natural formation contexts. Ultimately, no measure was taken to collect all the artifacts; significant collection maintained the site's wide image. Therefore, the samples were collected only to view the nature of cultural phases and contents. Although many artifacts were found in the canal during the survey, they were most likely to surface during the outer canal reconstruction project. If not, they must have been displaced during periods when the outer canal was active by the excess water.

During the initial observation, several irregular vertical soil profiles were observed in the center part of the study area. Regular profiles (100cm / 150cm x 15cm) were observed at such locations, and the field was named Profiles 1 - 6 (P1 - P6) for ease of study to identify soil layer patterns and artifact scatter (P1 - P6). The location of the observed profiles is indicated by a series of photographs in a study area map in Appendix 1.

3.1.2. Archaeological Excavations

The location for the first excavation pit (LMBA/YW/2018/Ex1) (Fig. 3.1) was selected considering the scatter of surface artifacts in the 1150-1200 m sampling unit. The excavation purpose was to sample (nature and culture facts) and record the surface-to-bottom debris deposit (maximum 0.50m to 0.80m). During 15 days in March 2018, excavation was carried out using the vertical method and systematically identified the layers and context; reported stratigraphically. Furthermore, the excavation pit was divided into nine (9) sub-sections of 1 meter each following the grid system. All the sample materials obtained during excavation were weighed, sorted, and stored separately in polythene bags.

The structural elements of the design and other metalwork debris found in the 700-750 m samples raised an exploratory need to determine the nature of the metalworking activity. Thus, the second excavation (LMBA/YW/2018/Ex2) (Fig. 3.2) was carried out for 17 days in March-April 2018 and systematically sampled and recorded all factors. This excavation contributed to the identification of the nature and physical parameters of the metal furnace. This excavation was run from 0.60 m to 0.75 m from the surface level. The second excavation's soil layers and assemblages were given a new series of context numbers, and all other functional parameters were the same as in the first excavation. No further excavation was carried out below the second cultural layer as no cultural evidence was found anywhere in the natural deposits below profile six. At the end of the excavation, the remaining artifacts, including the furnace, were safely covered with plaster of Paris and transported to the Archaeological Laboratory of Rajarata University of Sri Lanka for further observations in May 2020. The excavation process followed the established legal procedure (Standing Order No. 488 of the Department of Archaeology, Sri Lanka). Detailed statements, illustrations, measurements, and photography were used for the detailed contextual reporting.

3.2. Recording Method

Context-Harris matrix recording system was implemented to document the locality of the excavations' material culture, layers, and features. During recording, soil profiles were drawn focusing on surface and subsurface features, and context details and matrix were recorded. Sub-surface layers and features were numbered as contexts in ascending order, and the context matrix recording method was followed to register soil layers and other archaeological features (Harris, Brown III and Brown, 1993). For horizontal recording, 1:10 scale drawings were used, and vertical profiles were drawn at the end of the excavations. Dry sieving (3 mm) and flotation were followed to extract a maximum of the tiniest fraction of artifacts and charcoal from the different contexts.

Artifact types, the amount discovered from each sampling unit, and the date were regularly reported during and after the exploration. Slags are common in the site, and other metallurgical facts include crucible (base, body, rim, and lid) fragments, furnaces parts, tuyeres, metal objects, and other refractories. In addition, pottery, beads, pieces of glass, and other stone artifacts (such as grinding stones) are recorded individually but are not discussed at length here.

Fig. 3.1. During the *Yodhawewa* Ex-1 (Photo taken from South to North) © *Yodhawewa* excavation 2018.

Fig. 3.2. During the *Yodhawewa* Ex-2 (Areal photo view) © *Yodhawewa* excavation 2018.

The GPS (Garmin Montana 610 Handheld GPS) and Total Station (LEICA FLEXLINE TS06plus) were assisted in taking accurate location and measurements in the field. The *Munsell Soil Color Charts* (2009) were used to identify soil colors, and the Nikon D7100 DSLR camera was used for all photographic recordings on the site, always in daylight. During the entire fieldwork, science books (for context recording and 1:10 plans), sample recording books (Soil and Charcoal), Stratification (Harris-matrix) charts, and NoteBook for general notes were maintained in the field.

3.3. Artifacts collection and classification

Surface-scattered artifacts were collected to represent each sample unit to present a detailed and unbiased picture of the cultural and natural phenomena of the site following the survey procedure published by the Sri Lanka Department of Archaeology in 2015. The artifacts collected during the excavations vary in manufacture and function. Artifacts, such as sherds of refractory clay, crucible fragments, and slags found in the field, were collected without attention to classification. Other artifacts, such as foreign porcelain and coins, were collected and maintained in detailed field records—packed into the zip-lock bag after numbering. However, all the artifacts collected during the two excavations were included in the specific records of both the collection and the classification stages.

Many archaeologists consider Classification and typography to be an integral part of archaeological methodology and are used as a primary analytical strategy (Adams and Adams, 2008). The primary purpose of the antiquities classification was to manipulate objects to make it easier to identify ancient human activities associated with the site. First, collected artifacts were washed through distilled water and dried in the sunlight until all the water was removed (Fig. 3.3). Then, attributes were clustered based on three characteristics:

(a) Material of manufacture - Stone, clay, metal, glass, ceramic, bone, and shell were used for these artifacts, as found in the present study.

(b) Specific identities - Crucible Fragments (base, body, rim, lid), Earthenware (rim, body, decorated, Black and Red ware, Rauletted ware, Gray ware, Plain ware, etc.), Beads (disc, short, standard, long, etc.).

(c) Collected Location - Excavation 1 or 2, Profile 1-6, or Survey (contexts and layers)

Fig. 3.3. Dry all the artifacts in the sunlight after washing © *Yodhawewa* excavation 2018.

3.4. Archaeological Analysis

The collection of artifacts was the main factor in discussing the actual metalwork, technical parameters, and resource utilization pattern related to the *Yodhawewa* site to consider the structural nature, quantitative factors, and associated smelting debris to identify the actual utility of the *Yodhawewa* furnace. Accordingly, the data were compared with contemporary metal research in South Asia to elucidate the ancient metallurgy of *Yodhawewa*, comparing the macromorphological characteristics of the acquired materials. Collected metal artifacts (such as crucible fragments and slags) were compared with other research on iron smelting, copper-related metalworks, and crucible steel production. Minor artifacts such as waste metal droplets (less than 1 cm) were not recorded or included as artifacts here. Known ore samples and notes from previous research on local ores were examined to clarify the raw materials used for metal extraction. Furthermore, the other artifacts were also briefly described here to review the overall findings of the *Yodhawewa* site. compare or challenge

3.5. Geochemical Analysis

3.5.1. Soil Sampling

The overall soil sampling of the *Yodhawewa* site was based on five selected locations; first excavation pit (Ex.1), second excavation pit (Ex.2), and selected three profiles (P-1, P-2, and P-6). Topographic, geologic, aerial photographs, land use maps, and artifact distribution patterns were also helpful in determining corresponding soil sampling locations. The "Marshalltown steel pointing hand trowel" was used to collect thirty-three soil samples by cleaning alcohol. The verticle linear method was used for the sampling and digging into the wall for an average of 50 - 75 grams. We have considered removing the plant residues from the sample, packed in zip lock polyethylene bags after being numbered outside each sample, and maintaining detailed records in a field notebook. Two Soil samples from the first and second cultural layers on the east wall of the first excavation were collected (Fig. 3.4a, c).

Twenty-one samples were collected from three locations of the secondary excavation pit to represent essential detail of the entire soil layers. Seven samples (Ex.2:15 to Ex.2:21) were obtained from the cross-section of the ninth (9) context (Fig. 3.4b, d, e), including the clay and firebrick fragments attached to the furnace wall. The other 14 samples were collected from two vertical sampling points near the main furnace structures (Fig. 3.4b,f,g). The soil sampled represents profiles as n=3, n=3, and n=4 on P1, P2, and P6, respectively (Fig. 3.4h). During the archaeological field study, two natural surface layers of the Ex.1 area (Ex.1, P1, and P2) were identified; both layers with similar characteristics were considered a single surface natural layer in this research. The entire research designated the specific soil colors following the Munsell Soil Color Charts (2009).

Table 3.1. Total findings of *Yodhawewa* research in 2018.

Collected Area	Slags	Crucible Fragments	Furnace wall Fragments	Metal Objects or Fragments	Earthen ware Fragments	Other artifacts*	Total
Ex.1	32	26	1	27	2110	67	**2263**
Ex.2	6226	326	193	31	1217	25	**8018**
Profiles 1-6	188	65	47	ND	1158	ND	**1458**
Survey	368	63	10	12	1634	191	**2278**
Total	**6814**	**480**	**251**	**70**	**6119**	**283**	**14017**

*Beads, Glass fragments, Lithic artifacts, Floral and Faunal remains were represented in the category of Other artifacts. ND=Not Detected.

3.5.2. Slag Sampling

Out of the 6814 slags acquired from the entire *Yodhawewa* research (excavations, exploration, and profiles), three hundred and sixty-eight samples (368) were collected from the exploration (Table 3.1). Considering the morphological variations, 46 slag samples were selected for geochemical analysis (see the map in Fig. 2.6 for slag sampling locations). Further, two furnace wall fragments (FWF) were used for scientific analysis from 251 pieces to identify their geochemical signatures. Selected slag sample-related geochemical analyses were conducted at Shimane University in the first quarter of 2019.

3.5.3. X-ray Fluorescence (XRF) Analysis

X-ray fluorescence spectroscopy (XRF) was used to analyze the soil and slag samples. As a first step, all samples were oven-dried at 120°C for 24 h in Sri Lanka. After transporting to Japan, the samples were oven-dried at 160°C for 48 h. Then about 50 grams of each sample was ground into a fine powder (<63 μm) with the help of an automatic agate mortar and pestle grinder. The powdered samples were compressed into briquettes using a force of 200 KN for 60 s. The concentrations total of 22 major (TiO_2, Fe_2O_3, MnO, CaO, and P_2O_5) and trace elements (As, Pb, Zn, Cu, Ni, Cr, V, Sr, Y, Nb, Zr, Th, Sc, TS, F, Br, I) were then specified by X-ray fluorescence spectrometry using a Rigaku RIX-2000 spectrometer equipped with an Rh-anode tube in the Shimane University. Kimura and Yamada (1996) followed analytical methods, instrumental conditions, and calibrations. The analytical results were acceptable compared to the standard JSl-1 values proposed by the Geological Survey of Japan, and the average errors for all elements were ± 10% relative (Potts, Tindle and Webb, 1992).

3.5.4. Electron Probe Micro-Analyzer (EPMA) method

Chemical compositions of olivine and associated minerals were examined using an electron probe microanalyzer (JEOL JXA-8530F) in the Department of Earth Science, Shimane University. Analytical conditions applied were 15 kV accelerating voltage, 20 nA specimen current, and 1~5 ㎛beam diameter. Glass was analyzed with a lower specimen current of 10 nA. The matrix correction followed the method of (Bence and Albee, 1968). Representative chemical compositions of olivine and other minerals are listed in Table 3.2.

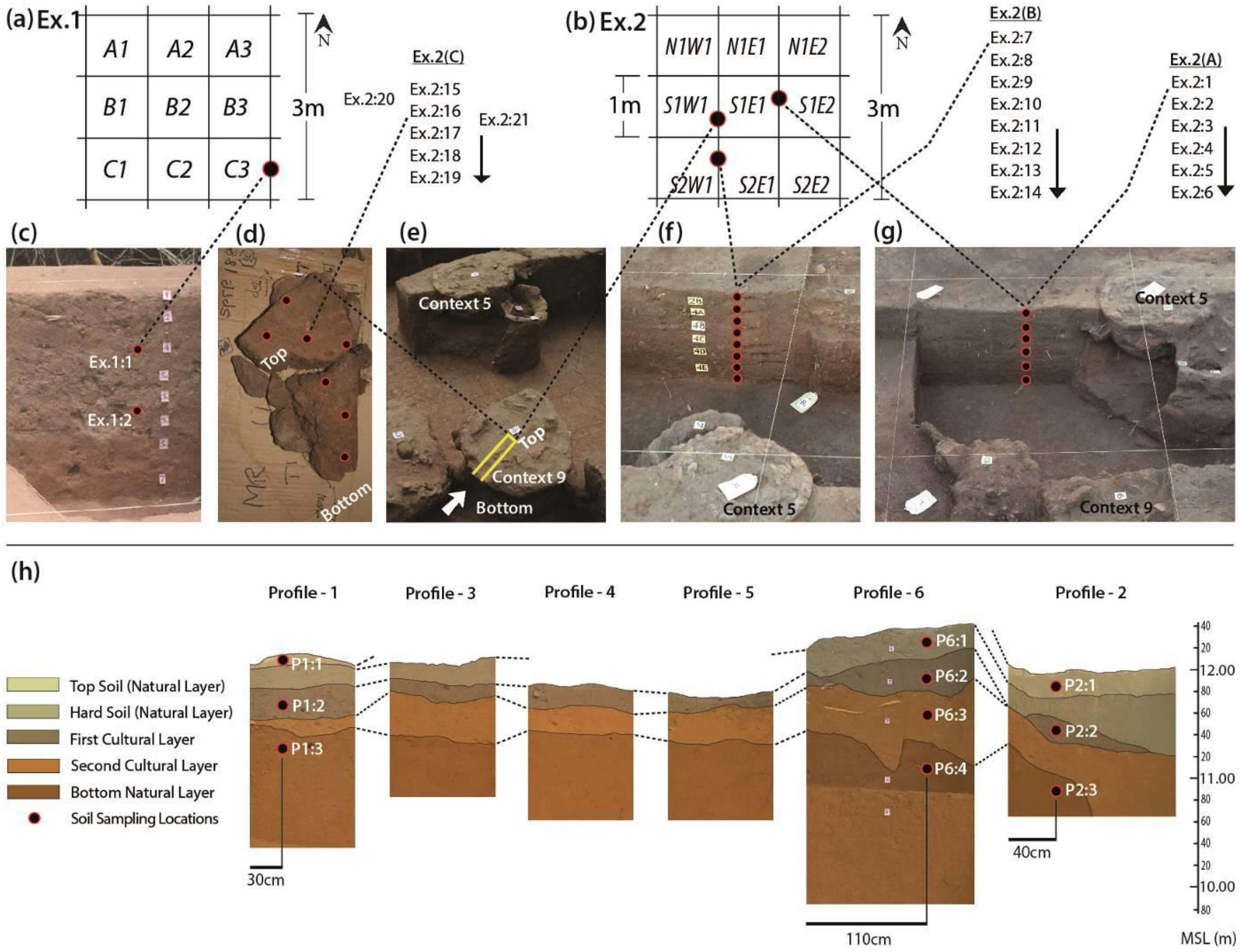


Fig. 3.4. Soil sampled locations (a) Sketch of Ex.1 pit including 3 x 3m subdivisions and soil sampling location (b) Sketch of Ex.2 pit including three soil sampling locations (c) East wall [section] and soil sampling locations (d) Section divided from context-9 including seven soil sampling locations (e) Top view context-9, and the area reserved for cross-section sampling (f) Eight soil sampling locations S2W1 East wall of Ex.2 (g) Six soil sampling locations S1E2 West wall of Ex.2 (h) Major soil layers distribution pattern of six profiles of *Yodhawewa* site including ten soil sampling locations of P1, P2, and P6.

Table 3.2. Chemical compositions of minerals in slags (Ishiga *et al.*, 2022)

material	numbers	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total
olivine	22	29.22	0.04	0.11	0.01	69.76	0.10	1.33	0.49	0.02	0.02	101.10
	STD	0.22	0.03	0.02	0.01	1.74	0.02	1.10	0.08	0.02	0.01	0.39
wustite	2	0.71	2.40	0.88	0.02	95.46	0.00	0.03	0.04	0.01	0.07	99.63
leucite	3	53.69	0.09	21.53	0.00	3.58	0.01	0.01	0.83	0.77	19.03	99.54
glass	6	39.33	1.28	13.34	0.01	24.75	0.02	0.01	9.37	2.10	6.89	97.10

3.5.5. Carbon 14 Dating

Artifacts acquired in the field contribute more to the achievement of the main objectives of the research, but absolute datings further enhance their quality. Six charcoal samples collected from Ex.2 were dated using Accelerator Mass Spectrometry (AMS) from Beta Analytical Laboratory, USA. All the conventional radiocarbon ages and sigmas were rounded to the nearest ten years based on conventions of the International Radiocarbon Conference in 1977. The absolute datings result, including ± 30 years in the date determination, and the reported results were accredited to ISO/IEC 17025:2005 testing accreditation PJLA #59423 standards. In the archeology field, in addition to absolute datings, relative dating also contributes to making interpretations. Thus, pieces of Porcelain, Roulette Ware (RW), Black and Red Ware (BRW), and some Indian metal coins found in the *Yodhawewa* site were used for the relative chronological discussions.

CHAPTER FOUR

ARCHAEOLOGICAL RESULTS: MATERIAL CULTURE OF THE *YODHAWEWA* SITE

4.1. Stratification of the Study Area

The study area had a varying topography for the most part, but there were similarities in areas named Ex-1, P1, and P2 (Fig. 3.4h; Fig. 4.2; Table 4.1). The general topography and the underground layering of the premises were given through six profiles and observed during the pre-excavation observations, revealing five main soil layers. The maximum recorded depth of exposed profile faces was 240cm from topsoil. The soil found on the surface level or at the 1-40 cm of depth was the Reddish Brown Earth, and reddish-brown soil (Dull Reddish Brown Layer) was available at the lower horizons. The two layers deposited between the upper two (or one) layers contained anthropogenic provenances found only in the Reddish Brown Earth. Archaeological content was not found in the Dull Reddish Brown soils on the lower horizon.

The first excavation reported five main layers and seven contexts (Fig. 4.1). The stratigraphic composition is similar to the profiles reported during the exploration, where two anthropogenic layers (Layers 3 and 4) were sandwiched between the top and bottom, and natural layers (Fig. 4.2). Here third (3) and sixth (6) contexts were sub-layers (Fig. 4.3a).

Table 4.1. Equivalence of soil distribution in the surveyed region. (ND=Not Detected)

Soil colours	Layers or contexts of each excavation and profile							
	Excavations Context No's		Profiles Layer No's					
	Ex-01	Ex-02	P.01	P.02	P.03	P.04	P.05	P.06
7.5 YR 3/4 Dark Brown	1	ND	1	1	ND	ND	ND	ND
7.5 YR 3/3 Dark Brown	2	1	2	2	1	ND	ND	1
5 YR 3/3 Dark Reddish Brown	4	2	3	3	2	1	1	2
5 YR 3/4 Dark Reddish Brown	5	4	4	4	3	2	2	3
5 YR 4/4 Dull Reddish Brown	7	21	5	5	4	3	3	4

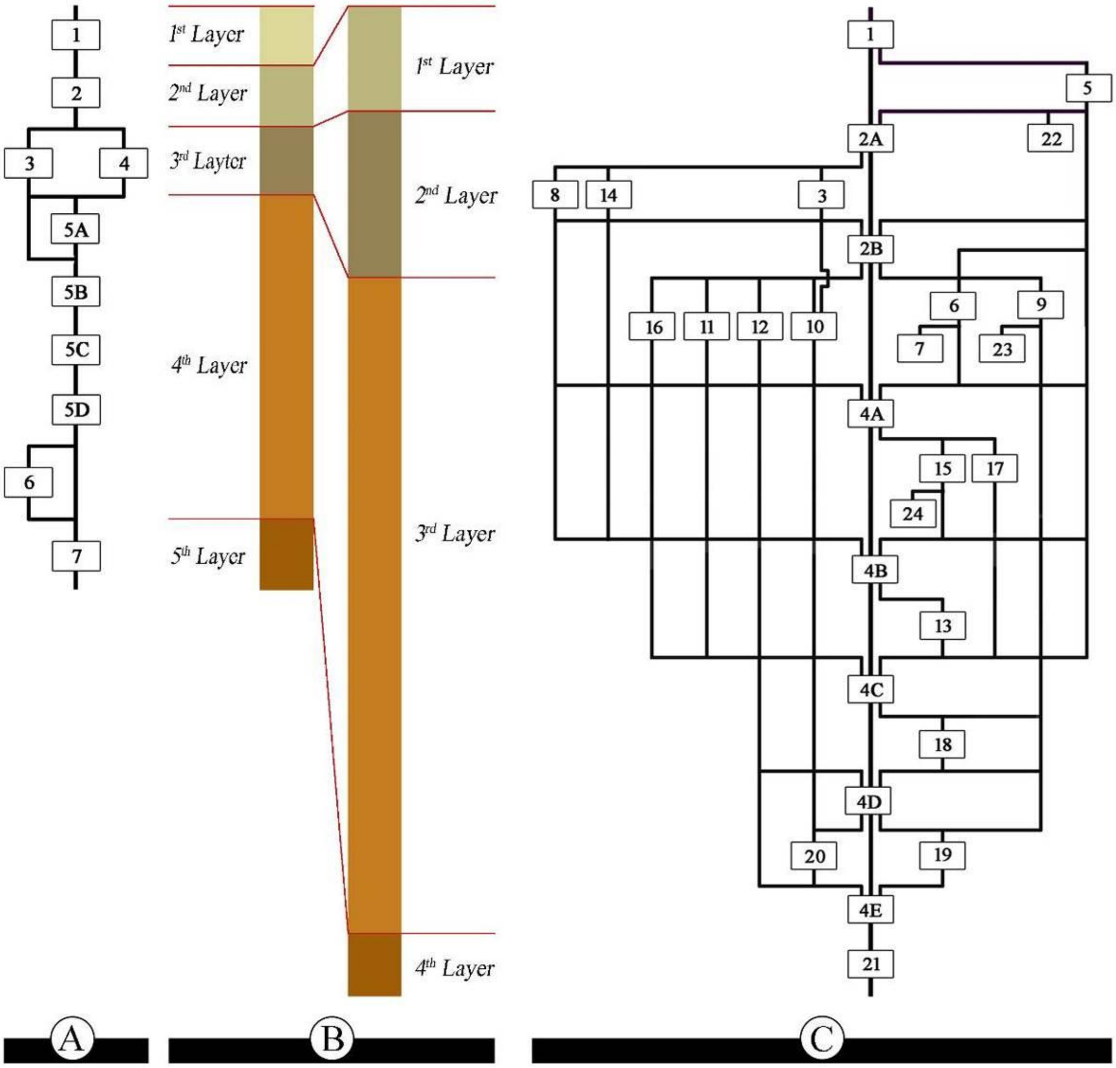


Fig. 4.1. (A) Matrix Context Charts of the LMBA/YW/2018/01 Excavation (B) Layer comparison of two excavations (C) Matrix Context Charts of the LMBA/YW/2018/02 Excavation**.**

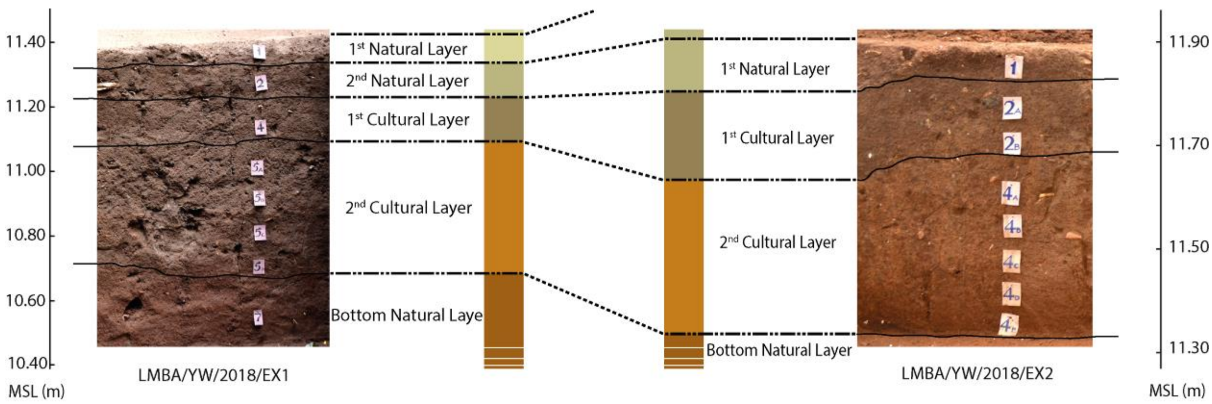


Fig. 4.2. Significant layer distribution pattern of *Yodhawewa* site; First excavation *(left)* and second excavation *(right)*

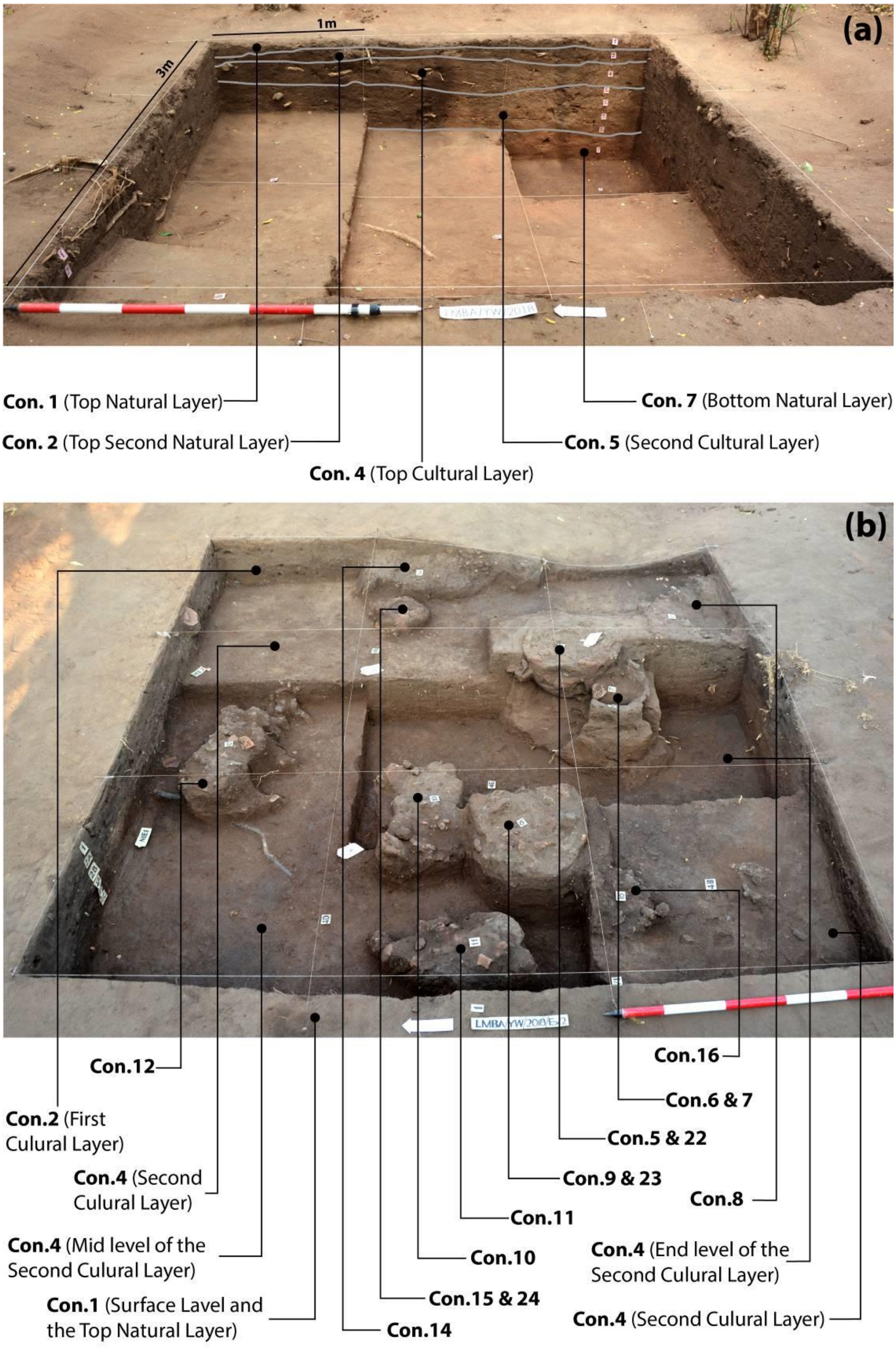


Fig. 4.3. Two excavations pits including specific contexts (a) First excavation (Ex-01) and (b) Second excavation (Ex-02) (Both Photo direction is west to east)

The second excavation reported 24 contexts in three main layers, and the layers were assigned the numbers (contexts) 1, 2, and 4. The top layer (context 1) is heavily disturbed through the recent canal expansion constructions and the monsoonal runoff. For recording purposes, the main second layer (context 2) was divided into two units; 2A and 2B. Context 3 and 13 (small layers) were deposited as sub-layers in context (layer) 2 (between 2A and 2B) and context (layer) 4 (between 4B and 4C), respectively. The fourth (4) context was divided into five approximate equal units in a sequence (5-10cm splits as 4A, 4B, 4C, 4D, and 4E) (Fig. 4.2), providing an incremental column of small samples.

Two circular features were exposed during the excavation and numbered contexts 5 and 9, identified as remnants of furnaces (Fig. 4.3b). Contexts 8 and 14 were identified from the 2A context, while contexts 6, 9, 10, 11, 12, and 16 were discovered from context 2B. Contexts 15 and 17 were revealed from context 4A. Context 15 was an overturned pottery, and context 18 was an assemblage of potsherds. Contexts 8, 10, 11, 12, 14, 16, and 17 were the accumulations of earthenware, glass and metal slags, glass fragments, and fragments of the furnaces. Layers 2 and 4 were the main anthropogenic layers, including the furnaces, operational debris accumulation, post-production abandonment, and human-induced debris from later settlement phases (Fig. 4.3b). The stratigraphic distribution of the region is almost evenly deposited and has similar attributes, as disclosed by all the profiles and excavations. However, layers' thickness varies to some extent (Table 4.1).

4.2. Material Culture

The total number of artifacts collected from the entire *Yodhawewa* study area was 14017. 57.20% (n=8018), or the majority of those, were unearthed from the second excavation premises. The balance was collected as: 16.25% (n=2278) by the exploration; 16.14% (n=2263) from the first excavation pit and 10.40% (n=1458) from the six profiles.

Quantitatively, most slags, crucible fragments, furnace wall fragments (FWF), metal artifacts, or metal fragments were acquired from the second excavation area (Table 3.1; Fig. 4.4).

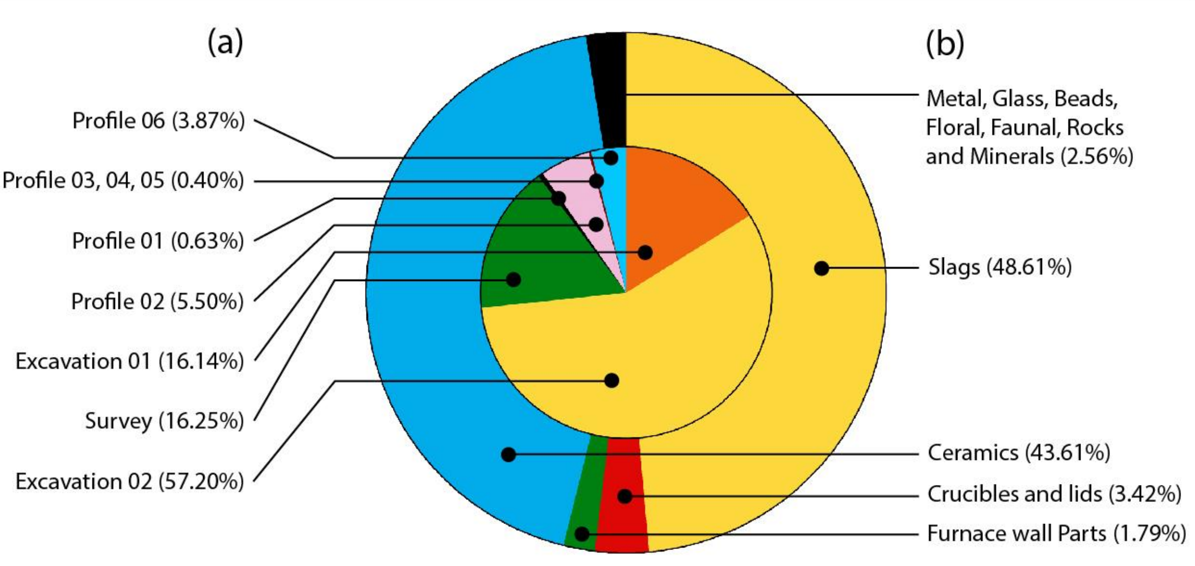


Fig. 4.4. Artifacts density of the *Yodhawewa* research in 2018 (a) Location-based percentage and (b) artifact type-based percentage.

The most significant detection of the Ex.1 area was that copper particles were abundant in the crucible and slag fragments. Crucible fragments (rim, body, and base) of this area were flat-based and cup-shaped. However, an unbroken crucible was not found. A significant discovery of Ex.2 was a below part of the lower half-spherical shaped (crucible shaped) furnace structure (context 5) (Fig. 4.3b). The furnace wall was built of burnt clay pieces and clay mortar, which fit nicely into a circular shape (Fig. 4.5). The remained furnace surface diameter was 35-44 cm with a wall thickness of 8-12 cm, and there was a bonded daub plaster (1-1.5 cm) inside the furnace chamber. An in-out-connected small hole (⌀ = 2.5 cm) was visible through the furnace wall to connect the bellow pipes.

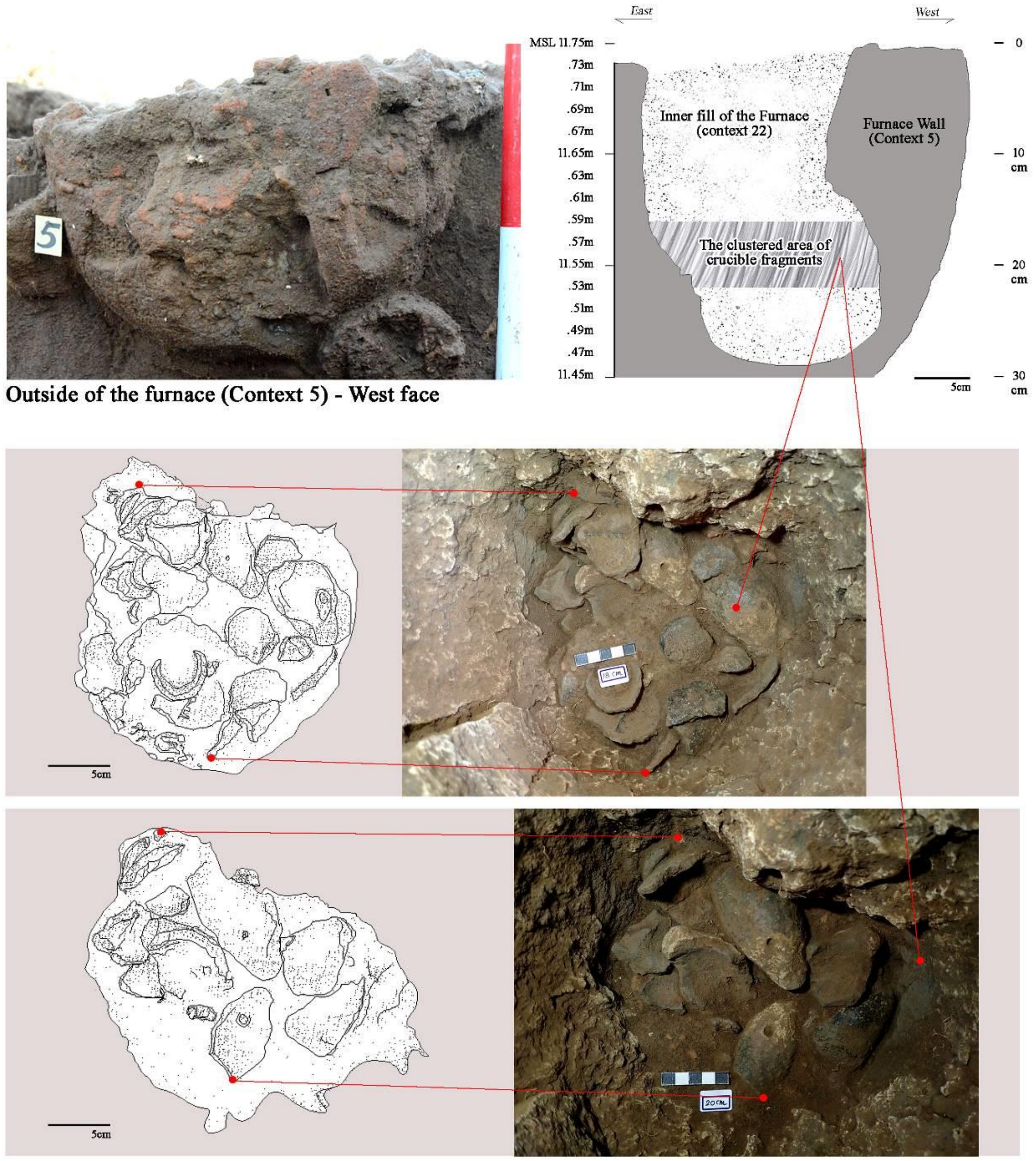


Fig. 4.5. The lower half-spherical (crucible-typed) furnace (context 5) was discovered at the *Yodhawewa* site. Outer west face of the furnace (top left), detailed drawing of the furnace with inner fill (context 22) (top right), and the details of the deposition of crucible fragments 18cm (middle) and 20cm depth (bottom).

The crucible fragments in this Ex.2 area were elongated tube shapes with a hemispheric base, approximately 4-6.5 cm in inner diameter, and thin-walled (c. 3-6 mm). Although the crucible base, body, rim, and lid fragments could be identified in the region, an unbroken crucible could not be detected (Fig. 4.6). The slag pool (n=6226) discovered from the Ex.2 was also the most extensive artifacts collection in the entire research. The morphological characteristics of selected slags used for geochemical analysis are described in chapter 4.6.

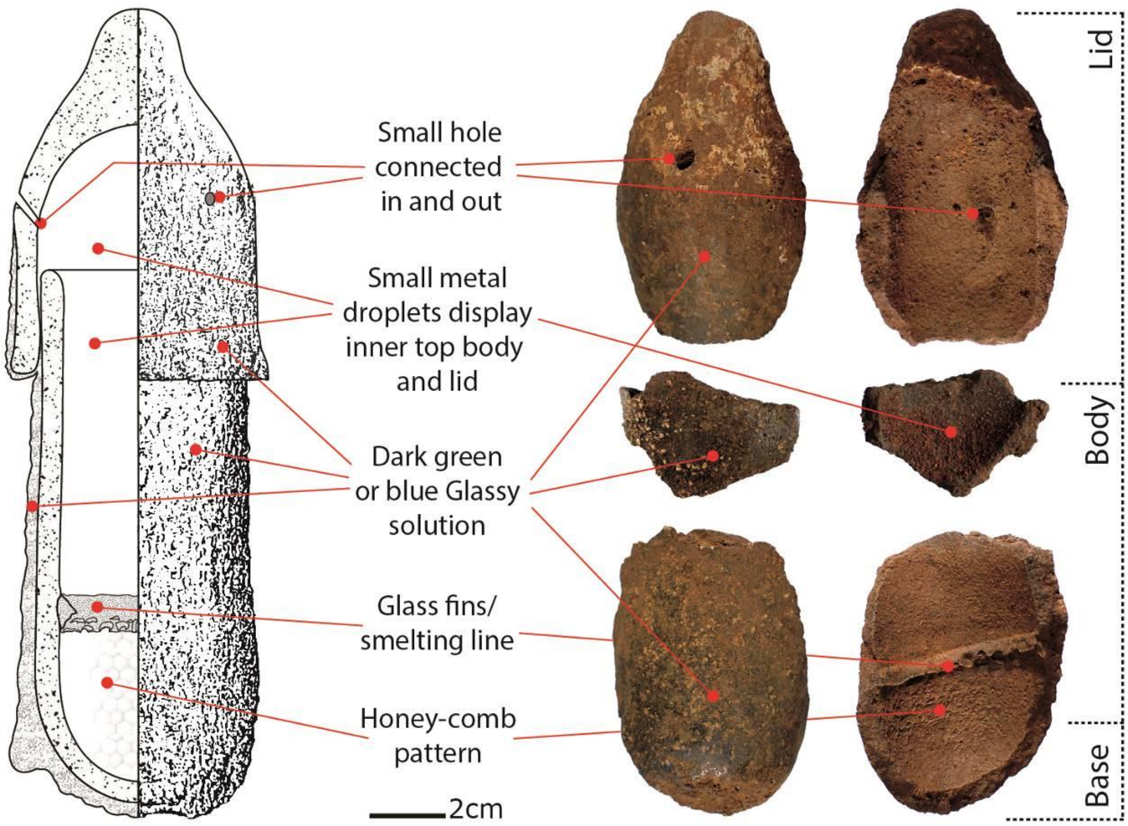


Fig. 4.6. The crucibles used for making steel (wootz) at the *Yodhawewa* site; detailed drawing (non-scale) of the crucible and lid setup (left), the outer surface of crucible and lid fragments (center), and inner detail of same crucible and lid fragments (right). The scale is only related to the photographic details.

4.3. Cultural and natural formation of the study area

Most of the study area contained the dark brown surface soil layer, granular and crumb structure, and fine and medium particles. The first cultural layer (dark reddish-brown) of the Ex-1 was slightly thicker than the surface layer, and the soil consisted mainly of fine, medium, and coarse particles. Much-diversified artifacts of pottery fragments, crucible fragments, slags, and beads were found from this layer. Parallel layers of nearest profiles (P2 and P1) resulted in a significant amount of crucible fragments (*n* = 26). The soil composition of the second excavation was similar to the first cultural layer; however, the density of artifacts was higher than the first cultural layer of the Ex.1 area. The pool of artifacts of the first cultural layer of Ex.2 consists of slags, ceramic fragments, crucible (including lid) fragments, weathered metal pieces, FWF, beads, and some glass pieces.

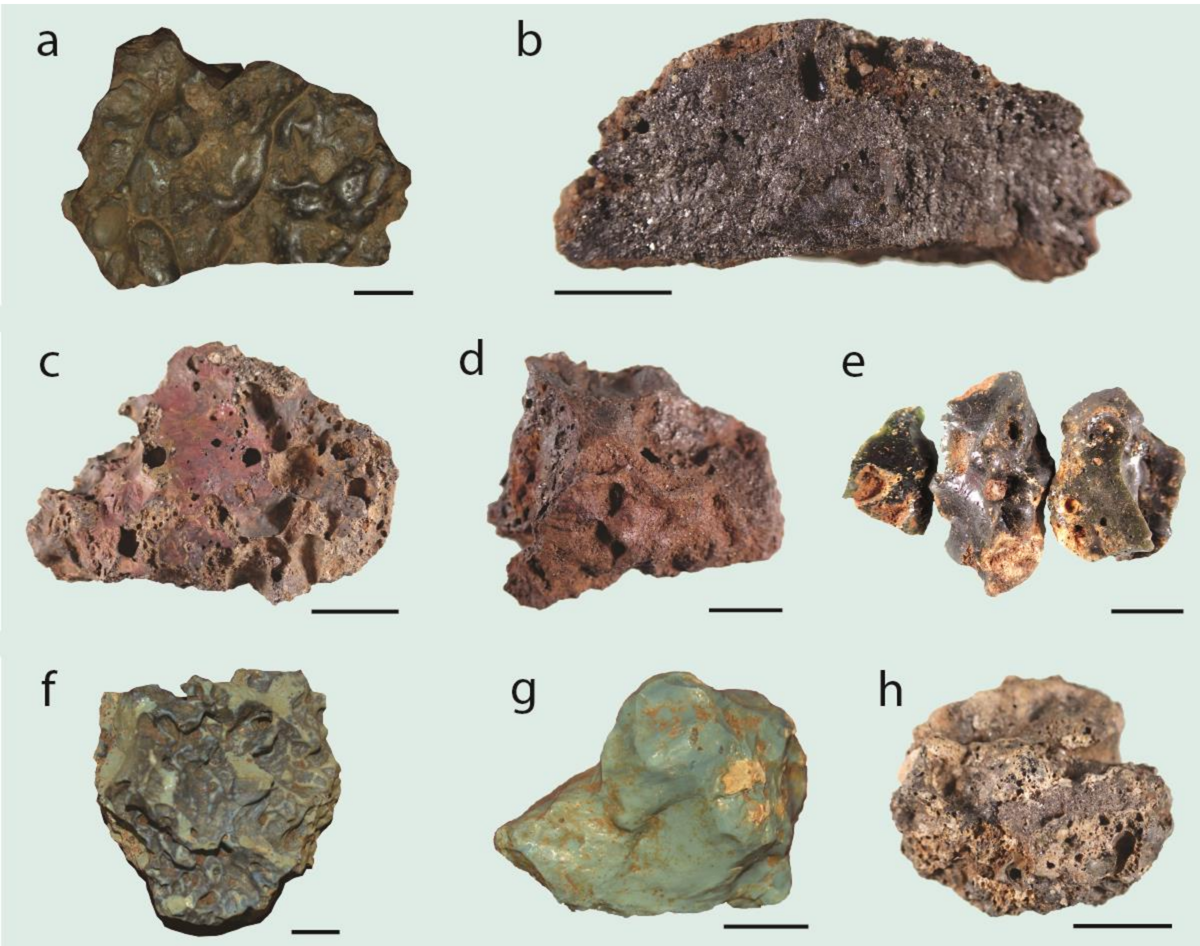


Fig. 4.7. Slags were analyzed in the study (a) The metallic tap slag sample [Y/18/S/39] denoted the highest Y, Nb, Sc, and MnO. (b) A broken view of the Y/18/S/16 sample contained the highest copper content among metallic slags. (c) High iron slag [Y/18/S/25] contained the highest CaO among HIS. (d) Slag sample [Y/18/S/3] contained the highest Fe_2O_3 as c. 49.63wt%. (e) Dark green glassy and low iron slag sample (three fragments) [Y/18/S/1]. (f) Glassy slag sample [Y/18/S/48] denoted the highest Pb, Ni, Zr, Th, and TiO_2 among LIS. (g) Light green semi-glass fragment divided from glassy slag [Y/18/S/41] denoted the highest Sr, Sc, and CaO levels among LIS. (h) Sample no. Y/18/S/7 represented the highest Cu (c. 50 ppm) among LIS (Scale: 1 cm).

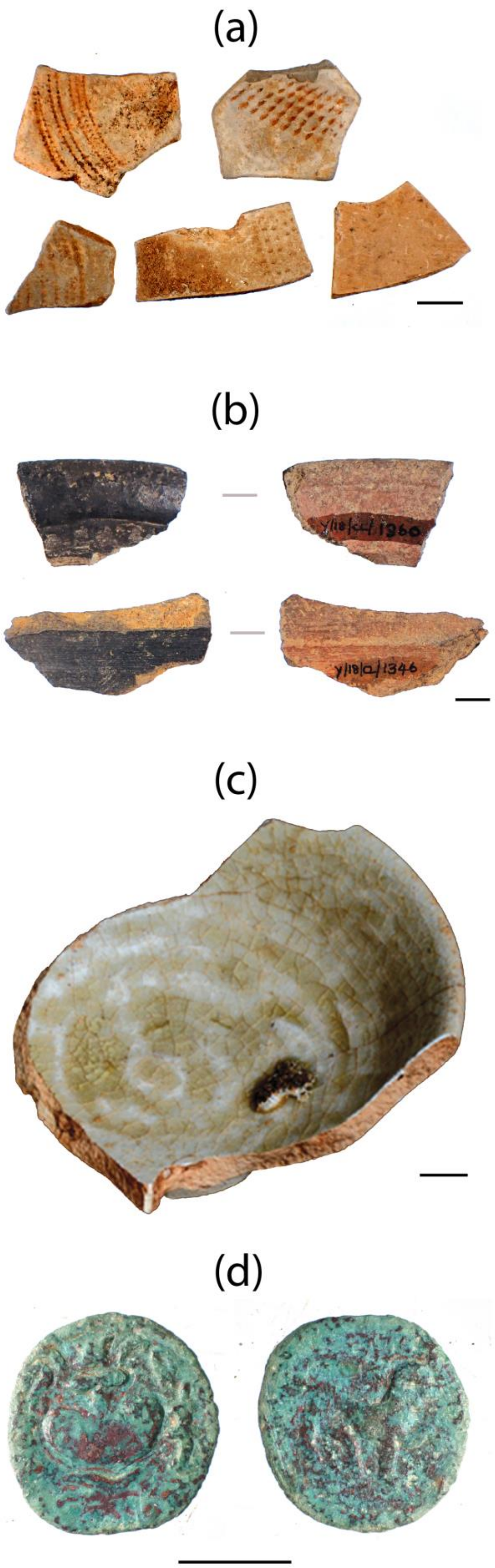
Medium and coarse particles were common in the dark reddish-brown second cultural layer of Ex.1 and Ex.2 and were almost similar to the first cultural layer. The height of this layer was almost 30 cm in Ex.1 and about 40 cm in Ex.2 (Table 4.2). The artifact types of this wide layer were similar to the first cultural layer but in different contents. The crucible fragments found in the areas of Ex.1 and Ex.2 identified significant physical and structural differences. The natural reddish-brown layer found underneath the second culture layer was slightly solid and consisted of fine, medium, and coarse particles and a low amount of very coarse particles. Table 4.2 presents the minimum to maximum values of each layer's top and bottom levels and soil samples related to the soil layers.

Table 4.2. Soil layout, minimum to maximum levels of Ex.1 and Ex.2 layers. Soil samples were represented based on excavations and profiles.

Layer	Soil color in Ex.1	Top and bottom (min-Max) levels of layers in Ex.1 (MSL)	Soil samples of total Ex.1 area	Soil color in Ex.2	Top and bottom (min-max) levels of layers in Ex.2 (MSL)	Soil samples of total Ex.2 area
Surface Natural Layer	7.5YR 3/3 dark brown	11.40-11.48cm 11.29-11.39cm	P1:1, P2:1	10YR 3/6 dark yellowish-brown	11.78-11.93cm 11.75-11.88cm	Ex2:1, P6:1
First Cultural Layer	5YR 4/4 reddish brown	11.29-11.39cm 11.23-11.30cm	Ex1:1, P1:2, P2:2	7.5YR 3/4 dark brown	11.75-11.88cm 11.63-11.72cm	P6:2, Ex2:2,7,8
Second Cultural Layer	5YR 3/4 reddish brown	11.23-11.30cm 10.91-10.97cm	Ex1:2	5YR 4/4 reddish brown	11.63-11.72cm 10.20-10.30cm	P6:3, Ex2:3-6, 9-14, 15-21
Bottom Natural Layer	5YR 4/4 reddish brown	10.91-10.97cm more depth	P1:3, P2:3,	5YR 4/4 reddish brown	10.20-10.30cm more depth	Ex2:14, P6:4

4.4. Relative dating for the *Yodhawewa* site

Selected unique artifacts discovered from the *Yodhawewa* site have been used for relative dating. During the survey collected 12 Rauletted Ware (RW) fragments (for the example, see a), 23 Black and Red Ware (BRW) fragments (see b), and six Porcelainware fragments;



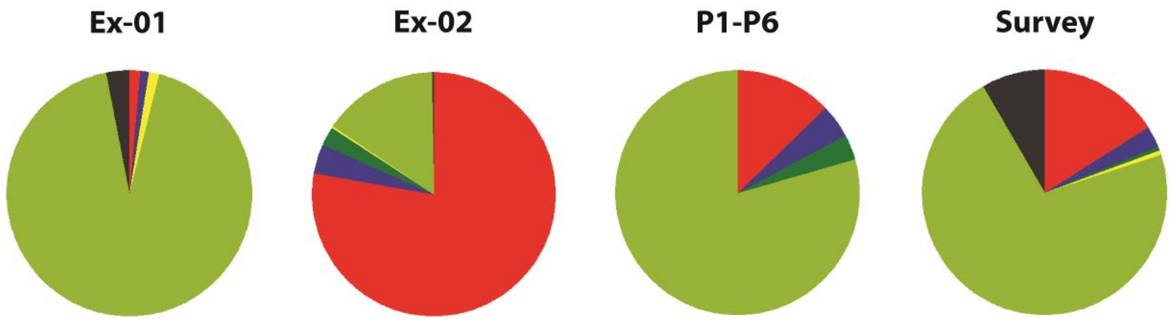
however, they have not been discovered during two excavations. One of the identified Changsha porcelain bowl fragments belongs to the Tang Dynasty period of China (c). The survey yielded five coins, of which four were severely oxidized, and one coin had excellent detail preserved (d). This coin is of the Pallava dynasty of South India, and it has a lion standing in the middle of a beads circle depicted on the obverse and a large flower pot on the reverse.

Fig. 4.8. (a) Rouletted ceramics (b) Black and Red Ware (c) Porcelainware (d) A copper coin obverse and reverse were discovered from the *Yodhawewa* site [scale: 1cm] (After Wijepala, Young and Ishiga, 2022).

4.5. Furnaces

The furnaces are among the most informative factors in ancient metalworking sites. The total number of 251 refractories (77.2%) of the *Yodhawewa* research were found to be significant structural evidence for the furnaces from the second excavation in contexts 5 and 9 (Fig. 4.3b Fig. 4.5). The lower half of a spherical (crucible-type) furnace (context 5) was exposed at the surface, which was well-preserved, but the upper parts were naturally destroyed.

The totally abandoned furnace chamber was filled with the debris of crucible fragments (n=32), slags (n=8), metal fragments (n=1), potsherds (n=3), and refractory clay fragments (n=21). The internal depth of the remaining half was 29 cm, and 18 pieces of crucible fragments and lids were detected at the level between 16–22 cm inside the furnace chamber (Fig. 4.5). There was no tuyere evidence found related to the furnace; however, features of a closed air tube could be seen about 15 cm from the base of the furnace chamber. The remains of the second furnace (context 9) discovered at the 2B context level contained an assemblage of furnace wall fragments (Fig. 4.3b).



	Ex-01	Ex-02	P1-P6	Survey
Slags	1.41%	77.65%	12.90%	16.15%
Crucible Fragments	1.14%	4.07%	4.46%	2.77%
Furnace Wall Fragments	0.04%	2.41%	3.22%	0.44%
Metal objects or Fragments	1.20%	0.39%	0.0%	0.53%
Earthenware Fragments	93.24%	15.17%	79.42%	71.73%
Other Artifacts	2.97%	0.31%	0.0%	8.38%

Fig. 4.9. Artifacts density and percentage of individual artifacts by each activity.

In terms of the structural preparation of the furnaces, the wall has been prepared by bonding with pre-prepared and fired clay pieces of various sizes using clay. A burnt and impressed clay (daub) coat could be seen inside the remains of the furnace, around the entire radius to 22 cm deep from the remaining furnace surface. The daub plaster thickness varied between 1.5-2.5cm due to the repeated application of that coat when the same furnace was used for an extended period. The clay tuyers were not used in the *Yodhawewa* crucible furnace, and the air was supplied into the furnace using the bellow method. A "Tube hole" of the air conduit was connected to the bellow and the furnace. This idea was confirmed by finding a fragment of clay tube among the artifacts in the furnace chamber (Fig. 4.5). However, based on individual activities, furnace wall fragments were uncovered from all profiles (P1-P6), Ex-2, Exploration, and Ex-1 were 3.22%, 2.41%, 0.44%, and 0.04%, respectively (Fig. 4.9).

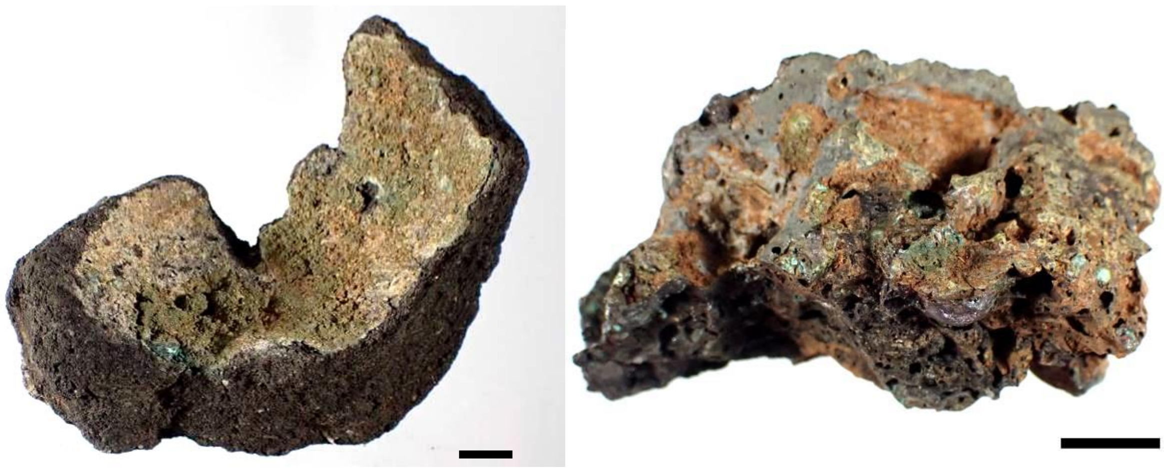


Fig. 4.10. Flatted-based crucible fragment with copper prills found from P-2 *(left)*. Slag with copper particles found from Ex-1 area. © *Yodhawewa* research 2018 [scale; 1cm]

The primary evidence that there should be remains of furnaces for the iron extraction to produce the raw iron is provided by iron slags and other smelting debris (including a few tuyere fragments) that were scattered throughout the area. There were slags and crucibles, including copper prills (spots of powdery green corrosion), in the vicinity of the *Yodhawewa* excavation-1 area (Fig. 4.10).

4.6. Slags

Slag is among the significant archaeological finds at the *Yodhawewa* site, with a total of 48.5kg (N=6814) slag fragments collected (Fig. 4.4, Fig. 4.7; Table 3.1). Two thousand fifteen fragments (38.3 kg) were larger than 1cm in size, and 4799 (10.2 kg) were less than 1cm Slags were detected between the 150-1600 m study area (see Fig. 2.6 for getting an idea about sampling units of the study area map), and a significant increase was observed in the 700–750 m and 1100–1200 m sample units. The area up to 150m in the exploration region closest to the *Yodhawewa* reservoir was devoid of slag and was rarely found until the 700m region. The highest slag density was found in the 700-750m sampling unit, with total slag fragments of 6447, and included Ex-2, profile-6, and the exploration (Table 4.3).

Almost all the slags found in this study were dislocated and broken. Considering the iron (Fe_2O_3) content in the slags (by XRF analysis), two kinds of slags were identified; (a) High Iron metal typed slags (HIS) and (b) Low Iron amorphous/glassy typed slags (LIS). The shape parameters and surface roughness showed morphological variation. The shape of the entire collection of slag samples was angular, irregular, and porous (vesicular). HIS was darker than LIS in color, and some glassy structured slags denoted various shades of blue, green, and white colors (Fig. 4.7e-g). Some glassy slags were transparent or translucent (Fig. 4.7e). Among HIS, different sizes of tap slag were observed (Fig. 4.7a). Many metal slags show oxidized conditions due to the deposition after metal extraction and prolonged exposure to oxy-hydroxide (Fig. 4.7a-d).

Table 4.3. Detailed artifacts density of *Yodhawewa* site 2018 (Wijepala, S M Young and Ishiga, 2022b)

Study Area	Context / *Area*	Furnace wall parts	Crucible Fragments	Slag pieces	Other artifacts	Total
Excavation-1	Context 4	0	4	1	338	343
	Context 5 all	1	22	11	1852	1886
	Other all contexts	0	0	20	14	34
	Total (EX-1)	**1**	**26**	**32**	**2204**	**2263**
Excavation-2	Context 1	0	48	382	244	674
	Context 2 all	69	46	4221	144	4480
	Context 4 all	3	99	975	670	1747
	Other all contexts	121	133	648	215	1117
	Total (EX-2)	**193**	**326**	**6226**	**1273**	**8018**
Profiles 1-6	Profile 01 all	0	6	77	5	88
	Profile 02 all	31	59	51	630	771
	Profile 03 all	2	0	2	34	38
	Profile 04 all	0	0	0	2	2
	Profile 05 all	0	0	17	0	17
	Profile 06 all	14	0	41	487	542
	Total (All Profiles)	**47**	**65**	**188**	**1158**	**1458**
Exploration/ Survey	0 – 50	0	0	0	0	0
	50 – 100	0	0	0	0	0
	100 – 150	0	0	0	0	0
	150 – 200	0	0	**1**	3	4
	200 – 250	0	**1**	**2**	**18**	21
	250 – 300	0	0	**2**	9	11
	300 – 350	0	0	**10**	28	38
	350 – 400	0	0	**7**	5	12
	400 – 450	0	0	**5**	9	14
	450 – 500	0	0	**5**	44	49
	500 – 550	0	0	**2**	43	45
	550 – 600	0	0	**15**	238	253
	600 – 650	0	**2**	**7**	**212**	221
	650 – 700	0	**1**	**2**	**54**	57
	700 – 750	**4**	**14**	**180**	**174**	372
	750 – 800	0	0	**9**	64	73
	800 – 850	0	0	**4**	62	66
	850 – 900	0	1	**2**	74	77
	900 – 950	0	0	**1**	40	41
	950 – 1000	0	0	**2**	21	23
	1000 – 1050	0	0	**3**	10	13
	1050 – 1100	0	**1**	**8**	**22**	31
	1100 – 1150	**5**	**28**	**33**	**238**	304
	1150 – 1200	**1**	**1**	**29**	**146**	177
	1200 – 1250	0	0	**6**	1	7
	1250 – 1300	0	9	**15**	152	176
	1300 - 1350	0	5	**5**	53	63
	1350 – 1400	0	0	**3**	3	6
	1400 – 1450	0	0	**2**	29	31
	1450 – 1500	0	0	**2**	40	42
	1500 – 1550	0	0	**4**	37	41
	1550 – 1600	0	0	**2**	8	10
	Total (Exploration)	**10**	**63**	**368**	**1837**	**2278**
Total Artifacts content of the *Yodhawewa* site		**251**	**480**	**6814**	**6472**	**14017**

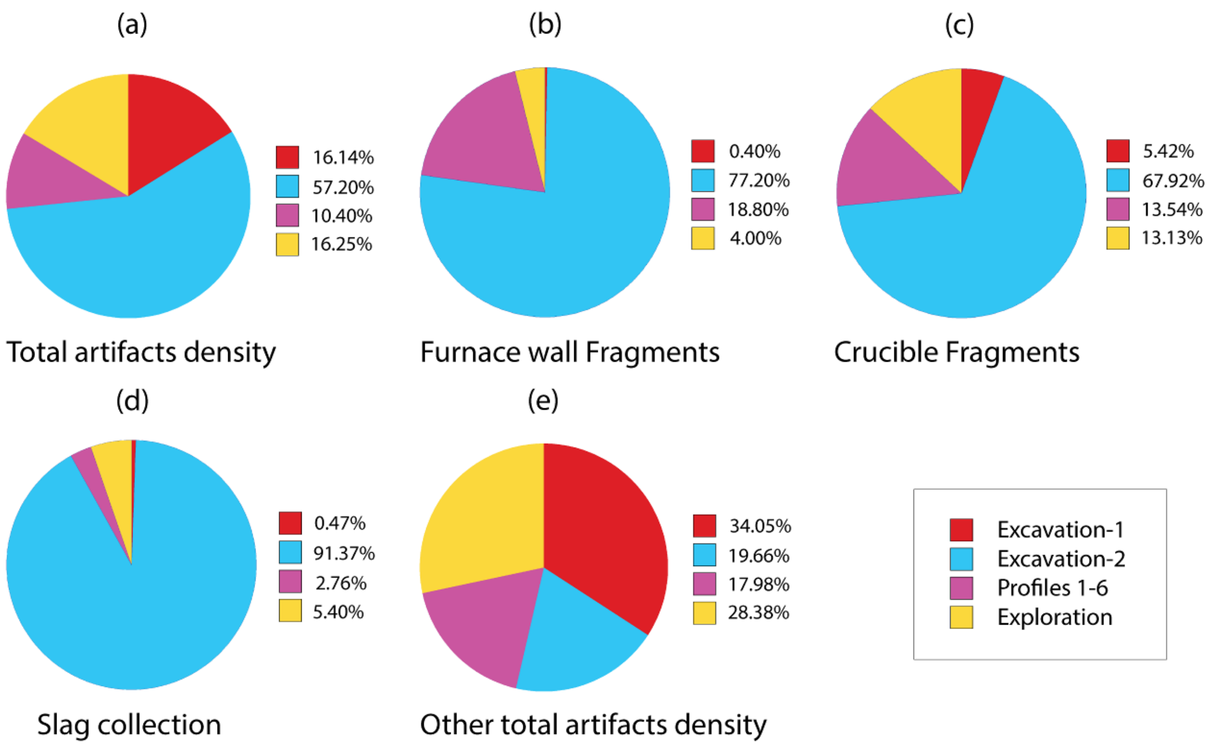


Fig. 4.11. The percentages of the *Yodhawewa* artifacts density are based on individual artifact types (Wijepala, S M Young and Ishiga, 2022b).

4.7. Crucible Fragments

The crucible and lid fragments represented 3.42% (n=480) of the entire artifacts density of the *Yodhawewa* collection (Fig. 4.4). However, the second excavation pit revealed 67.92% when considering only crucible fragments. The balance (32.08%) was collected from the survey (13.13%), Profiles (13.53%), and the first excavation (5.42%) (Fig. 4.11c). However, a non-damaged (complete) crucible was not among the crucible fragments collected from the *Yodhawewa* entire site, and the fragments were parts of the rim, body, base, and lids (Fig. 4.6 and Fig. 4.10). The shape, size, and thickness of crucibles in the Ex-1 area displayed a larger variation when compared to the crucibles found in the Ex-2 area. Crucibles in the Ex-1 area were shaped into round bowls with a flat base, n and some of the crucible fragments had copper fragments deposited inside (Fig. 4.10). Compared to those, the crucibles of the Ex-2 area represented an elongated tube-shaped design with rounded base (Fig. 4.6).

The inner diameter of all crucible fragments found in the second excavation area was 4 - 6.5 cm. Macro-morphologically, the outer surface was completely dark green or blue (mixed) with glazy vitrification or a waxy solution, including tiny white splots. Glassy fins show a smelting line on the inner middle or lower area, and some honey-comb pattern was visible in the bottom part of that line. Crucible lids of the *Yodhawewa* assemblages appear to be unique in shape; all the lids examined show evidence of being pierced with one or more small perforations; however, an unbroken lid also was not found to identify their form precisely. In some cases, traces of tiny metal droplets were visible inside the upper parts of crucibles or lids (Fig. 4.6). However, not a single crucible steel ingot was found on the *Yodhawewa* site for further metallurgical investigations.

CHAPTER FIVE

GEOCHEMICAL RESULTS: SOIL, SLAGS, AND CHARCOAL

5.1. Soil – XRF results - Geochemical characteristics of the Soil and FWF

The major and trace element concentrations of soil in the Ex.1 and Ex.2 areas with mean, minimum to the maximum range with the Upper Continental Crust (UCC) were given in Table 5.1, and the summarized data included in Table 5.3. The elemental concentrations of both areas' cultural and natural soil layers showed slight variation against UCC (Mean values in Table 5.3).

Major element concentrations are mentioned here as oxides (wt%), following the common convention for signifying major-element bulk chemical composition, chemical concentrations of crystalline oxides, and silicates (Piatak, Parsons and Seal, 2015). Average abundance of major elements TiO_2 (Cultural Layers 1.68wt%, Natural Layers 1.82wt%, and Furnace Wall Fragments 1.26wt%), Fe_2O_3 (6.97, 6.55, and 4.36wt% respectively), MnO (0.21, 0.23, and 0.13wt%), CaO (0.88, 0.83, and 3.78wt%), and P_2O_5 (0.34, 0.18, and 0.51wt%) vary in the first and second excavation areas. The mean percentage of Fe_2O_3 is higher in the cultural layers than in the natural layers and the furnace wall fragments. The TiO_2 and MnO percentage concentrations were higher in the natural layers than in the others, while CaO and P_2O_5 percentages were higher in the FWF (Table 5.1).

Table 5.1. XRF analytical results of soil and furnace wall fragments of *Yodhawewa* site 2018 (nd=not detected). UCC average from Rudnick and Gao, 2003.

Sample No.	Trace elements (ppm)																	Major Elements (wt%)				
	As	Pb	Zn	Cu	Ni	Cr	V	Sr	Y	Nb	Zr	Th	Sc	TS	F	Br	I	TiO_2	Fe_2O_3	MnO	CaO	P_2O_5
Soil Cultural Layers - Ex.1 area (n=4)																						
Ex.1:1	9	18	65	47	100	143	218	35	25	14	298	11	21	848	120	2	2	1.63	9.35	0.22	0.79	0.16
Ex.1:2	8	17	59	42	80	137	195	33	21	13	304	9	19	846	42	2	2	1.66	7.72	0.19	0.77	0.17
P1:2	6	22	54	470	54	142	176	47	15	12	393	8	14	860	44	2	50	1.93	5.58	0.29	0.87	0.17
P2:2	5	19	66	261	66	117	176	56	16	11	387	9	16	861	137	2	22	1.56	6.62	0.20	1.15	0.33
Mean	**7**	**19**	**61**	**205**	**75**	**135**	**191**	**43**	**19**	**12**	**345**	**9**	**18**	**854**	**86**	**2**	**19**	**1.70**	**7.32**	**0.23**	**0.90**	**0.21**
Minimum	5	17	54	42	54	117	176	33	15	11	298	8	14	846	42	2	2	1.56	5.58	0.19	0.77	0.16
Maximum	9	22	66	470	100	143	218	56	25	14	393	11	21	861	137	2	50	1.93	9.35	0.29	1.15	0.33
Soil Cultural Layers - Ex.2 area (n=20)																						
Ex.2:2	7	18	50	56	60	118	165	36	18	13	385	10	14	878	200	2	8	1.75	6.43	0.20	0.76	0.20
Ex.2:3	7	18	60	57	92	139	189	37	19	13	328	9	15	869	nd	2	10	1.69	7.45	0.22	0.83	0.31
Ex.2:4	7	17	56	47	66	120	179	34	19	13	363	8	16	855	41	2	8	1.69	7.24	0.18	0.77	0.19
Ex.2:5	7	18	60	56	80	144	194	35	20	13	348	9	18	868	120	2	15	1.73	7.97	0.24	0.79	0.18
Ex.2:6	7	17	58	53	77	131	198	33	20	13	329	10	17	851	105	2	15	1.74	7.67	0.21	0.76	0.18
Ex.2:8	8	17	56	52	76	126	194	34	20	13	330	10	17	856	364	2	1	1.71	7.67	0.21	0.76	0.18
Ex.2:9	7	17	61	46	81	130	205	32	21	13	363	10	18	845	296	2	10	1.73	8.21	0.21	0.76	0.17
Ex.2:10	7	19	47	76	61	124	182	37	17	13	374	9	13	863	152	2	8	1.79	6.54	0.21	0.79	0.18
Ex.2:11	7	18	52	56	68	142	198	37	18	13	378	10	20	869	89	2	15	1.91	7.36	0.25	0.82	0.18
Ex.2:12	7	19	46	62	57	129	201	39	16	13	401	9	15	875	42	2	18	2.08	6.95	0.26	0.85	0.20
Ex.2:13	7	16	51	48	64	135	188	34	19	13	361	9	19	859	25	2	4	1.73	7.02	0.19	0.76	0.17
Ex.2:15	8	18	57	49	77	129	195	35	20	13	310	10	17	860	43	2	4	1.68	7.90	0.21	0.78	0.18
Ex.2:16	10	19	68	50	136	137	183	82	22	13	298	11	19	853	40	2	nd	1.23	7.64	0.21	0.97	0.98
Ex.2:17	11	17	67	54	141	175	200	98	22	13	284	9	19	855	nd	2	5	1.29	8.23	0.23	1.06	1.23
Ex.2:18	11	18	60	40	112	133	189	88	20	13	330	12	18	843	213	2	nd	1.35	7.25	0.23	0.97	0.90

Table 5.1. (ctd.) XRF analytical results of soil and furnace wall fragments of *Yodhawewa* site 2018 (nd=not detected). UCC average from Rudnick and Gao, 2003**.**

Sample No.	Trace elements (ppm)																	Major Elements (wt%)				
	As	**Pb**	**Zn**	**Cu**	**Ni**	**Cr**	**V**	**Sr**	**Y**	**Nb**	**Zr**	**Th**	**Sc**	**TS**	**F**	**Br**	**I**	**TiO_2**	**Fe_2O_3**	**MnO**	**CaO**	**P_2O_5**
Ex.2:19	15	12	47	66	59	134	261	59	16	10	278	7	13	918	nd	nd	nd	1.51	4.66	0.17	1.70	0.41
Ex.2:20	8	18	52	46	71	124	186	44	20	12	315	9	20	871	29	2	5	1.59	7.65	0.18	0.91	0.16
Ex.2:21	9	17	58	39	120	122	169	70	17	13	379	11	17	844	42	2	nd	1.47	6.19	0.14	0.89	0.93
P6:2	4	16	33	26	28	136	164	48	11	12	447	7	14	898	15	2	20	2.11	3.54	0.22	0.82	0.16
P6:3	5	18	44	39	44	112	154	49	15	13	429	9	14	861	2	2	14	1.79	4.55	0.20	0.79	0.15
Mean	**8**	**17**	**54**	**51**	**78**	**132**	**190**	**48**	**19**	**13**	**352**	**9**	**17**	**865**	**107**	**2**	**10**	**1.68**	**6.91**	**0.21**	**0.88**	**0.36**
Minimum	4	12	33	26	28	112	154	32	11	10	278	7	13	843	2	2	1	1.23	3.54	0.14	0.76	0.15
Maximum	15	19	68	76	141	175	261	98	22	13	447	12	20	918	364	2	20	2.11	8.23	0.26	1.70	1.23
Soil Natural Layers - Ex.1 area (n=4)																						
P1:1	4	18	37	180	28	89	131	43	12	12	419	8	10	853	122	2	30	1.74	3.29	0.18	0.77	0.11
P1:3	7	17	63	261	79	129	201	38	20	13	367	14	19	851	25	2	14	1.66	7.53	0.22	0.81	0.19
P2:1	5	18	52	166	48	145	179	47	14	13	440	7	13	880	41	2	25	2.13	4.53	0.28	0.83	0.15
P2:3	8	18	63	85	92	150	218	43	20	13	343	11	20	835	41	1	8	1.73	8.66	0.27	0.92	0.22
Mean	**6**	**18**	**54**	**173**	**62**	**128**	**182**	**43**	**17**	**13**	**392**	**10**	**16**	**855**	**57**	**2**	**20**	**1.82**	**6.00**	**0.24**	**0.83**	**0.17**
Minimum	4	17	37	85	28	89	131	38	12	12	343	7	10	835	25	1	8	1.66	3.29	0.18	0.77	0.11
Maximum	8	18	63	261	92	150	218	47	20	13	440	14	20	880	122	2	30	2.13	8.66	0.28	0.92	0.22
Soil Natural Layers - Ex.2 area (n=5)																						
Ex.2:1	6	17	41	56	49	134	176	41	16	13	402	8	16	890	nd	2	13	2.08	6.06	0.24	0.82	0.21
Ex.2:7	8	17	59	50	78	157	205	36	20	13	346	9	17	854	120	2	11	1.74	8.13	0.21	0.80	0.17
Ex.2:14	7	19	51	56	68	125	185	37	19	13	364	8	16	867	nd	2	9	1.67	7.14	0.21	0.79	0.18
P6:1	5	16	42	69	40	113	157	42	12	12	385	7	14	1018	183	3	21	1.87	4.13	0.19	0.89	0.23
P6:4	11	18	60	37	100	151	234	36	23	14	329	12	23	836	120	2	nd	1.77	9.45	0.23	0.80	0.17
Mean	**7**	**17**	**51**	**54**	**67**	**136**	**192**	**38**	**18**	**13**	**365**	**9**	**17**	**893**	**141**	**2**	**13**	**1.83**	**6.98**	**0.22**	**0.82**	**0.19**
Minimum	5	16	41	37	40	113	157	36	12	12	329	7	14	836	120	2	9	1.67	4.13	0.19	0.79	0.17
Maximum	11	19	60	69	100	157	234	42	23	14	402	12	23	1018	183	3	21	2.08	9.45	0.24	0.89	0.23

Table 5.1. (ctd.) XRF analytical results of soil and furnace wall fragments of *Yodhawewa* site 2018. UCC average from Rudnick and Gao, 2003**.** (nd=not detected).

Sample No.	Trace elements (ppm)																	Major Elements (wt%)				
	As	**Pb**	**Zn**	**Cu**	**Ni**	**Cr**	**V**	**Sr**	**Y**	**Nb**	**Zr**	**Th**	**Sc**	**TS**	**F**	**Br**	**I**	**TiO_2**	**Fe_2O_3**	**MnO**	**CaO**	**P_2O_5**
Furnace Wall Fragments (n=2)																						
Y/18/FW/1	3	8	23	25	68	114	92	183	19	11	245	9	nd	934	nd	nd	nd	1.01	4.23	0.12	3.55	0.73
Y/18/FW/2	4	12	42	29	40	100	117	213	19	13	313	9	16	831	105	nd	nd	1.50	4.48	0.14	4.00	0.28
Mean	**3**	**10**	**32**	**27**	**54**	**107**	**105**	**198**	**19**	**12**	**279**	**9**	**16**	**883**	**105**	**nd**	**nd**	**1.26**	**4.36**	**0.13**	**3.78**	**0.51**
Minimum	3	8	23	25	40	100	92	183	19	11	245	9	16	831	105	nd	nd	1.01	4.23	0.12	3.55	0.28
Maximum	4	12	42	29	68	114	117	213	19	13	313	9	16	934	105	nd	nd	1.50	4.48	0.14	4.00	0.73
UCC	**5**	**17**	**67**	**28**	**47**	**92**	**97**	**320**	**21**	**12**	**193**	**11**	**14**	**621**	**557**	**2**	**1**	**0.64**	**5.04**	**0.10**	**3.59**	**0.15**

Table 5.2. XRF analytical results of selected slag samples of *Yodhawewa* site 2018. UCC average from Rudnick and Gao, 2003. (nd=not detected).

Sample no.	Trace elements (ppm)																Major Elements (wt%)				
	As	Pb	Zn	Cu	Ni	Cr	V	Sr	Y	Nb	Zr	Th	Sc	TS	F	Br	TiO_2	Fe_2O_3	MnO	CaO	P_2O_5
High Iron Slag (HIS) (n=33)																					
Y/18/S/2	2	7	8	106	nd	82	377	133	8	5	128	2	nd	1550	231	nd	0.43	27.91	1.05	2.36	0.84
Y/18/S/3	16	7	6	111	198	51	637	81	7	4	105	1	nd	1122	367	nd	0.36	49.63	0.06	2.35	0.51
Y/18/S/4	4	7	5	45	nd	65	317	118	7	5	157	2	nd	1324	205	nd	0.65	22.63	0.06	1.89	0.40
Y/18/S/5	2	7	15	15	nd	242	931	130	28	11	138	9	12	1044	nd	nd	1.44	32.29	0.55	2.75	0.46
Y/18/S/6	3	8	2	67	9	67	422	139	10	6	123	3	nd	1096	nd	nd	0.47	33.95	0.05	6.40	0.40
Y/18/S/10	10	7	9	130	39	49	440	73	6	5	148	3	nd	928	61	nd	0.60	34.47	0.05	1.85	0.65
Y/18/S/11	18	23	38	43	17	147	562	17	16	10	168	7	6	813	511	nd	1.11	16.09	1.00	0.71	0.46
Y/18/S/12	3	8	10	32	nd	86	330	422	8	5	118	3	3	1150	nd	nd	0.46	22.94	1.71	4.46	0.57
Y/18/S/13	5	7	3	50	nd	64	266	169	9	5	137	2	6	1045	nd	nd	0.44	19.12	0.08	2.86	0.56
Y/18/S/15	12	7	5	95	nd	71	332	233	8	6	167	3	4	1105	nd	nd	0.80	23.79	0.07	3.72	0.41
Y/18/S/16	5	8	7	333	47	47	339	195	8	5	139	2	6	936	69	nd	0.60	25.12	0.06	5.29	0.55
Y/18/S/17	18	9	21	166	30	77	267	598	14	6	97	4	7	1119	nd	nd	0.63	17.38	0.09	6.49	0.80
Y/18/S/18	6	7	6	35	4	68	234	296	10	7	192	3	4	1003	64	nd	0.96	14.91	0.11	2.89	0.84
Y/18/S/20	2	7	5	60	nd	54	381	121	19	8	123	3	7	1364	39	nd	0.30	27.80	2.16	2.24	0.22
Y/18/S/23	4	8	11	62	7	97	218	253	10	7	185	4	7	910	152	nd	0.78	14.17	0.06	3.56	1.17
Y/18/S/24	7	8	7	187	53	32	435	107	6	5	123	4	5	874	128	nd	0.45	34.90	0.05	2.80	1.47
Y/18/S/25	6	8	10	98	nd	99	235	249	12	7	191	6	10	923	159	nd	0.92	15.45	0.08	7.25	0.39
Y/18/S/26	15	7	4	49	nd	81	512	154	13	6	121	1	6	1101	144	nd	0.49	37.91	0.14	3.08	0.71
Y/18/S/27	3	8	11	49	nd	116	414	195	20	9	149	3	8	1132	173	2	0.80	26.57	0.15	2.62	0.60

Table 5.2. (ctd.) XRF analytical results of selected slag samples of *Yodhawewa* site 2018. UCC average from Rudnick and Gao, 2003. (nd=not detected).

Sample no.	Trace elements (ppm)																Major Elements (wt%)				
	As	**Pb**	**Zn**	**Cu**	**Ni**	**Cr**	**V**	**Sr**	**Y**	**Nb**	**Zr**	**Th**	**Sc**	**TS**	**F**	**Br**	**TiO_2**	**Fe_2O_3**	**MnO**	**CaO**	**P_2O_5**
Y/18/S/29	2	7	7	63	nd	95	444	123	20	9	134	3	7	1435	120	2	0.46	28.75	1.49	2.22	0.36
Y/18/S/30	4	9	99	16	nd	78	343	111	27	19	350	18	14	1551	nd	nd	2.35	12.96	0.48	1.90	0.74
Y/18/S/31	17	15	39	27	36	186	426	44	19	10	225	7	9	834	212	nd	0.90	13.10	2.32	0.76	0.86
Y/18/S/32	3	8	25	14	nd	99	374	324	14	8	151	3	6	1005	67	2	0.81	22.66	0.30	4.26	0.87
Y/18/S/33	2	7	23	27	nd	135	592	361	24	11	134	6	15	1144	89	2	1.44	24.81	0.42	3.43	1.25
Y/18/S/34	38	7	8	109	264	187	368	228	10	5	132	3	7	941	60	nd	0.51	28.10	0.07	5.71	0.71
Y/18/S/35	7	8	10	42	16	69	299	115	8	6	172	4	3	1012	66	nd	0.73	20.04	0.10	1.62	0.74
Y/18/S/36	13	8	8	38	41	41	342	160	8	nd	156	2	8	958	173	nd	0.56	25.03	0.09	6.58	0.57
Y/18/S/37	14	8	8	85	45	68	397	100	8	5	125	1	1	1155	89	nd	0.52	29.11	0.10	1.56	0.48
Y/18/S/38	2	8	88	16	nd	167	838	161	31	25	293	27	23	1053	34	2	3.86	18.35	0.38	2.06	0.95
Y/18/S/39	1	8	53	25	nd	171	512	198	263	109	118	5	30	1141	50	2	1.45	26.37	2.92	3.68	0.91
Y/18/S/42	2	7	221	35	146	1519	3821	2	2	4	46	1	8	1006	98	2	5.81	23.53	0.21	0.57	0.04
Y/18/S/43	27	8	7	90	41	37	462	45	4	4	106	3	2	1378	50	1	0.42	37.43	0.06	1.52	0.31
Y/18/S/47	15	8	21	39	15	263	540	217	12	7	164	5	8	1058	99	1	0.65	26.19	0.28	3.51	0.86
Mean	**9**	**8**	**24**	**72**	**59**	**143**	**528**	**178**	**20**	**11**	**152**	**5**	**8**	**1097**	**135**	**1**	**1.00**	**25.26**	**0.51**	**3.18**	**0.66**
Minimum	1	7	2	14	4	32	218	2	2	4	46	1	1	813	34	1	0.30	12.96	0.05	0.57	0.04
Maximum	38	23	221	333	264	1519	3821	598	263	109	350	27	30	1551	511	2	5.81	49.63	2.92	7.25	1.47

Table 5.2. (ctd.) XRF analytical results of selected slag samples of *Yodhawewa* site 2018. UCC average from Rudnick and Gao, 2003. (nd=not detected).

Sample no.	**Trace elements (ppm)**																**Major Elements (wt%)**				
	As	**Pb**	**Zn**	**Cu**	**Ni**	**Cr**	**V**	**Sr**	**Y**	**Nb**	**Zr**	**Th**	**Sc**	**TS**	**F**	**Br**	**TiO_2**	**Fe_2O_3**	**MnO**	**CaO**	**P_2O_5**
Low Iron Salgs (LIS) (n=13)																					
Y/18/S/1	2	8	5	14	6	107	76	783	20	11	51	10	nd	940	945	nd	1.11	2.78	0.12	17.14	0.22
Y/18/S/7	5	8	14	50	22	79	156	350	15	8	198	6	3	901	nd	nd	0.95	8.18	0.09	4.07	0.77
Y/18/S/9	5	8	13	39	12	56	138	330	13	7	161	5	3	959	nd	nd	0.66	8.00	0.06	4.03	1.21
Y/18/S/14	2	7	4	13	nd	70	98	1146	19	11	112	11	nd	931	nd	nd	1.25	3.54	0.08	12.60	0.57
Y/18/S/19	2	9	16	19	31	115	85	584	19	11	154	8	nd	941	103	nd	1.06	3.27	0.12	11.56	0.34
Y/18/S/21	3	8	7	18	25	138	62	492	38	16	190	6	nd	1306	48	nd	0.99	2.28	0.19	13.46	0.36
Y/18/S/28	3	10	30	29	12	68	196	441	24	11	185	9	17	887	116	2	0.93	6.49	0.42	9.47	0.46
Y/18/S/40	2	8	4	16	3	81	95	1066	18	11	110	8	22	918	62	1	1.19	3.57	0.08	10.97	0.54
Y/18/S/41	2	7	3	18	1	76	75	1299	30	13	160	7	26	931	nd	1	0.89	2.59	0.07	17.96	0.37
Y/18/S/44	2	7	6	15	nd	76	73	758	24	12	59	8	28	1291	101	2	0.94	2.92	0.10	18.23	0.40
Y/18/S/45	3	7	5	25	11	56	77	933	21	10	120	8	26	908	31	2	1.03	3.77	0.11	15.84	0.56
Y/18/S/46	11	8	14	51	102	44	136	705	13	6	67	4	12	999	nd	1	0.62	8.27	0.06	7.03	1.03
Y/18/S/48	6	9	17	31	40	135	157	165	19	14	399	13	20	854	12	1	1.71	6.35	0.07	2.57	0.42
Mean	**4**	**8**	**11**	**26**	**24**	**85**	**109**	**696**	**21**	**11**	**151**	**8**	**17**	**982**	**177**	**1**	**1.03**	**4.77**	**0.12**	**11.15**	**0.56**
Minimum	2	7	3	13	1	44	62	165	13	6	51	4	3	854	12	1	0.62	2.28	0.06	2.57	0.22
Maximum	11	10	30	51	102	138	196	1299	38	16	399	13	28	1306	945	2	1.71	8.27	0.42	18.23	1.21
UCC	**5**	**17**	**67**	**28**	**47**	**92**	**97**	**320**	**21**	**12**	**193**	**11**	**14**	**621**	**557**	**2**	**0.64**	**5.04**	**0.10**	**3.59**	**0.15**

Table 5.3. Average, minimum to maximum elemental concentrations of soil, furnace wall fragments, and slag of *Yodhawewa* study compared to the upper continental crust. UCC from Rudnick and Gao (2003). nd=not detected.

Element	Soil Samples						Slag samples				UCC
	Soil Samples from Cultural Layers		Soil Samples from Natural Layers		Furnace Wall Fragments		High Iron (metal typed) slag		Low Iron (glass typed) salgs		
	(n=24)		(n=9)		(n=2)		(n=33)		(n=13)		
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	
Major elements (wt%)											
TiO_2	1.68	1.23 - 2.11	1.82	1.66 - 2.13	1.26	1.01 - 1.50	1.00	0.30 - 5.81	1.03	0.62 - 1.71	0.64
Fe_2O_3	6.97	3.54 - 9.35	6.55	3.29 - 9.45	4.36	4.23 - 4.48	25.26	12.96 - 49.63	4.77	2.28 - 8.27	5.04
MnO	0.21	0.14 - 0.29	0.23	0.18 - 0.28	0.13	0.12 - 0.14	0.51	0.05 - 2.92	0.12	0.06 - 0.42	0.10
CaO	0.88	0.76 - 1.70	0.83	0.77 - 0.92	3.78	3.55 - 4.00	3.18	0.57 - 7.25	11.15	2.57 - 18.23	3.59
P_2O_5	0.34	0.15 - 1.23	0.18	0.11 - 0.23	0.51	0.28 - 0.73	0.66	0.04 - 1.47	0.56	0.22 - 1.21	0.15
Trace Elements (ppm)											
As	8	4 - 15	7	4 - 11	3	3 - 4	9	1 - 38	4	2 - 11	5
Pb	18	12 - 22	18	16 - 19	10	8 - 12	8	7 - 23	8	7 - 10	17
Zn	55	33 - 68	52	37 - 63	32	23 - 42	24	2 - 221	11	3 - 30	67
Cu	77	26 - 470	107	37 - 261	27	25 - 29	72	14 - 333	26	13 - 50	28
Ni	78	28 - 141	65	28 - 100	54	40 - 68	59	4 - 264	24	1 - 102	47
Cr	132	112 - 175	133	89 - 157	107	100 - 114	143	32 - 1519	85	44 - 138	92
V	190	154 - 261	187	131 - 234	105	92 - 117	528	218 - 3821	109	62 - 196	97
Sr	47	32 - 98	40	36 - 47	198	183 - 213	178	2 - 598	696	165 - 1299	320
Y	19	11 - 25	17	12 - 23	19	19 - 19	20	2 - 263	21	13 - 38	21
Nb	13	10 - 14	13	12 - 14	12	11 - 13	11	4 - 109	11	6 - 16	12
Zr	351	278 - 447	377	329 - 440	279	245 - 313	152	46 - 350	151	51 - 399	193
Th	9	7 - 12	9	7 - 14	9	9 - 9	5	1 - 27	8	4 - 13	11
Sc	17	13 - 21	16	10 - 23	16	16 - 16	8	1 - 30	17	3 - 28	14
TS	863	843 - 918	876	835 - 1018	883	831 - 934	1097	813 - 1551	982	854 - 1306	621
F	103	2 - 364	93	25 - 183	105	105 - 105	135	34 - 511	177	12 - 945	557
Br	2	2 - 2	2	1 - 3	nd	nd	1	1 - 2	1	1 - 2	2

Table 5.4. Bulk chemical compositions of selected slags from the *Yodhawewa* site 2018

Sample no.	Trace elements (ppm)																Major Elements (wt%)				
	As	Pb	Zn	Cu	Ni	Cr	V	Sr	Y	Nb	Zr	Th	Sc	TS	F	Br	TiO_2	Fe_2O_3	MnO	CaO	P_2O_5
Y/18/S/13	5	7	3	50	nd	64	266	169	9	5	137	2	6	1045	nd	nd	0.44	19.12	0.08	2.86	0.56
Y/18/S/27	3	8	11	49	nd	116	414	195	20	9	149	3	8	1132	173	2	0.80	26.57	0.15	2.62	0.60
Y/18/S/28	3	10	30	29	12	68	196	441	24	11	185	9	17	887	116	2	0.93	6.49	0.42	9.47	0.46
Y/18/S/29	2	7	7	63	nd	95	444	123	20	9	134	3	7	1435	120	2	0.46	28.75	1.49	2.22	0.36
Y/18/S/30	4	9	99	16	nd	78	343	111	27	19	350	18	14	1551	nd	nd	2.35	12.96	0.48	1.90	0.74
Y/18/S/31	17	15	39	27	36	186	426	44	19	10	225	7	9	834	212	nd	0.90	13.10	2.32	0.76	0.86
Y/18/S/32	3	8	25	14	nd	99	374	324	14	8	151	3	6	1005	67	2	0.81	22.66	0.30	4.26	0.87
Y/18/S/33	2	7	23	27	nd	135	592	361	24	11	134	6	15	1144	89	2	1.44	24.81	0.42	3.43	1.25
Y/18/S/34	38	7	8	109	264	187	368	228	10	5	132	3	7	941	60	nd	0.51	28.10	0.07	5.71	0.71
Y/18/S/35	7	8	10	42	16	69	299	115	8	6	172	4	3	1012	66	nd	0.73	20.04	0.10	1.62	0.74
Y/18/S/36	13	8	8	38	41	41	342	160	8	nd	156	2	8	958	173	nd	0.56	25.03	0.09	6.58	0.57
Y/18/S/37	14	8	8	85	45	68	397	100	8	5	125	1	1	1155	89	nd	0.52	29.11	0.10	1.56	0.48
Y/18/S/38	2	8	88	16	nd	167	838	161	31	25	293	27	23	1053	34	2	3.86	18.35	0.38	2.06	0.95
Y/18/S/39	1	8	53	25	nd	171	512	198	263	109	118	5	30	1141	50	2	1.45	26.37	2.92	3.68	0.91
Y/18/S/40	2	8	4	16	3	81	95	1066	18	11	110	8	22	918	62	1	1.19	3.57	0.08	10.97	0.54
Y/18/S/41	2	7	3	18	1	76	75	1299	30	13	160	7	26	931	nd	1	0.89	2.59	0.07	17.96	0.37
Y/18/S/42	2	7	221	35	146	1519	3821	2	2	4	46	1	8	1006	98	2	5.81	23.53	0.21	0.57	0.04
Y/18/S/43	27	8	7	90	41	37	462	45	4	4	106	3	2	1378	50	1	0.42	37.43	0.06	1.52	0.31
Y/18/S/44	2	7	6	15	nd	76	73	758	24	12	59	8	28	1291	101	2	0.94	2.92	0.10	18.23	0.40
Y/18/S/45	3	7	5	25	11	56	77	933	21	10	120	8	26	908	31	2	1.03	3.77	0.11	15.84	0.56
Y/18/S/46	11	8	14	51	102	44	136	705	13	6	67	4	12	999	nd	1	0.62	8.27	0.06	7.03	1.03
Y/18/S/47	15	8	21	39	15	263	540	217	12	7	164	5	8	1058	99	1	0.65	26.19	0.28	3.51	0.86
Y/18/S/48	6	9	17	31	40	135	157	165	19	14	399	13	20	854	12	1	1.71	6.35	0.07	2.57	0.42
Mean	**8**	**8**	**31**	**40**	**55**	**167**	**489**	**344**	**27**	**14**	**160**	**7**	**13**	**1071**	**90**	**1**	**1.26**	**18.09**	**0.45**	**5.52**	**0.63**
Minimum	1	7	3	14	1	37	73	2	2	4	46	1	1	834	12	1	0.42	2.59	0.06	0.57	0.04
Maximum	38	15	221	109	264	1519	3821	1299	263	109	399	27	30	1551	212	2	5.81	37.43	2.92	18.23	1.25

The abundance of heavy metals average (As, Pb, Cu, Ni, Cr, V, and TS) of cultural and natural layers of both areas was higher than UCC values. However, In the furnace wall fragments, the average concentrations of As, Pb, and Cu were lower than UCC. In contrast, 94% of all samples had a zinc concentration lower than the UCC. A high percentage of copper was present in the cultural and natural layers of P1 and P2 (Ex.1 area), with a maximum value of 470 ppm, nearly 17 times higher than the UCC (Fig. 5.1).

There was no significant difference in the average abundance of lithophile and High Field Strength Elements (HFSE) such as Sr, Y, Nb, Zr, Th, Sc, and halogens like Bromine and Iodine between the two areas. However, the average abundance of Sr and F was lower than UCC, with a higher value of Zr, while the concentrations of the other elements were relatively similar to the UCC (Table 5.3).

5.2. Slags – XRF results - Geochemical characteristics of slags

Table 5.2 describes the geochemical abundances of HIS and LIS with mean, minimum to maximum range, and UCC values. Also, the summarized data is displayed in Table 5.3. The major elements such as TiO_2, Fe_2O_3, MnO, CaO, and P_2O_5 in the high iron slags were indicated as 1.01, 22.49, 0.47, 4.40, and 0.64 wt%, respectively. They were signified as 1.03, 7.02, 0.12, 9.66, and 0.57 wt% in the law iron slag means. The Fe_2O_3 content in the high iron slags varies between 2.92 - 49.63 wt% (Table 5.3; Fig. 4.7d), and c. 2.28 - 8.27 wt% were in law iron slags. The average abundance of Fe_2O_3 shown in high iron slags was approximately five (5) times higher than that of UCC. MnO and P_2O_5 were around five (5) times and four (4) times higher than UCC. Oxides other than CaO are relatively high in HIS, and LIS shows a significant growth (2.57 – 18.23 wt% on average) in CaO (Table 5.2).

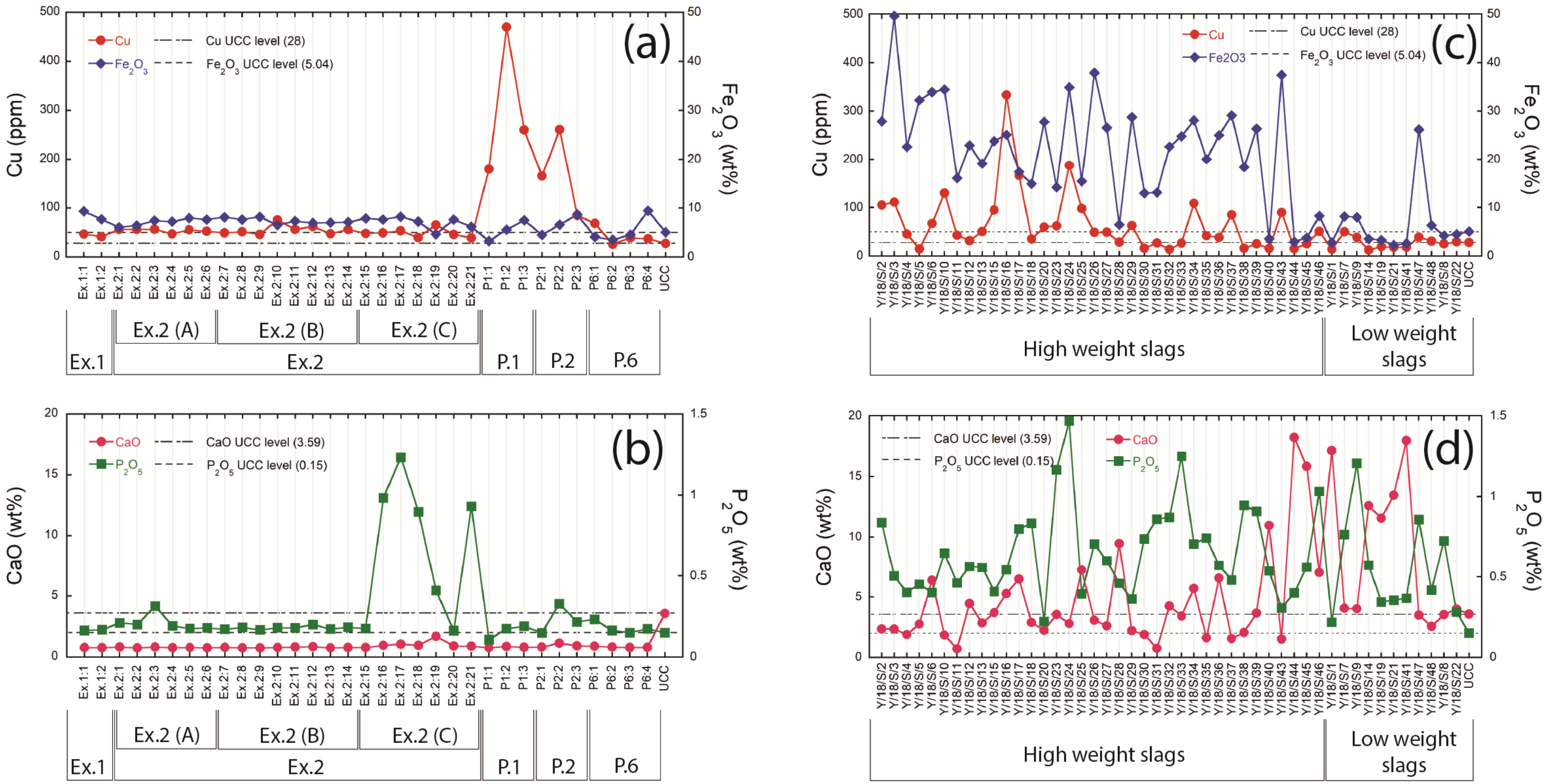


Fig. 5.1. Selected element concentrations of soil and slags (HWS and LWS) of the *Yodhawewa* site. (a) Cu and Fe_2O_3 concentration of soil, (b) CaO and P_2O_5 concentration of soil, (c) Cu and Fe_2O_3 concentration of slags, and (d) CaO and P_2O_5 concentration of slags.

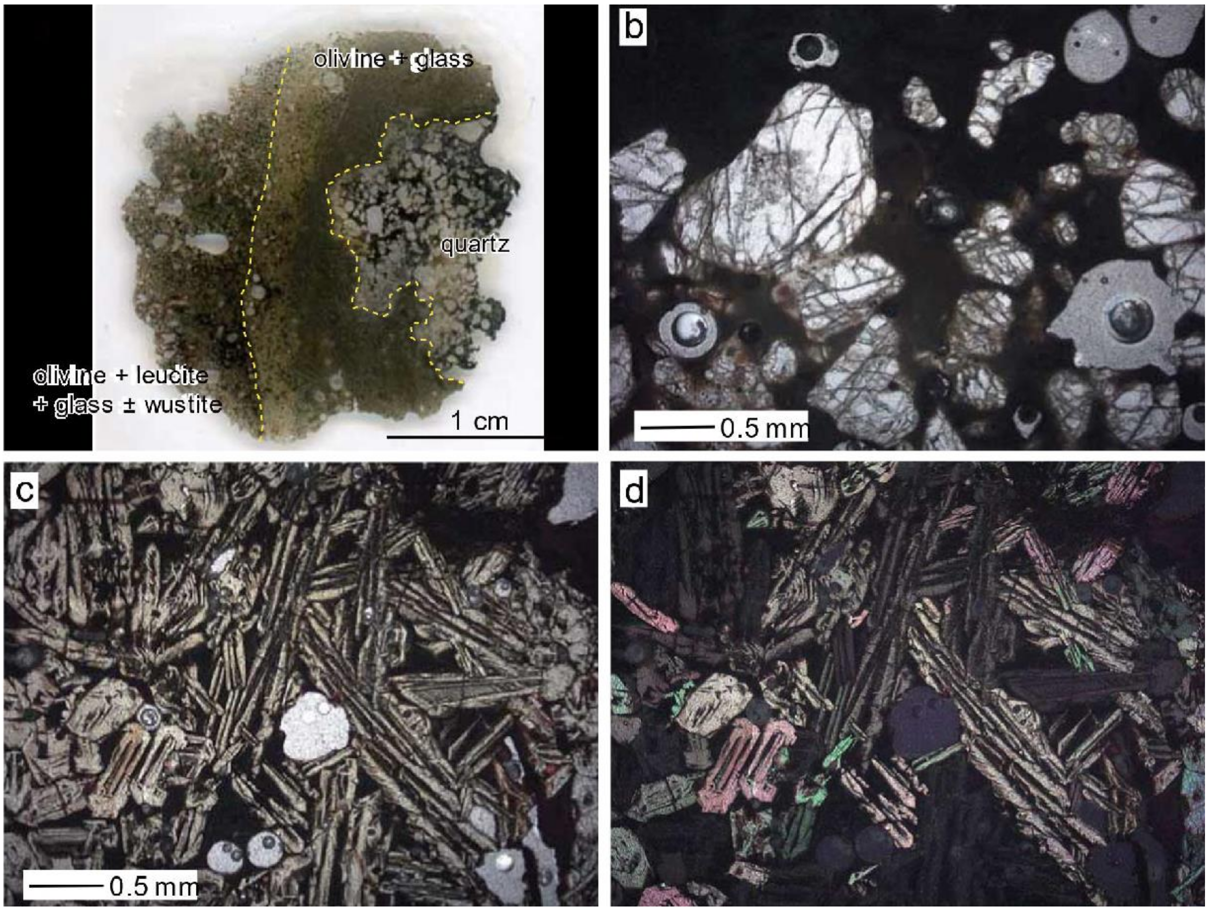


Fig. 5.2. Thin-section scanned image (a) and photomicrographs (b-d) of slags from the *Yodhawewa* site. Olivine-bearing slag is in contact with a domain containing rounded quartz grains (a, b; sample no. Y/18/S/13 in Table 5.4). Acicular olivine in the glass matrix (c, d; sample no. Y/18/S/35 in Table 5.4). b and c; plane-polarized light, d; crossed polarized light.

The average abundances of almost all heavy metals (As, Pb, Zn, Cu, Ni, Cr, V, and TS) concentrations of high iron slags were higher than law iron slags. The composition of the heavy metals As, Cu, Ni, Cr, V, and TS average of HIS exceeded the UCC value. The average of vanadium (471 ppm) was five (5) times higher than the UCC value, and that was the highest concentration ratio of all the elements in the entire slag samples. The maximum concentrations of heavy metals among HIS were represented as As (38 ppm), Pb (23 ppm), Zn (221 ppm), Cu (333 ppm) (Fig. 4.7b), Ni (264 ppm), Cr (1519 ppm), V (3821 ppm), and TS (1551 ppm). Concentrations of these elements of law iron slags were 15 ppm, 9 ppm (Fig.

4.7f), 21 ppm, 50 ppm (Fig. 4.7h), 40 ppm, 263 ppm, 540 ppm, and 1306 ppm, respectively (Table 5.2; Fig. 4.7). The average abundances of lithophile and HFSE elements (Sr, Y, Zr, Th, Sc, and F) in law iron slags were high, and the Nb and Br values were equal to those of high iron slags.

Cu and Cr (excluding sample Y/18/S/42, 1519 ppm) contents show 14-109 ppm and 37-263 ppm, respectively. Sample of no. Y/18/S/42 showing an extraordinarily higher value of V (3821 ppm) is an entirely different slag of the origination than others. TiO_2 and Fe_2O_3 contents of the slags (Table 5.4) range from 0.42 to 5.81 wt% and 2.59 to 37.43 wt%, respectively. P_2O_5 contents range from 0.04 to 1.25 wt%.

Table 5.5. Compositions of olivine and glass in slags of the *Yodhawewa* site and estimated olivine crystallization temperature (°C) from phase equilibrium.

no.	material	FeO (wt%)	D (Fe)	Ln (D)	T °C
1	glass	22.17	3.23	1.17	1087
2	olivine	71.55			
3	glass	26.94	2.66	0.98	1128
4	olivine	71.60			
5	glass	25.80	2.77	1.02	1119
6	olivine	71.44			
	average				1111

5.3. Slags – EPMA results

Two olivine-bearing slags (Y/18/S/13 and Y/18/S/35 in Table 5.4） were selected for the EPMA examination. Backscattered electron images show as Olivine in both samples is almost homogeneous (Table 5.3). The olivine compositions can be expressed as a solid solution among three end-members; fayalite (Fa: Fe_2SiO_4), forsterite (Fo: Mg_2SiO_4), and kirschteinite (Kir: $CaFeSiO_4$). The compositional range of olivine is $Fa_{92-98}Fo_{7-1}Kir_{3-1}$, suggesting near end-member fayalite. Leucite is close to ideal composition (KAlSi2O6). The exact composition of matrix glass cannot be determined due to submicron scale crystals. Glass enclosed in olivine crystals (Fig. 5.2a) has no precipitated minerals and is characterized by high FeO, K2O low SiO2 contents (Table 3.2). Euhedral olivine is surrounded by olivine-leucite intergrowths (Fig. 5.2d).

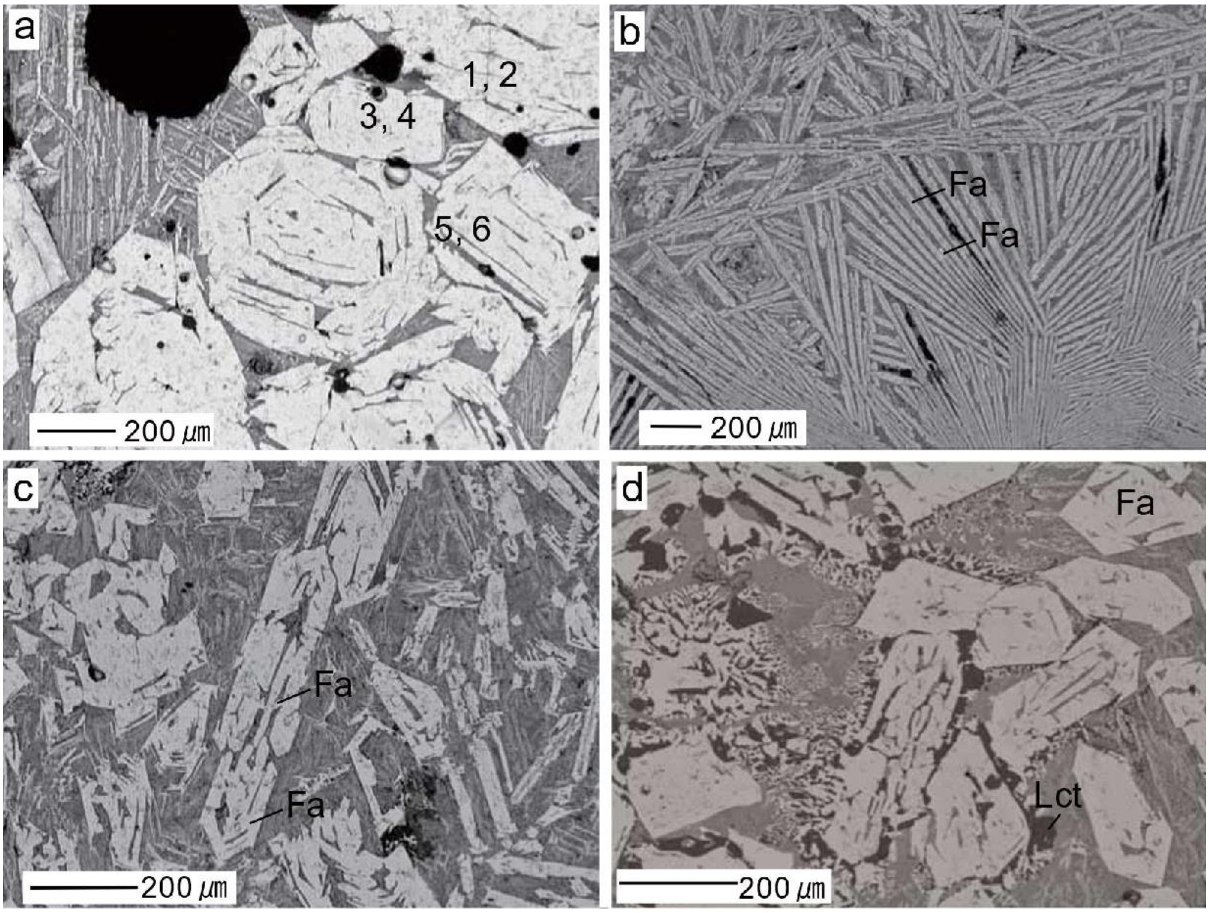


Fig. 5.3. Backscattered electron (BSE) images of olivine included in slags from the *Yodhawewa* site show various morphologies and textural relationships between olivine and other minerals. (a) euhedral olivine in the matrix (sample Y/18/S/35 in Table 5.4). The olivine contains inclusions of glass. Open circles show paired glass/olivine portions to examine the equilibrium partition coefficient using EPMA (Table 5.5). The matrix consists of glass and acicular olivine. (b) Elongated acicular olivine crystals (Fa). (c) olivine (Fa) of fletching shape (central portion) and olivine of irregular shape in the matrix. The matrix consists of glass and lint-shaped olivine. (d) Fine-scale olivine-leucite intergrowths locally surround euhedral olivine. Lct indicates leucite. b, c and d are sample no. Y/18/S/13 in Table 5.4, and away from the quartz-bearing domain (Fig. 5.2a) in this order.

Table 5.6. Conventional radiocarbon dating of each context of the second excavation of the *Yodhawewa* research in 2018 (After Wijepala, Young and Ishiga, 2021, 2022)

Sample No. (at the study - top, at the Beta analytic laboratory - bottom)	Locality		AMS dating results (Conventional radiocarbon age)		Accuracy
	Context No.	Height (MSL)	Calibrated date (cal AD)	Radiocarbon determination (cal BP)	
Y/18/Ex2/Sample/48 Beta- 517843	4C	11.45 m	**760 ± 30**	**1190 ± 30**	**95.40%**
			766 - 898	1184 - 1052	89%
			924 - 945	1026 - 1005	3.50%
			722 - 740	1228 - 1210	2.90%
Y/18/Ex2/Sample/64 Beta- 517844	4C	11.38 m	**730 ± 30**	**1220 ± 30**	**95.40%**
			762 - 887	1188 - 1063	74.50%
			692 - 748	1258 - 1202	20.90%
Y/18/Ex2/Sample/78 Beta-517343	4C	11.36 m	**730 ± 30**	**1220 ± 30**	**95.40%**
			762 - 887	1188 - 1063	74.50%
			692 - 748	1258 - 1202	20.90%
Y/18/Ex2/Sample/241 Beta-621697	22	11.55 m	**680 ± 30**	**1270 ± 30**	**95.40%**
			663 - 775	1287 - 1175	83.70%
			786 - 828	1164 - 1122	11.20%
			862 - 866	1088 - 1084	0.40%
Y/18/Ex2/Sample/27 Beta - 517342	5	11.61 m	**430 ± 30**	**1520 ± 30**	**95.40%**
			505 - 609	1445 - 1341	65.50%
			428 - 498	1522 - 1452	29.90%
Y/18/Ex2/Sample/159 Beta- 517842	12	11.45 m	**70 ± 30**	**1880 ± 30**	**95.40%**
			66 - 222	1884 - 1728	95.40%

5.4. Absolute dating

In preparing a contextual note chronologically, it is essential to inquire about the context in which the samples were acquired. Six charcoal samples collected from four different contexts in the Ex-2 were dated. The S-159 sample was obtained from (MSL=11.45) an accumulation (context 12) and was dated back to the c. 1st century AD. The S-27 sample was collected from (MSL=11.61) the context 4A, and its date was confirmed as belonging to the c. 5th century AD. The charcoal collected from the bottom filling (context 22) of the main furnace (context 5) dates back to the 7th century AD. The three subsequent samples were collected from layers unrelated to other contexts: the S-48 (MSL=11.41) sample was collected from the 4C context, and the S-64 (MSL=11.36) and S-78 (MSL=11.32) samples were collected from the 4D context. The datings confirmed that these three samples belong to the c. 8th century AD (Table 5.6; Fig. 5.4). Appendix-2 provides detailed radiocarbon dating results related to the *Yodhawewa* research provided by Beta Analytic laboratory, USA.

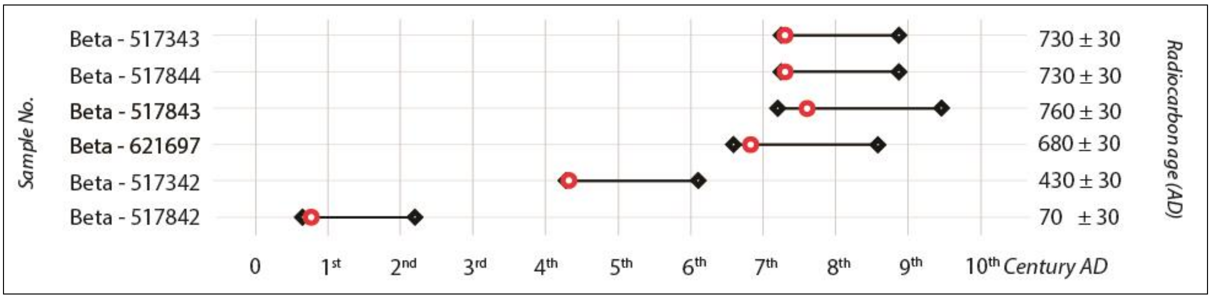


Fig. 5.4. Six conventional radiocarbon datings of the second excavation, *Yodhawewa* research in 2018

CHAPTER SIX

DISCUSSION: ARCHAEOLOGICAL SIGNIFICANCE OF *YODHAWEWA* SITE

6.1. Crucible typed furnaces and other furnaces used in metalworking

6.1.1. Lower half-spherical furnaces

The discovery of a lower half spherical metal furnace for the first time in Sri Lanka was a reason for the archaeological importance of the *Yodhawewa* premises. Inspection of the furnace chamber revealed that the artifacts pile was a natural or cultural filler of materials formed after being discarded from the furnace. The artifact collection contained many crucible and lid fragments used to make crucible steel. Many crucible and lid fragments used to make crucible steel have also been discovered in and around the second excavation. Although no such lower spherical metal furnaces were found in Sri Lanka until 2018, such crucible steel furnaces were found at the *Kodumanal* Megalithic site in Southern India (Sasisekaran and Raghunatha Rao, 2001; Gullapalli, 2009). In addition to the physical and structural similarities of *Yodhawewa* furnaces and *Kodumanal* furnaces, the surrounded crucible & lid fragments and other debris at the Yodhawewa site prove that the furnace used to produce crucible steel.

Solangaraarachchi (2011), quoting Coomaraswamy (1908) and Davy (1821), points out that the steelmaking furnaces were smaller than the iron ore smelting furnaces and were built at ground level. According to the description, this type of furnace was semi-circular and made of a low clay wall about six inches above the ground. After considering the above statements and the practical functionality, it was decided that the name "Crucible-shaped-Furnace" was more suitable for the *Yodhawewa* furnace. Inevitably, since several ingots were needed at once, the furnace's mouth should be prepared more openly so that several crucibles could be handled simultaneously and wood charcoal could be fed into the furnace as needed. In practicality, this operation, which takes a lot of time and effort, cannot be assumed to have taken place in anticipation of a single steel ingot.

The interior plaster of the furnace chamber usually acts as a thermal insulation layer, as shown by other research (Weisshaar, Roth and Wijeyapala, 2001; Parr and Boyd, 2002). The furnace's thermal insulation plaster (daub) had weakened over long periods of use and has been maintained by recoating.

Furnace construction and use: According to the archaeological evidence, the lower half-spherical furnaces should pass several stages in the user context.

(a) Crucible-shaped furnace made on the ground using clay pieces

(b) Firing the air-dried crucible furnace structure - Open firing on the ground

(c) Making the functional Furnace wall (daub) in a pit

(d) Finish with an inner plaster coat on the top half of the furnace

(e) Secondary firing after complete furnace preparation

(f) Functional step for crucible-steel making

The furnace was not a finish made of separately prepared bricks or pieces of bricks. Since the furnace wall's shape represents a spherical shape, it is clear that the furnace was designed in a completely separate location (Fig. 6.1a). During this time, space should also be saved for the air intake pipe leading out of the furnace wall. The clay pieces on the furnace outside the wall were also very well burned, which was a reason to interpret that the clay structure had been burned before the furnace was installed at the working site (Fig. 6.1b). A wall made of unglazed clay is a condition that can be expected to crack during drying and firing (Fig. 6.1c).

For making the functional furnace wall (daub), burnt clay pieces' assembly in a suitable pit has been done with a specially prepared clay mortar. Straw-like plant parts may be added during the preparation of this clay mortar to withstand the furnace surface's compression and dispersion during combustion. It was revealed that the upper part of the remaining furnace was covered with a plaster coat (daub) about 1-2 cm thick and that on several occasions, several coatings were applied on top of each other. This is an excellent example of how the same furnace has been used for long-term steelmaking. This layer often acts as a thermal insulation coat (Parr and Boyd, 2002; Weisshaar, Schenk and Wijeyapala, 2001) and may be reapplied to cover the damage caused by the wall during the long-term firing (Wijepala, S M Young and Ishiga, 2022a).

The furnace wall should be raised slightly (about 15-20 cm) to above ground level (Solangaraarachchi, 2011), then lightly air-dried and fired a second before actual usage. The furnace may have been activated using the charcoal and ballow method like the actual furnace for this second fire (Fig. 6.1d). Juleff (1996b) followed a similar approach in his section on experimental archeology in *Samanalawewa*. Eventually, the furnace was used for long-term use for crucible-steel production. Coomaraswamy (1962) points out that about six crucibles were activated in a Steel furnace like this at once. Chronology has also confirmed that the only furnace designed in this manner has been in use for a long time, especially on the *Yodhawewa* premises (Wijepala, S M Young and Ishiga, 2022a).

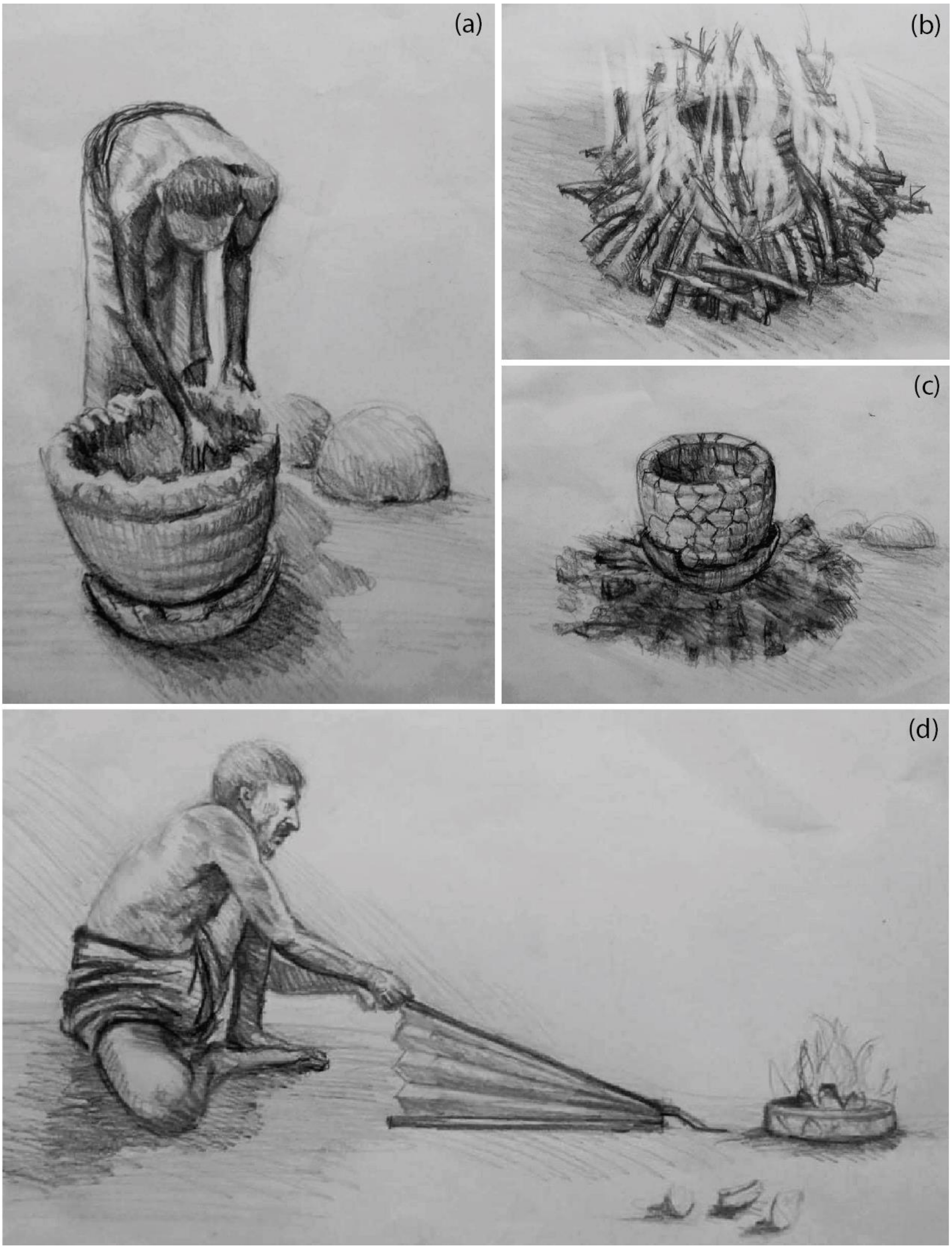


Fig. 6.1. Steps to make a crucible-shaped steel furnace until activated. (a) Crucible-shaped furnaces are made on the ground using clay pieces. They may use a rounded fragmented earthenware base for making the rounded crucible base (b) Open firing the Crucible Furnace structure on the ground (c) Cracked furnace structure after the open firing process (d) Furnace activated by the bellow method after re-built furnace fragments in a pit (Drawn by Nalin Jayarathna) (after Wijepala, S M Young and Ishiga, 2022).

6.1.2. Other Furnaces

Although archaeological evidence confirms that copper-based metalwork (extraction, refining, alloying, or manufacturing) took place in the Ex-1 area, no clear evidence of such furnaces was found in this research. The metal extraction work has taken place at the Yodhawewa premises, as confirmed by air supply tuyeres, refractory clay fragments of the furnaces, and a slag pool discovered at the site. However, evidence of the nature or functionality of such a furnace was not found in field excavations.

6.2. Metal (Iron) Extraction in the *Yodhawewa* site

Archaeological studies have uncovered much important information about metalworking in the *Yodhawewa* site. Slags, crucible, metal, and furnace wall fragments are the main material factors in the focus on metalworking in this site. Many slags (n=6226) were recovered from the Ex-02 premises (Table 3.1); the context of 2, 4, 8, 10, 11, 12, 14, and 16 shows the highest density. Slags were collected at 48.61% of the total artifact density of the *Yodhawewa* research (Fig. 4.4). Excavations in the *Samanalawewa*, *Matale*, and *Sigiriya* areas of Sri Lanka have uncovered many more essential facts about iron smelting furnaces (Juleff, 1996b, 2013, 2015; Solangaraarachchi, 2011).

As essential factors that confirm iron smelting in the *Yodhawewa* site, tuyere, tap slag, and furnace wall fragments have been identified here. Two fragments of unvitrified air supplying tuyeres (into metal extraction furnaces) were discovered during the exploration (Fig. 6.2). The *Yodhawewa* tap-slags were usually black, red, or reddish-brown in color (Fig. 4.7a). The color of the slag functions in the 'metallurgical chain', and the chemical composition usually hinders using slags to identify the initial metallurgical processes (Killick, 2014). With their unique visual appearance, Typical tap slags are the best indicators for identifying the iron smelting locations (Eliyahu-Behar *et al.*, 2013). The tap slags are recognized from the ropey texture on their upper surfaces, indicating they cooled from molten, flowing slag, most probably out of the furnace (Georgakopoulou, 2014). Oxidation of slag (Fig. 4.7c,d) exposed to the environment due to environmental influences can be seen on the surface as not all iron has been removed from the source during the iron smelting process (Ettler *et al.*, 2015). Otherwise, Slags were largely discarded during the smelting process, which also usually acts as an indicator of the amount of metal extracted (Juleff, 1996b).

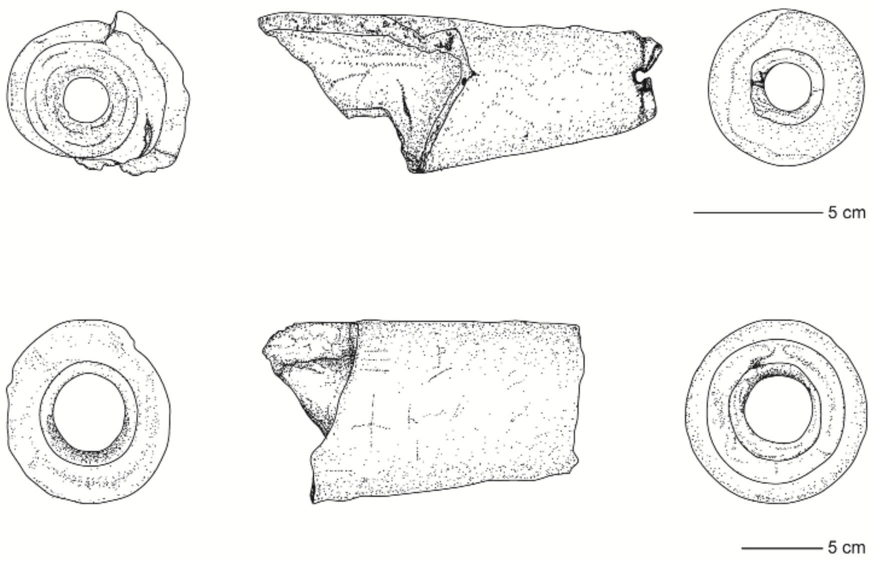


Fig. 6.2. Different types of two 'Tuyere' fragments were collected from the *Yodhawewa* survey 2018 (Wijepala, Young and Ishiga, 2021).

In total, 251 furnace wall fragments (1.79% of total artifacts) were discovered during the *Yodhawewa* research (Table 3.1; Fig. 4.4), confirming an abundance of iron extraction at this site. However, this research did not identify the complete or fragmented iron-smelting furnaces in sitve evidence.

6.3. Crucible Steel Production of *Yodhawewa* Area

The crucible fragments of *Yodhawewa* (Ex-2 area) show similar characteristics to the *Mawalgaha* (Juleff 1996b) and the *Hattota-Amune* crucibles (Juleff 2015) found in the central highlands of Sri Lanka (Fig. 6.3). *Yodhawewa* and *Mawalgaha* crucibles have following similarities: (a) dark blue/green glassy vitrification shows the entire outer surface, (b) elongated tube shape rounded base, (c) quite rough texture, and (d) very dark brown/black fabric. The contents are more comfortable to smelt and more accessible to handle when the crucible is elongated (Erb-Satullo, Gilmour and Khakhutaishvili, 2015; Juleff, 2015). The lining of glass slags and the honeycomb pattern found on the bottom part of the inner crucibles would have been the result of being occupied by molten charge and solid ingot (cake) of some steel crucibles in South and Central Asia (Srinivasan, 1997; Feuerbach, 2002; Srinivasan and Ranganathan, 2004; Srinivasan *et al.*, 2009). These particular characteristics can also be seen in the crucibles of *Yodhawewa* and the other two locations (Fig. 6.3).

Small iron particles were deposited on the upper inner wall of the crucibles and lids due to explosive droplets (splashes) with bubbles in the melting metal solution (Srinivasan, 1997), which can also be seen in *Yodhawewa* steel crucibles (Fig. 6.3c). One or more perforations (Fig. 6.3b,c) can be seen in the crucible lids used to make steel in *Yodhawewa* and elsewhere in Asia (Juleff, 1996b, 2015; Prakash, 2001; Feuerbach, 2002). Perforations of lids balance the heating pressure when melting the charge inside the crucible (Coomaraswamy, 1962). The physical forms of the steel crucible in Sri Lanka fit well with Srinivasan's account of the steel-producing crucibles found at *Mel-Siruvalur* near the *Tiruvannamalai* city of *Tamil Nadu* and *Machnur* and *Tintini* near the banks of the Krishna river in the *Raichur* in *Karnataka* District (Juleff, 1996b, 2015; Srinivasan, 1997, 2013; Srinivasan *et al.*, 2009).

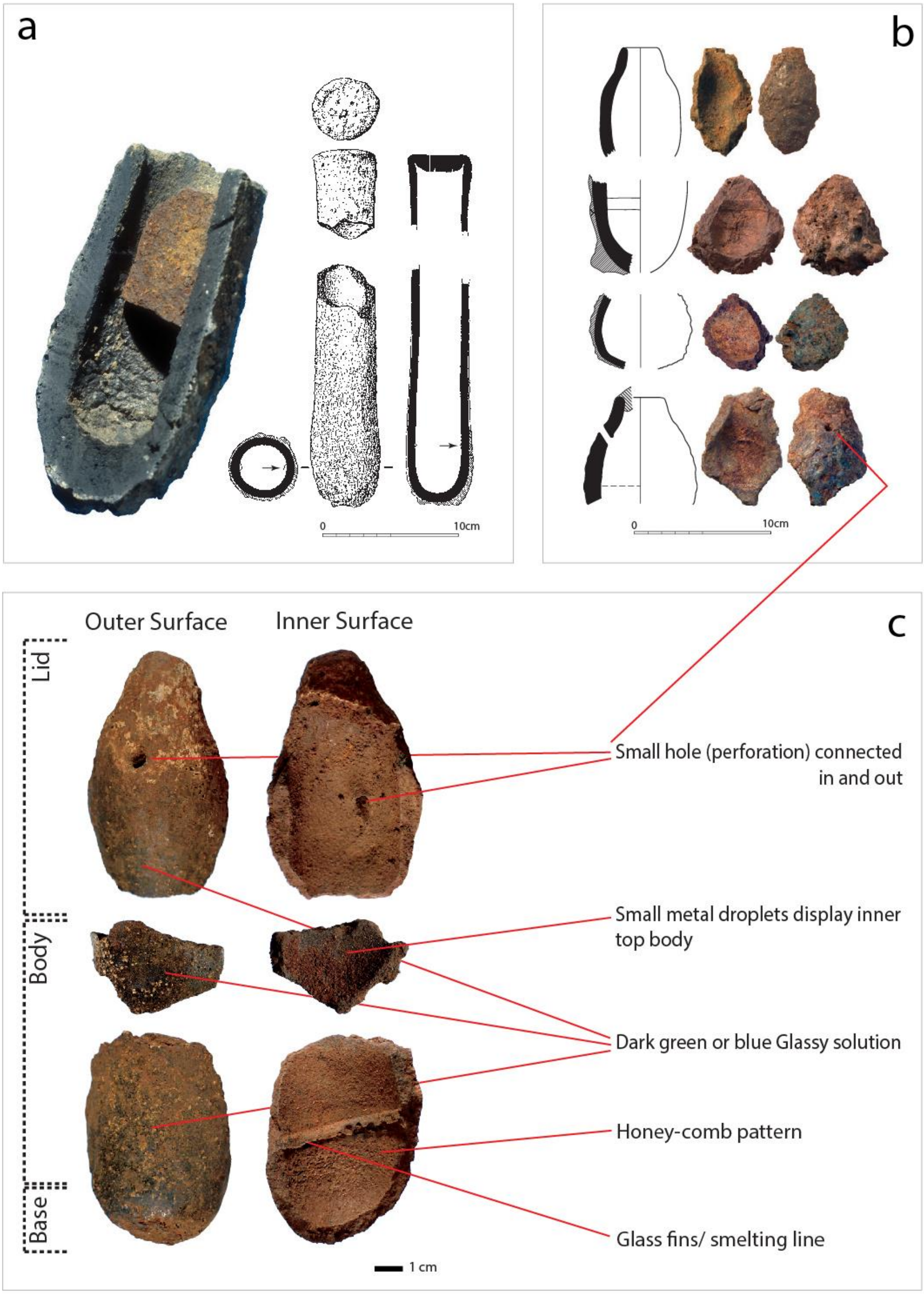


Fig. 6.3. Crucibles for making carbon steel in Sri Lanka (a) Early crucibles from the Samanalawewa area. (b) Most complete crucible fragments, including an example with sidewall perforation (bottom). (c) Crucibles were found at the *Yodhawewa* site in 2018. (Reference for a and b; Juleff, 2015)

Crucibles can be pointed out as a significant artifact in studying ancient steel production through carburization. Strengthening by adding carbon to wrought iron is known as the cementation process or carburization, and the second step described as decarburization is to remove carbon from cast iron (Srinivasan and Ranganathan, 2004). The macro-morphological features of crucibles from Mawalgaha, Hattota-Amune, and some South Indian archeological sites were identified, which reflected similar characteristics of the Yodhawewa (Ex-2 area) crucibles.

Crucible steel production was one of the significant metal activities identified in the *Yodhawewa* research. Crucible steel production was one of the significant metal activities identified in the Yodhawewa research. The site reveals several significant facts about iron extraction, and it can be concluded that steelmaking was also carried out at the site in parallel with iron extraction. Three main iron production processes can be identified in the past; wrought iron, cast iron, and steel —moreover, steel products were the most qualitative variant (Srinivasan and Ranganathan 2004). The raw iron (wrought iron) produced soon after the extraction process is a soft and spongy substance that must be mixed with carbon in the right proportions to obtain sufficient quality and hardness (Solangaraarachchi 2011; Juleff 1996b; Saravanan 2017). The acceptable carbon content of the steelmaking process results in sufficient metal hardening without instability (Gururaja Rao, 1970).

As mentioned above, it has been established that the *Yodhawewa* metalworking site was operated in the 1st – 8th centuries AD, based on the relative and absolute chronology. Reports of Al-Kindi and other Islamic writers state that high-quality steel was produced in Sarandibi (Sri Lanka) in the 9th century AD (Juleff, 1996b). Further, she suggests that Sri Lanka must have produced high-quality steel in the 6th and 7th centuries, as the peak of the high carbon steel trade between Sri Lanka and the Islamic world was in the 9th century. Technologically advanced west-facing steel furnaces in the *Samanalawewa* area and the contemporary steel production at *Hattota-Amune* further strengthen this suggestion (Juleff 2013, 2015). However, considering the chronological results of *Yodhawewa* Ex-2, research into the contemporary Sri Lankan crucible steel production, and the statements of Islamic writers such as al-Kindi, it can be pointed out that the ancient metalworkers of *Yodhawewa* produced the most dynamic crucible steel in the 8th century AD.

Mannar port was the primary gateway for Sri Lanka's exposure to the world in the past. Thus, the main commercial port during the early *Anuradhapura* Kingdom period was *Mantai (see Chapter 2.2)*, and there was a high probability of global technological migration to Sri Lanka through South India. The *Yodhawewa* is a primary production site established near the significant harbor of *Mantai* at the commencement of the metal ore search journey towards the central highlands of Sri Lanka. Besides, the above information confirms that the crucible steel production technology development took place simultaneously in the central highlands and coastal areas of Sri Lanka, parallel to South India. It is possible to assume the acceptance of an inevitable global or South Indian influence if an indigenous technological source did not influence crucible-Steel production.

6.4. *Yodhawewa* Copper working

The physical characteristics and inclusions of the *Yodhawewa* crucibles in the Ex-1 area conclude that they were used for copper metalwork such as extraction, refining, alloying, or production. The wall thickness and the reddish fabric on the outer crucible surface found at the *Yodhawewa* Ex-1 area were similar to crucibles reported to have been uncovered during the Mannar excavations in 1980-84 (Juleff, 2013).

The main reason for assuming that copper was extracted here is the presence of copper particles in the slag (Fig. 4.10 *right*). Further, it should be noted that slag containing copper particles can be removed as a by-product in the iron extraction process using composite metal ores (Craddock and Meeks, 1987). The presence of copper particles in the crucibles (Fig. 4.10 *left*) discovered in the Ex-1 area (especially in profiles 1 and 2) indicates that copper worked here. In addition, sub-heading 6.5 describes how glass content in slag can be formed as a by-product in copper extraction. Crucibles were used in copper work to make copper tools and alloying (Juleff, 2013). Considering the source material (copper ore), following a few researchers' hypotheses (Seneviratne, 1985; Juleff, 2013; Srinivasan, 2016), it can be assumed as copper ore transported from the *Seruvila* deposit in the eastern part of Sri Lanka has been utilized for the copper needs of *Mannar* and South India. Also, geological facts about copper ore have not been revealed in the *Yodhawewa* area.

6.5. Slag: a by-product of metal extractions and refining

The physical properties of the *Yodhawewa* slag collection were compared with several previous studies on the physical properties of iron, copper, and steel slags. According to Juleff (1996b), the presence of circular slag "cakes" of various sizes indicates bowl or shaft furnace designs. Johansen (2014) confirms that approach, quoting Craddock (1995), Schmidt (1997), Sim (1998), and declaring separated slag gangue from the iron smelting furnaces. Furthermore, tap slag has also been found on that sites. Slag cakes abounded in the *Yodhawewa* slag collection, and tap slag was predominantly red and black (Fig. 4.7a).

Juleff (1990, 1996b, 2013, 2015) pointed out that a certain amount of glassy slag originates from the steel ingot in the crucible during crucible steel production. Inside the crucibles, this slag strip is visible as glassy fins (Fig. 6.3 a,b,c). Hence, some of the slags found in the

Yodhawewa premises can be identified as glassy slag formed during crucible steel production.

Examination of the physical and macro-morphological characteristics of the Yodhawewa slag with the other research findings can confirm their association with the iron, copper, and crucible-steel metalwork of the premises. Red, gray, brown, or black colored metal slag and blue, white, and green vitreous or "glassy" type slag can be identified as proof of the copper extraction process (Hegde, 1981; Gorai, Jana and Premchand, 2003; Rehren, Boscher and Pernicka, 2012). It has been confirmed that glassy slag is released during copper and crucible steel production. It is shown that residual slag is transformed into light-color glassy ceramics during the separation of iron from the copper batch (Yang et al., 2013). Some of the slags found during the Yodhawewa exploration had oxidized copper particles and this confirms the availability of a certain percentage of copper in the metal ores used for the extraction (Fig. 4.10 right).

6.6. Relative Dating for *Yodhawewa* chronological sequence

Since the possibility of a significant change in stratification of important ancient metalworking sites in the South Asian region due to long-term utilization, researchers have focused on strengthening chronological interpretations using comparative data from other material cultures, in addition to the absolute chronology (Solangaraarachchi 2011; Juleff 1996; 2015; Srinivasan and Ranganathan 2004). Accordingly, materials, such as selected fragments of foreign ceramics, porcelain, and numismatics evidence, were used as relative dating materials.

Black and Red Ware (BRW) is a unique type of pottery that went through a technologically developed process from the Early Iron Age (related to the megalithic burial practices) to the historical period of India (Mohanty, 2013). Despite some differences in typography and fabrics, there are more than 150 archaeological sites with BRW pottery in Sri Lanka, including early Iron Age megalithic burial sites, regional and urban settlements, and port cities (Begley, Lukace and Kennedy, 1981; Seneviratne, 1984; Dharmawardene, 2015). However, a "Fine Gray Pottery" tradition, including the Rouletted Ware (RW) type, was developed as an extension of the Black and Red Ware pottery type in the South Asian region from 200 BC to 200 AD (Schenk, 2006). These two types of ware fragments were homogeneous in shape and texture and were found in more than 150 places, mainly in the early settlements of South Asia. These were found in *Mantai*, *Anuradhapura citadel*, and *Tissamaharama* in Sri Lanka (Deraniyagala 1972; Begley 1988; Schenk 2001; 2006; 2015; Magee 2010; Mohanty 2013).

Black and red ware (BRW) and Rauletted ware (RW) ceramics (Fig. 4.8a,b) were discovered during the *Yodhawewa* survey; however, they were not found in excavations. Archaeological evidence suggests that the BRW pottery type was produced locally over a long period (Seneviratne, 1984; Dharmawardene, 2015); however, by examining their physical characteristics, it can be identified whether the BRWs are local or imported. There was no evidence of making RW locally in Sri Lanka. Since both BRW and RW found in the *Yodhawewa* site represent the "Fine Gray Pottery" type, the study area dates back to BC. 200 to 200 AD (Schenk, 2006) can be determined to have been used for human needs.

In addition, a close cultural relationship between China and Sri Lanka existed in ancient times due to the trade and travel through the silk road, and this has been confirmed archaeologically by Chinese porcelain found in various sites in Sri Lanka. Many types of

Chinese porcelain have been unearthed in such sites inland and along the sea coast of Sri Lanka. These types include Stoneware, Yueh ware, Dusun type Storage Jars, Changsha Stoneware, Black glazed ware of the Tang Dynasty (617-908 AD), and the Yue celadon ware of the Middle Tang period (756-827 AD) (Carswell, 2013). Similarly, various types of Chinese porcelain have been unearthed from several excavation sites in *Mantai*, and the excavations of 1980-84 have paid particular attention to Changsha porcelain (Carswell, 2013; Linrothe, 2013). These Changsha porcelain sherds (Fig. 4.8c) represent the relevant period, and evidence suggests that the *Yodhawewa* evidence maintained direct or indirect international relations with China from 7th to 10th centuries AD.

Based on the ancient Mannar port, Sri Lank rulers' diplomatic and personal relations with the South Indian Kingdoms were previously discussed *(see chapter 2.2)*. The coin's obverse depicts a lion standing in the middle of a circle of beads, and the reverse portrays a large flower pot (d) and belongs to the Pallava dynasty of South India. The Pallava kingdom was established in the 7th – 8th centuries AD, centered around the *Kanchipuram* area, and the Pallava kings implemented a regime that brought significant political stability to the South Indian region (Dirks, 1976; Avari, 2016). It was a short-lived kingdom, but they maintained political relations with Sri Lanka during that period, confirming that *Mannar* was an important port in those relations (Bohingamuwa, 2017). Codrington (1994) points out that Pallava coins were acquired by the ancient *Mannar* port city area (*Tirukketisvaram*, a Hindu pilgrimage place) and various archaeological sites in *Anuradhapura*.

CHAPTER SEVEN

DISCUSSION: GEOCHEMICAL SIGNIFICANCE OF THE *YODHAWEWA* SITE

7.1. *Yodhawewa* Soil - Verticle distribution of elements Ex.1 and Ex.2 areas

More detailed geochemical signatures were studied on selected elements (As, Pb, Cu, Zn, Cr, Ni, Sr, V, Zr, Nb, Fe_2O_3, TiO_2, MnO, and P_2O_5) in the vertical soil layers of Ex.1 and Ex.2 areas (Fig. 7.1, Fig. 7.2). Although the cultural and natural stratification of both areas is similar, the artifacts show the difference in territorial and cultural activities. The first and second cultural layers of Ex.1 do not indicate a drastic change in elemental composition, and such differences can be seen in the vertical layers of P1 and P2. Overall, Cu stands out among the elemental contents, signifying significant differences in the cultural and natural layers of P1 and P2 (Fig. 7.1). The Maximum copper value represents P1 and P2 anthropogenic layers and suggests the copper is exotic to the context, not expressing such a high composition from the nearest Ex.1 pit or entire Ex.2 area (Fig. 7.1, Fig. 7.2, Fig. 7.3a). They are more likely to accumulate in the soil due to copper-related production activities. Manganese is often associated with minerals such as iron, copper, nickel, and cobalt, and the concentration may vary during extraction or raw material used in the premises (Fuerstenau and Han, 1983). Therefore, changes in the reactivity of MnO of that area's cultural layers may result from copper metal works. The P_2O_5 and Zn enrichment can be highly correlated with human waste and wood ash inputs (Aston, Martin and Jackson, 1998). Thus, prolonged metallurgical activity over a long period may have influenced changes in other mineral compositions indicated by the vertical distribution (Fig. 7.1a,b,c) of the Ex.1 area.

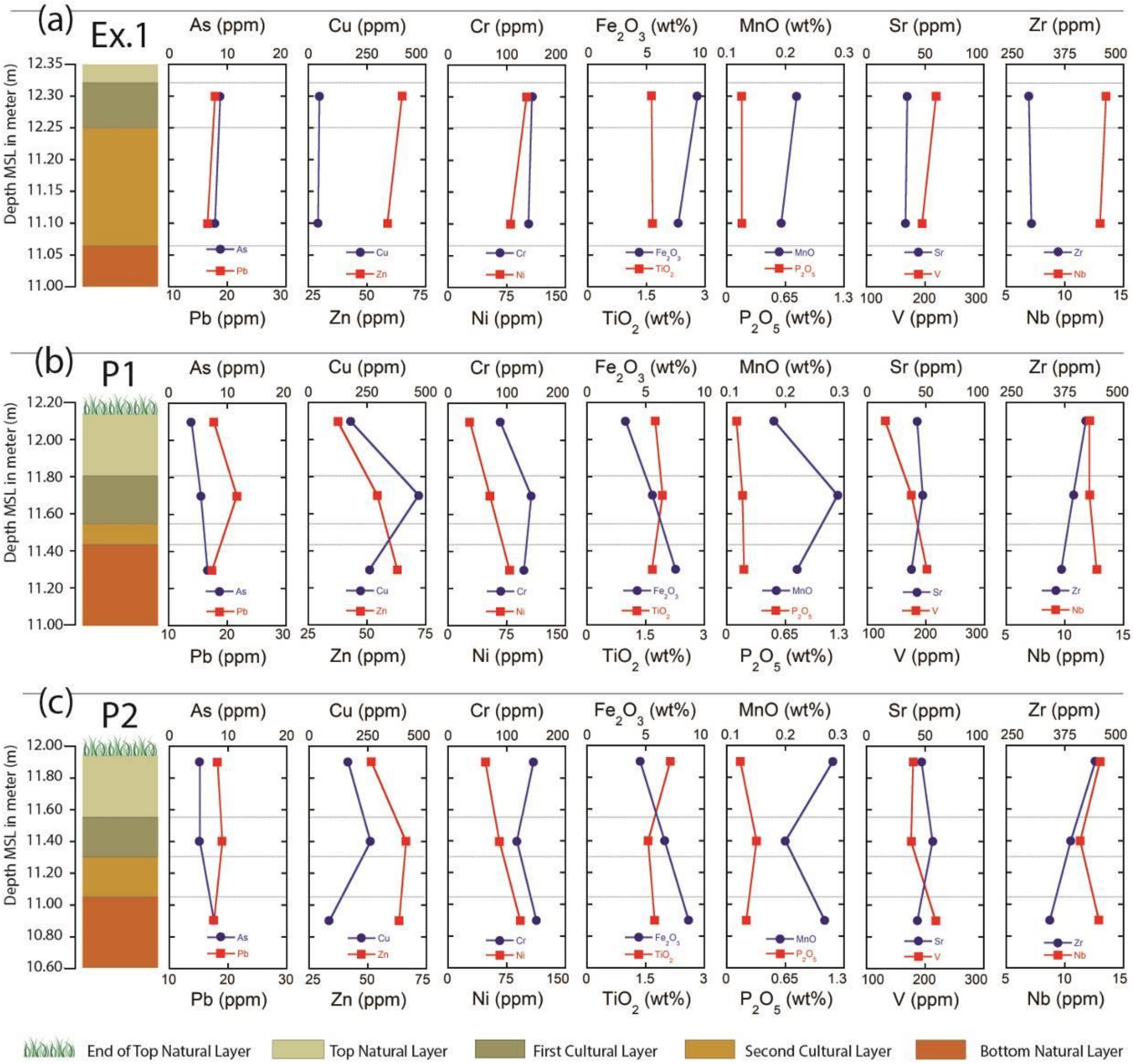


Fig. 7.1. Vertical distribution of As, Pb, Cu, Zn, Cr, Ni, Sr, V, Zr, Nb, Fe_2O_3, TiO_2, MnO, and P_2O_5 in Ex.1 area *Yodhawewa* site (*n*=8). (a) Ex.1, (b) P1, and (c) P2.

Twenty-five samples from Ex.2(A) (n=6), Ex.2(B) (n=8), Ex.2(C) (n=7), and P6 (n=4) were studied to analyze the vertical concentration pattern of elements in Ex.2 area (Fig. 7.2). Significant variations in major oxides and heavy metals can be identified in the cultural layers of this region. It has been identified from much research in different areas that the composition of heavy metals and major oxides in soils varies with industrial mining and smelting (Aston, Martin and Jackson, 1998; Gautam *et al.,* 2016). However, low Cu content could be detected in the natural and cultural layers of the Ex.2 region.

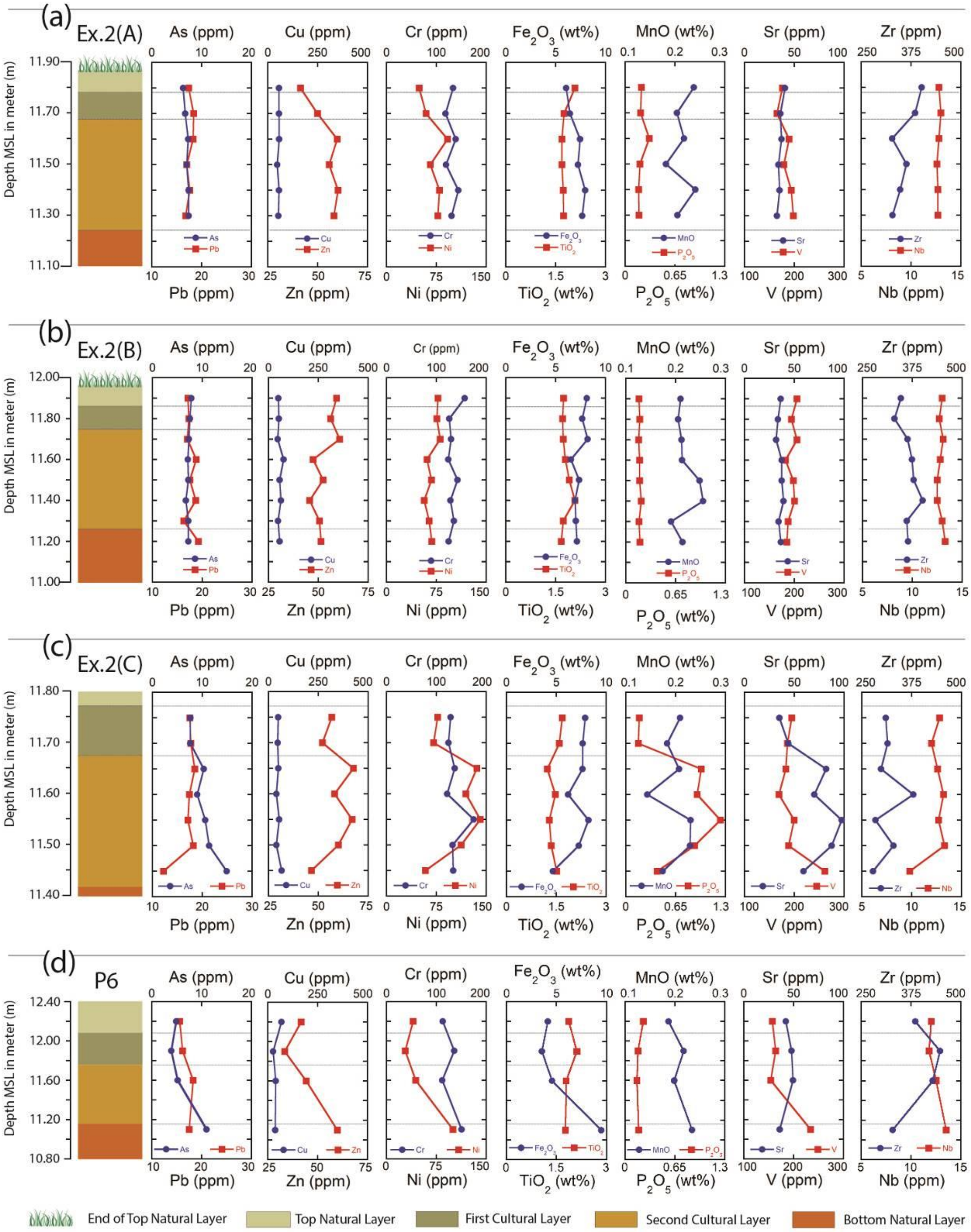


Fig. 7.2. Vertical distribution of As, Pb, Cu, Zn, Cr, Ni, Sr, V, Zr, Nb, Fe_2O_3, TiO_2, MnO, and P_2O_5 in Ex.2 area *Yodhawewa* site (*n*=25). (a) Ex.2(A), (b) Ex.2(B), (c) Ex.2(C), and (d) P6.

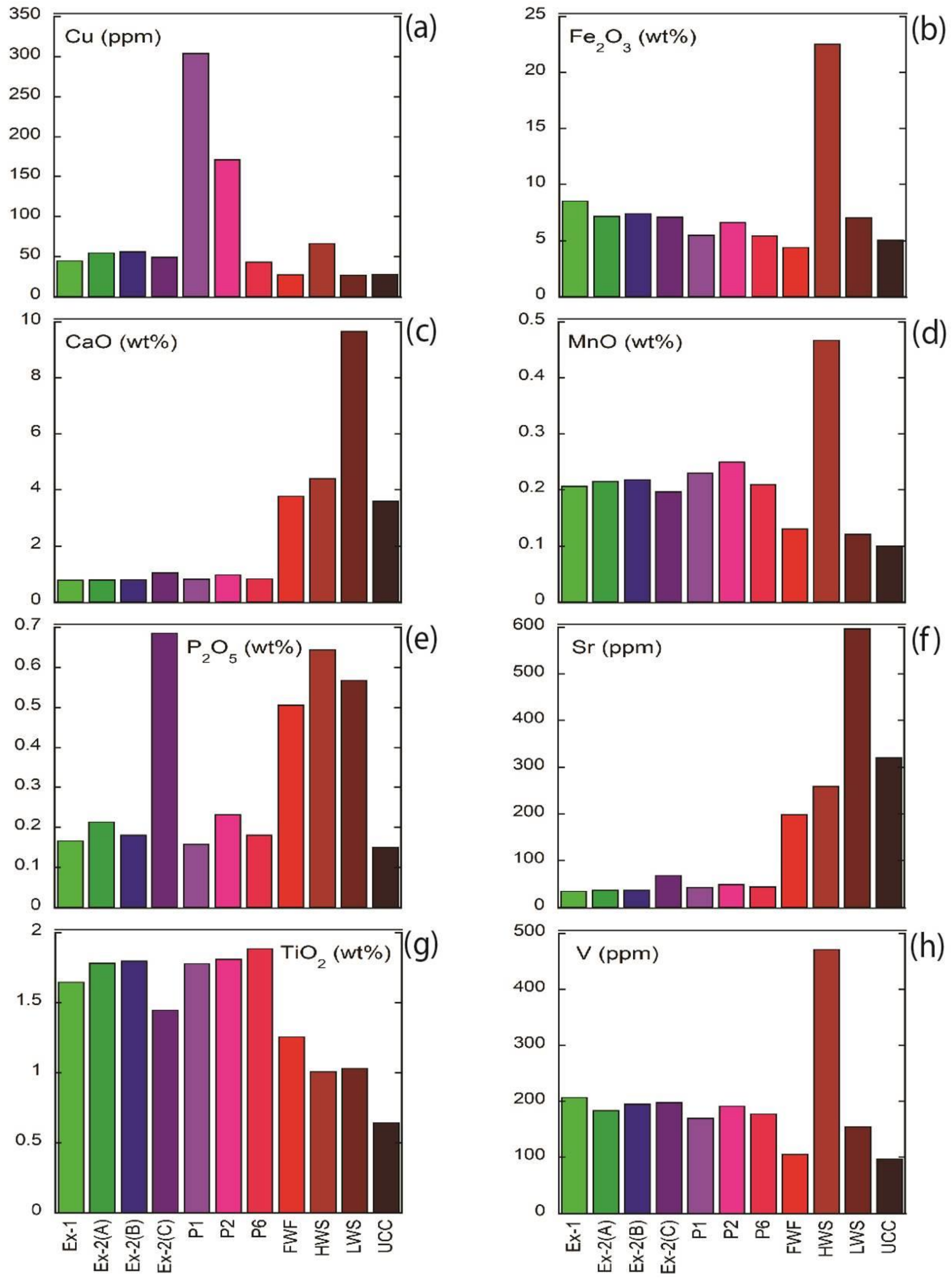


Fig. 7.3. Selected element concentrations of different soil (Ex.1, Ex.2(A), Ex.2(B), Ex.2(C), P1, P2, P6), Furnace Wall Fragments (FWF), HIS (n=33) and LIS (n=13) samples of the *Yodhawewa* site with UCC. (a) Cu (b) Fe_2O_3 (c) CaO (d) MnO (e) P_2O_5 (f) Sr (g) TiO_2 (h) V.

Significant changes in the vertical deposition pattern of the elements in this premise were identified in the Ex.2(C) samples. The second cultural layer shows significant changes in some elements such as Zn, Cr, Ni, V, MnO, P_2O_5, Sr, and Zr (Fig. 7.2c, Fig. 7.3d,e,f,h). The vertical arrangement of elements such as As, Pb, Cu, Cr, Ti, V, and Nb remains stable, confirming that none of the region's significant cultural or natural activities affected those elements (Fig. 7.3g). Juleff (1996b) states that the clay was prepared to construct the *Samanalawewa* experimental furnace based on indigenous knowledge of the area (by mixing black paddy-field mud, termite-mound earth, river sand, red alluvial gravel, fresh paddy husk, charred paddy husk, and cut paddy straw), which is durable and resistant to high temperatures. The use of such unique raw materials in the design of the *Yodhawewa* furnace wall may be reflected in the different elemental arrangements of Ex.02(c). The presence of phosphorus concentrations in Ex.02(c) samples (Fig. 7.3e), which are not present in the soil samples of the entire *Yodhawewa* research, also confirms the use of organic matter in the preparation of these clays.

The red color of the reddish earth results from the long-term release of free iron oxide from the ferromagnesian minerals (Reuter, Harzhauser and Piller, 2020). As Koralegedara *et al.* (2021) point out, magnetite (~1 wt%) and ilmenite (~1 wt%) are the major Fe-containing minerals in the red soil of the *Mannar* region. Thus, it is confirmed that this region's earth contains a certain percentage of iron. However, the Fe content of the soil in the entire *Yodhawewa* area did not exceed twice the UCC value (5.04 wt%), and the maximum was 9.45 wt% (Table 5.3, Fig. 7.3b). In the Fe extraction process, it was common practice to extract near the ore deposit; however, when the soil composition of the premises was examined, it was revealed that no such raw material had been obtained from the premises and that the metal processing ore had been imported from outside. Evaluating soil and slag correlations against Tio_2 also does not show similar correlations (Table 7.1).

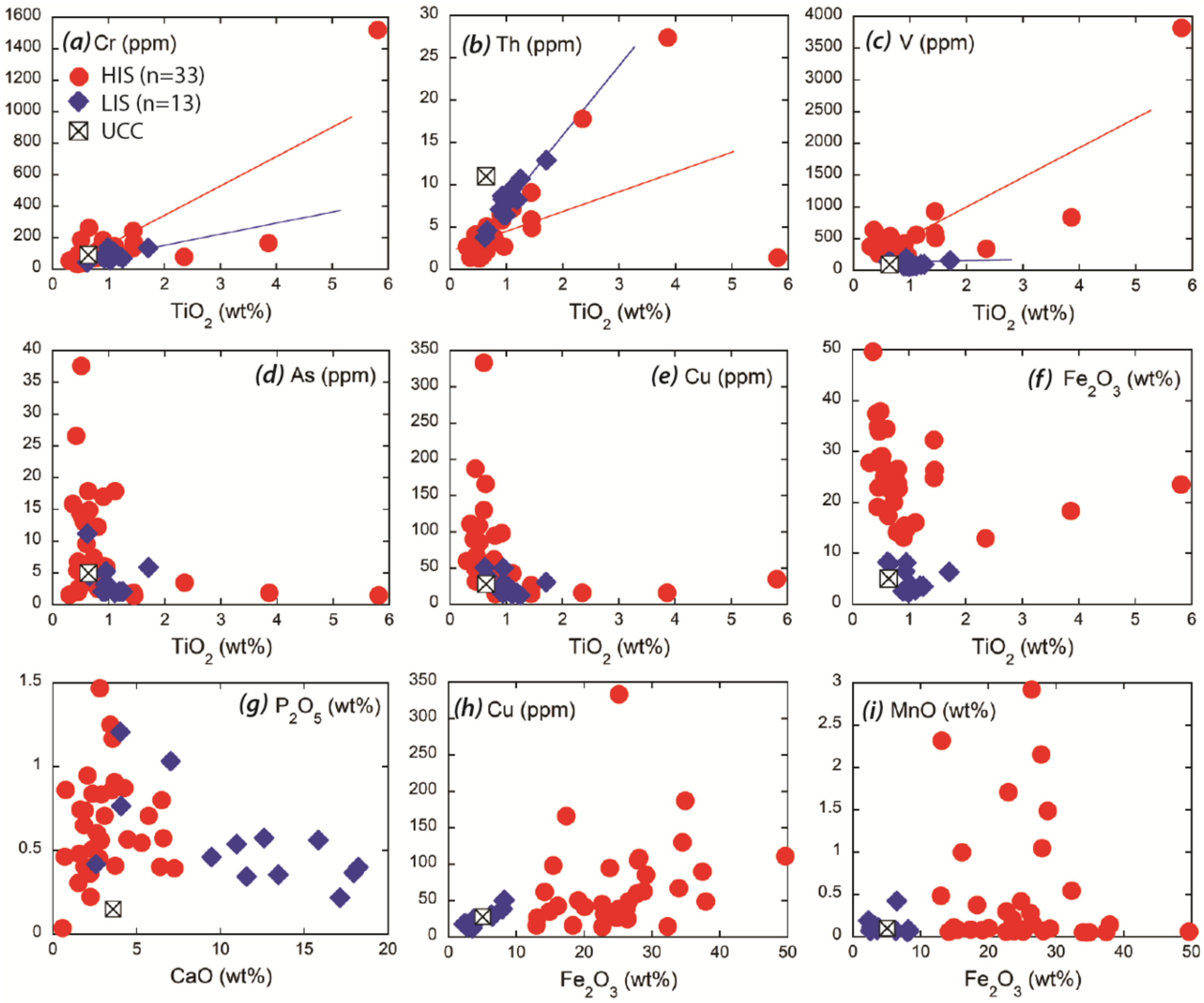


Fig. 7.4. Element correlations with TiO_2, CaO, and Fe_2O_3. *(a)-(b)* Strong positive (Cr and Th) correlations of HIS and LIS with TiO_2. *(c)* A strong positive of HIS and a Weak negative of LIS represented V against TiO_2. *(d)-(f)* As, Cu and Fe_2O_3 presented a weak negative correlation of both slags against TiO_2. *(g)* Correlation between P_2O_5 and CaO of both slags. *(h)* Cu against Fe_2O_3 and *(i)* MnO to Fe_2O_3 relationships presented HIS and LIS. (n=46).

7.2. Inter-element relationship of slags

The *Yodhawewa* geochemical data of HIS and LIS (n=45) was subjected to correlation analysis to explore possible associations between variables (Table 7.1). Titanium (TiO_2) indicated correlations with other HIS and LIS elements; their reduction or conversion during smelting is relatively low (Takeda, Ouchi and Okabe, 2020). Analyzing the correlations between HIS and LIS in the slag sample revealed evident discrepancies. Coefficient correlations resulted under four categories: strong, moderate, weak, and no-correlated (Table 7.1). Zink (r=0.95), Cr (r=0.82), and V (r=0.84) of HIS showed strong positive correlations against TiO_2 (Fig. 7.4a,c). Among LISs, only Th presented a strong positive correlation (r=0.92) (Fig. 7.4b). The overall slag analysis observed no strong negative correlations of elements; however, Cu represented weak negative correlations (r=-0.30 and -0.40) of HIS and LIS (Fig. 7.4e). Some elements show strong or moderate positive correlations in one slag type (Zn, V, Nb, and Zr) and do not show in another (Table 7.1, Fig. 7.4c). The elements As, Ni, Sr, Y, TS, F, Fe_2O_3, and MnO do not significantly correlate with both types of slags (Fig. 7.4d,f). Basal linear tendencies are rare in the elemental deposition pattern against TiO_2 and often have scatterings of one or both types of slag (Fig. 7.4a-i). In general, the stability and content of the major and trace elements change during a metal extraction process. Also, the metal ore elements at the extraction end can be integrated with the raw metal (result) in various quantities to strengthen or weaken the metal, mix with slags, or be lost during combustion (Coustures *et al.*, 2003; Ettler *et al.*, 2015). During metal extraction, refining, or steel-making stages, the correlation levels between the elements may also change due to the reduction or conversion of the essential elemental components (Coustures *et al.*, 2003).

In a typical iron extraction process, elements such as nickel or copper combine with iron, and elements such as manganese and zinc are mixed into the slag (Tylecote, 2002; Maslak and Skiba, 2015). The correlations between TiO_2- Fe_2O_3, CaO-P_2O_5, Fe_2O_3-Cu, and Fe_2O_3-MnO (Fig. 7.4f-i) are presented separately in HIS and LIS suggesting that the results from two or more different processes. Fig. 7.4i shows that a significant number of samples of HIS had a considerable amount of MnO (0.5–3 wt%). It allows defining that HIS is the waste of iron extraction.

Table 7.1. The r-value of soil and slag correlations against TiO_2.

Elements	Soil with TiO_2		Slags with TiO_2	
	Coeffiicent *r* (Cultural Layers) (n=24)	Coeffiicent *r* (Natural Layers) (n=9)	Coeffiicent *r* (HIS) (n=33)	Coeffiicent *r* (LIS) (n=13)
As	-0.71	-0.31	-0.29	-0.27
Pb	0.17	-0.10	0.02	0.30
Zn	-0.71	-0.43	0.95	-0.04
Cu	0.17	-0.09	-0.30	-0.40
Ni	-0.83	-0.46	0.14	-0.22
Cr	-0.23	0.13	0.82	0.64
V	-0.21	-0.25	0.84	0.01
Sr	-0.70	0.63	-0.21	-0.09
Y	-0.57	-0.50	0.11	0.09
Nb	-0.05	-0.06	0.18	0.55
Zr	0.70	0.67	0.17	0.60
Th	-0.41	-0.60	0.50	0.92
Sc	-0.37	-0.35	0.46	0.10
TS	0.34	0.34	-0.05	-0.27
F	-0.14	-0.03	-0.10	0.10
Br	0.38	0.39	0.46	0.11
Fe2O3	-0.37	-0.44	-0.27	-0.28
MnO	0.41	0.47	-0.01	-0.07
CaO	-0.42	0.15	-0.31	-0.09
P2O5	-0.78	0.04	-0.13	-0.56

	Coefficient *r*	
	Positive	Negative
Strong	1.00 to 0.80	-0.80 to -1.00
Modarate	0.79 to 0.50	-0.50 to -0.79
Weak	0.49 to 0.30	-0.30 to -0.49
No correlation	0.29 to 0.00	0.00 to -0.29

The P_2O_5 in HIS samples increases while CaO in LISs gradually increases (Fig. 7.4g). The high or low P_2O_5 composition of the slag is mainly based on combustion nutrients (charcoal) used in the extraction process. Further, phosphorus is reduced under conditions very close to iron, and the decisive factor is that charcoal behaves as essential to reducing conditions during iron smelting (Craddock, 2000; Morel and Serneels, 2021). However, in crucible steel production, a minimal amount of dried wood is incorporated into the crucible, which does not remove the slag as it absorbs enough of the steel ingot (Juleff, 1996b; Srinivasan and Ranganathan, 2004).

The increase in CaO in LIS compared to HIS is significant. Charcoal contains about 5wt.% of ashes, including CaO (Morel and Serneels, 2021). Also, due to the reduction properties of CaO, refining slags may contain a higher percentage of CaO than iron extraction slags. Some evidence use of various carbonates (such as oyster shells) in wootz steel production has been found in historical crucible-steel production sites of Southern Iran (Feuerbach, 2002). The glass fins in the crucible inside revealed by the *Yodhawewa* research were primarily a slimy green glass content removed as slags (Wijepala, S M Young and Ishiga, 2022b). Juleff (1996b, 2015) described that these slag fins were made of thin slag skin on top of the molten metal inside the crucible (Fig. 6.3). In addition, discoveries of green glass slag have been reported from the South Indian region and Central Asia. Therefore, it is undeniable that transparent or translations, green glassy slags (Fig. 4.7e) among LIS are the by-products of crucible steel production.

Variation of bulk chemical compositions of slag suggests stages of refining iron to the steel product. The slag in the crucibles is almost not removed during crucible steel production and is released into the environment when the ingot is removed after the steel forming required level. Removing the slag during the production process is possible to keep the charge at the desired rate in the crucible. However, It is natural for the slag as well as the crucible to be damaged when this ingot is taken out. Green transparent or translucent glass slag can be a few centimeters in size and largely unstable due to this action.

7.3. Olivine Crystallization and the Wüstite

The glassy slag can be considered waste generated when sequentially smelted iron. Under the condition of higher temperatures over 1200 ^{o}C, cast iron could be in a liquidus state. The melting temperature of iron slags with impurities is supposed to be much lower than this temperature. Then they were cooled and led to the crystallization of olivine. The present description clearly demonstrated the morphological variation of olivine crystals (Fig. 5.2 and Fig. 5.3). The euhedral shape indicates the slower temperature drop, and the fletching shape and acicular crystals represent relatively faster crystallization. This morphological change is related to the distance from the quartz-bearing domain (Fig. 5.2b-d). Therefore, the slag might have been quenched in contact with quartz sand.

During the Old Iron Age, fayalite, wüstite, and leucite were reported from smelting and smithing slags from Lithuania (Selskienė, 2007). Similarly, fayalite and hercynite were recorded in the iron slags in Thailand, and their supposed operating temperatures exceeded 1100 ^{o}C (Chuenpee *et al.*, 2014). They both considered that the bloomy process conducted smelting. As for others, Eliyahu-Behar *et al.* (2012) reported olivine and wüstite in iron slags in Isreal. Further, Humphris *et al.* (2018) did the experimental smelting at an archaeological site in Sudan. Juleff (1996) examined the large furnace using natural wind-powered iron smelting in Sri Lanka. The systematic construction of a furnace and a blast by bellows is like Japanese "*Tatara*" steel manufacturing (Inoue, 2010). Few reports appeared on the determination of slag melting temperature using the calibration of the equilibrium partition coefficient and occurrence of index minerals. The next issue is the identification of the source material. It is still tricky for no evidence, such as iron ore, found near the study area.

7.4. Upper continental crust – normalized geochemical characteristics of slags

Concerning the normalization of *Yodhawewa* slags, the average compositions of HIS and LIS types represent high, parallel, and departure patterns against the UCC (Fig. 7.5). Almost all heavy metals are shown at higher and lower levels of HIS above UCC, and Pb and Zn are aligned parallel to the regression line. Considering the average of major oxides, CaO was moderately high in LIS, while Fe_2O_3 and MnO were high than UCC in HIS. However, TiO_2 and P_2O_5 coincided with UCC levels. The lithophile element was almost all aligned with the reaction line, and only the Sr average of the LIS was high. All heavy metals are absorbed into HIS with a higher composition than LIS, and V reflects the highest density. However, it should be noted that some heavy metals, such as zinc (Zn) or arsenic oxide (As_2O_3), may be volatilized partially or entirely during the extraction process (Morel and Serneels, 2021). Since the melting point of vanadium is 1929 ^{o}C, it is more likely to combine with slag during the iron extraction process before homogenizing with the metallic phase (Moskalyk and Alfantazi, 2003; Morel and Serneels, 2021). Further, researchers predict that the lithophile elements (Sr, Y, Nb, Zr, Th, Sc, F, and Br) are more likely to be combined with slags during the iron smelting process (Coustures *et al.*, 2003; Brauns *et al.*, 2013).

Strontium (Sr) is an alkaline earth element whose properties closely follow the CaO origins of plagioclase, calcite, and feldspars (Simmons, 1999). The composition of Sr with the raw material used for CaO requirement is more likely to establish in LIS. Only Sr and CaO are higher in LIS than HIS among normalized lithophile and major oxide elements (Fig. 7.5). Some glassy slags and siliceous residuals were reported among the copper smelting slags, with low Fe_2O_3 and high CaO contents from historical metallurgical sites (Derkowska, Świerk and Nowak, 2021; Hauptmann, 2021). Since iron and copper ores are often intertwined, it is futile to look for completely separate slag from each other. Seneviratne (1995), who focuses on the metal deposit in the *Seruwila* area of Sri Lanka, points out that it contains both magnetite and copper sulfides. However, the presence of geochemical clues regarding the copper extraction here also confirms the archaeological evidence of copper metalworks.

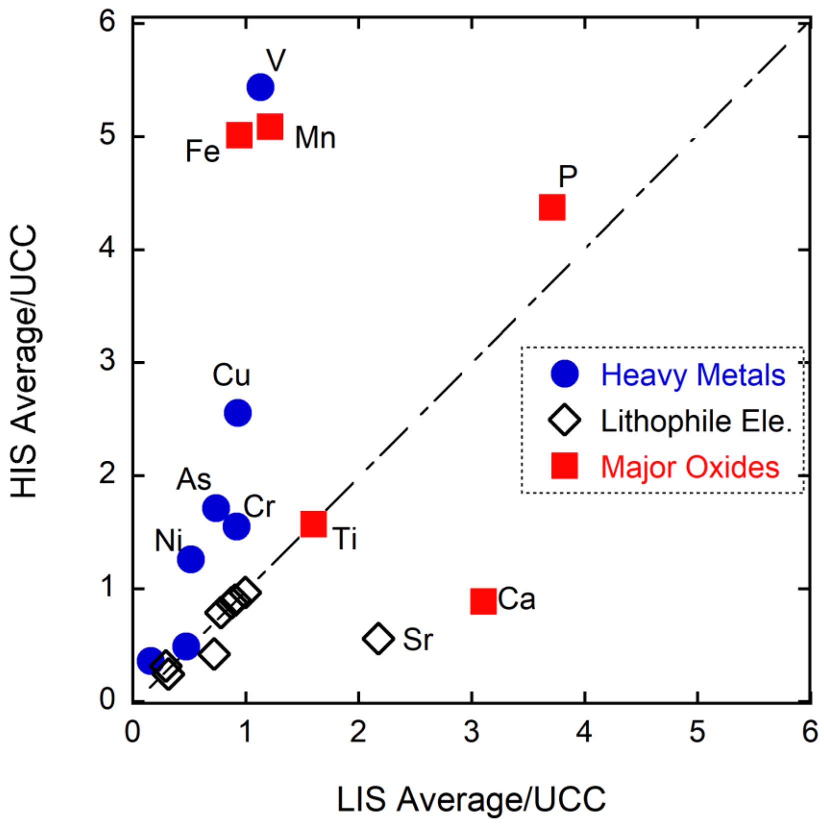


Fig. 7.5. *Yodhawewa* HIS and LIS samples normalized against the Upper continental crust (UCC). The regression line = UCC. Lithophile elements were Sr, Y, Nb, Zr, Th, Sc, F, and Br.

7.5. Olivine in the slags

Olivine in the slags is close to the end-member fayalite composition ($Fa_{92\text{-}98}$). The glass composition is roughly intermediate between fayalite and leucite, except for high CaO content (Table 3.2). As the first approximation, we discuss the crystallization sequence of the slags based on the phase diagram of the fayalite-leucite binary system (Roedder, 1951; Barron, 1972). Euhedral fayalite crystals are surrounded by fayalite-leucite intergrowths (Fig. 5.2d). During cooling, this texture implies a crystallization sequence from the fayalite field to the fayalite-leucite eutectic line. The fayalite-leucite eutectic temperature in the binary system is 1128°C at 1 atm (Roedder, 1951; Barron, 1972). This temperature represents the crystallization temperature of leucite in the slags. The initial crystallization temperature of olivine must be higher than the eutectic temperature but much lower than the single-phase fayalite melting temperature of 1205℃.

Olivine crystallization is limited in the range 1128–1205℃ in the fayalite-leucite binary system, but the deviation of the slag compositions from the binary system results in lowering the lower limit olivine crystallization temperature. Therefore, we also estimated olivine crystallization temperature based on Fe partitioning between olivine and glass. The simplest expression of the relation between partition coefficient and temperature is written as follows.

Ln D (Fe) =A / T + B ; where D (Fe) is equilibrium partition coefficient given by olivine / glass ratio. A (9016) and B (-5.46) are given coefficients by Leeman and Scheidegger (1977). Values of D (Fe) of sample 10-A (Fig. 5.2a) are indicated in Table 5.5. The estimated temperature is to be 1111 ℃ on average (Table 5.5), suggesting a representative crystallization temperature of olivine. The olivine crystallization temperature derived from both approaches is consistent (>1100 ℃), which constrains the smelter's minimum temperature.

7.6. Dating for the *Yodhawewa* metalworking site

There are three main stages in the chronology of the *Yodhawewa* second excavation pit; 1^{st}, 5^{th}, and 7-8^{th} centuries AD (Table 5.6). S-159 Sample demonstrated 70 ± 30 and is the oldest date the *Yodhawewa* site has received. Context 12 was an assemblage containing slags, pottery pieces, and crucible fragments stretched from the beginning to the end of the second (bottom) cultural layer (context 4). The bottom level of context-12 represents the excavation's ending level (context-4E); the S-159 sample can be interpreted as an accurate dating determination of the context. However, the S-27 sample was inverted in terms of the stratigraphic sequence. We have considered the possible causes of the inversion, such as land preparation for furnace construction, post-production activities, incorrect labeling of the samples, or misidentifying the sample (The exact dates can be compared in Table 5.6). All three samples from the 4C and 4D contexts represented the 8th century AD, and relevant contexts in which the samples were collected were unaffected by other contexts. The charcoal date obtained from the main furnace's inner base represents the end of the 7th century AD. It is the last period of using the furnace.

CHAPTER EIGHT

SUMMARY AND CONCLUSIONS

Among the archeological evidence related to South Asian historical metalwork, the archeological findings of Sri Lanka have a significant place. Through its latest survey, *Yodhawewa* research (2018) was possible to make some remarkable discoveries regarding ancient metalwork in Sri Lanka. This thesis aimed to present definitions of past metalworking through the multidisciplinary approach to the cultural and natural factors revealed in the *Yodhawewa* site.

The thesis consisted of seven chapters concerning archaeological and geochemical analyses. Chapter One; A fundamental approach was taken to explain the origins and development of the archaeometallurgy discipline focusing on geochemical research. Further, there was an overview of research based on South Asian copper, iron, and crucible steel production technology. The later part of the chapter covered a historical and archaeological outline of metallurgy in Sri Lanka. Considering recent archaeological records, Juleff's *Samanalawewa* research (1990-1996) and Solangaraarachchi's Sigiriya (Kiri Oya basin) research (2004-2006) stand out as notable metallurgical research.

The second chapter focused on the geo-environmental setting of the study area, including the macro-environmental vicinities and the historical background of Sri Lanka. A brief focus was given to the archaeological research history based on the *Mantai* ancient port city near (12 km) *Yodhawewa* because it was directly correlated to the geopolitics of Sri Lanka as the main port city during the Anuradhapura kingdom period for over 1500 years. Accordingly, it is highlighted that *Yodhawewa* is not an isolated village but a metalwork site that can be affected by long-term socio-cultural activities. The chapter concludes with a commentary on the location of the *Yodhawewa* study area covering 201,600 m^2 in land. The third chapter consists of an overview of the research methodology. The methods in the field and the laboratories include comprehensive artifacts collection, recording, nature-facts sampling, classification, and sample preparation for the analysis (archaeological and geochemical analysis such as XRF, EPMA, and C14 dating) were discussed here.

The fourth chapter of the thesis describes the archaeological results. The initial focus was on the stratigraphy in the first and second excavation pits. After that, the material culture discovered through extensive explorations and excavations was described in depth. A total of 14,017 artifacts were unearthed from the *Yodhawewa* site; however, detailed results were presented based on selected materials. The archaeological analysis was mainly based on slag, crucible fragments, and furnace factors in particular. Chapter five consists of the geochemical analysis results. Thus, concentrations of major elements (wt%) and trace elements (ppm) were explained based on soil, furnace wall fragments, and slag analysis. Radiocarbon dating has provided corresponding dates to three main periods for the *Yodhawewa* site 1st, 5th, and 7-8th centuries AD.

Chapter six contained an archaeological discussion of the research. The constant relative probability was considered in interpreting artifacts in the archaeological context. The slag revealed the highest artifacts density (n=6,814 of 48.5 kg) on the premises, significantly contributing to the definition of the *Yodhawewa* metallurgical site. Archaeological studies were conducted after the general classification of lightweight and heavy slags. Several production conditions represented physical factors such as color configuration, high or low vascularity, oxidation, and glassy texture. Discovered crucible-shaped (lower half-spherical typed) furnace (activated by the 'Bellow method') was used for ancient crucible steel production, and it was the first discovery of such a furnace in Sri Lanka. Identified elongated tube-shaped crucibles in the second excavation area have been used to make crucible steel, and the other (crucibles found from Ex-1 area) for copper works.

Chapter seven consists of the discussion related to the geochemical analysis based on soil and slag samples. Observing the vertical soil distribution of the study area revealed that copper residues were abundantly mixed into the soil in the first excavation area. The law iron (Fe_2O_3) content of the cultural layers (6.97 wt%) and natural layers (6.55 wt%) confirmed two points; the iron smelting has minimal impact on the environment, and the source material (metal ore) was not obtained from the study area. After the geochemical analysis of slag, High Iron Slags (HIS: 10-50 wt%) and Low Iron Slag (LIS: 1-9 wt%) were observed. Analyzing the correlations between HIS and LIS showed clear anomalies, confirming that they are not the result of the same metal process. Significantly LIS shows luster and are transparent by observation of thin section through EPMA analysis.

Noteworthy is an occurrence of olivine in the slags with higher iron contents. Olivine crystals show various morphologies, namely, almost euhedral (0.5-1.0 mm in size), fletching, and acicular, which might be related to cooling mode. Electron probe microanalysis of olivine demonstrates that they are fayalite in composition. Fayalite in the slags is associated with glass, leucite and wüstite. The phase equilibrium examination of olivine and glass in the crystal showed that the crystallization temperature of olivine was estimated to be over 1100 ℃. Leucite forms fine-scale intergrowth with fayalite, suggesting its crystallization at the fayalite-leucite eutectic temperature of ~1128 ℃.

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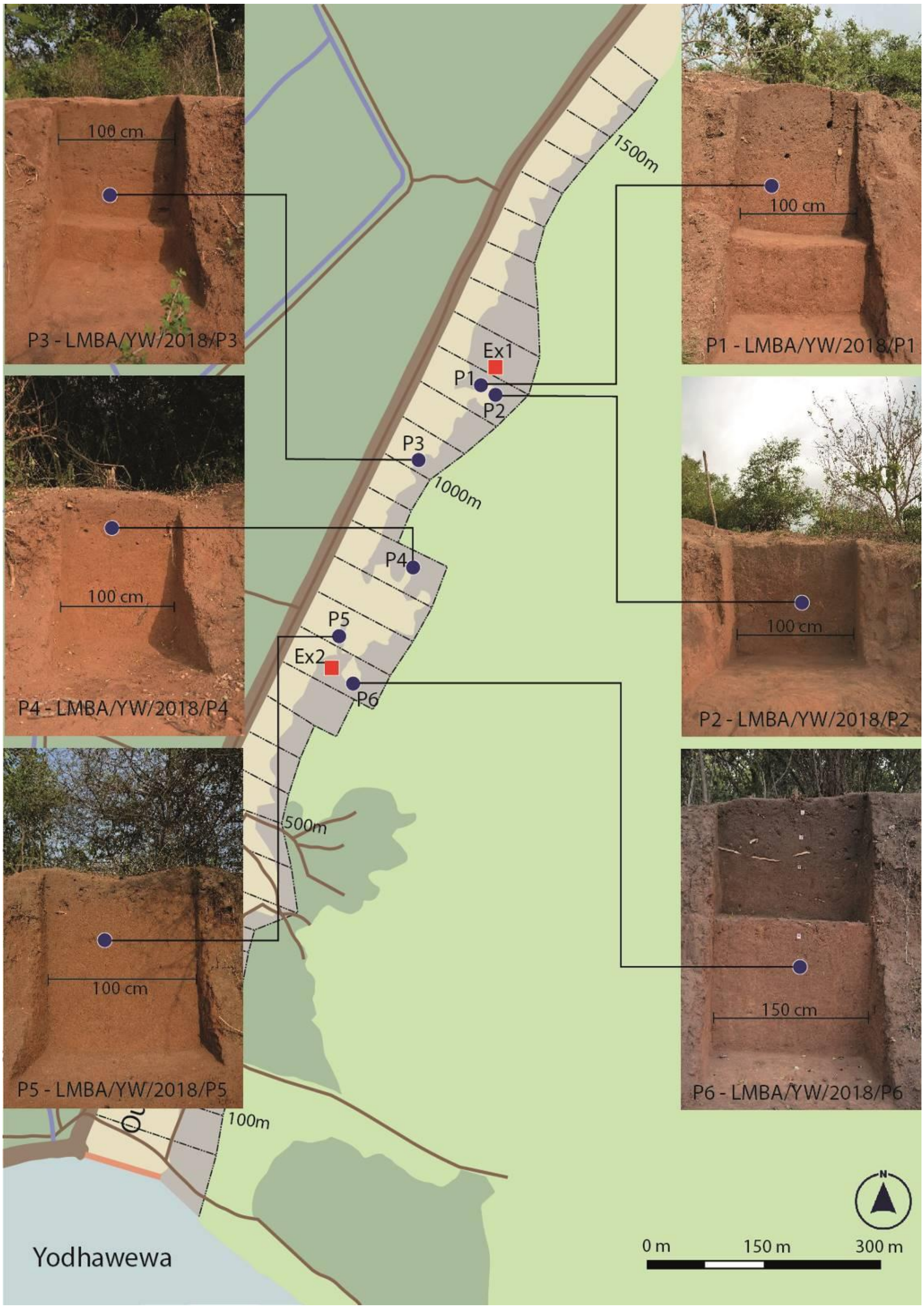
Yahalom-Mack, N. and Eliyahu-Behar, A. (2015) ‘The Transition from Bronze to Iron in

Canaan: Chronology, Technology, and Context’, *Radiocarbon*, 57(2), pp. 285–305. doi: 10.2458/azu_rc.57.18563.

Appendix

Appendix – 1. Observed six profiles parallel to the *Yodhawewa* survey in 2018, presented in a site map.



Appendix – 2. The six reports of Radiocarbon dating analysis of the *Yodhawewa* research in 2018.

BetaCal 3.21

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -25.4 o/oo)

Laboratory number **Beta-517843**

Conventional radiocarbon age **1190 ± 30 BP**

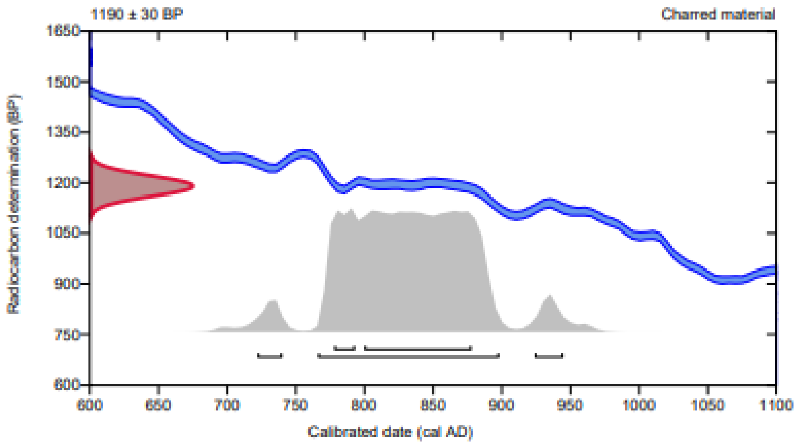
95.4% probability

(89%)	766 - 898 cal AD	(1184 - 1052 cal BP)
(3.5%)	924 - 945 cal AD	(1026 - 1005 cal BP)
(2.9%)	722 - 740 cal AD	(1228 - 1210 cal BP)

68.2% probability

(57.2%)	800 - 878 cal AD	(1150 - 1072 cal BP)
(11%)	778 - 793 cal AD	(1172 - 1157 cal BP)

HI-2/57074



Database used
INTCAL13

References
References to Probability Method
Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.
References to Database INTCAL13
Reimer, et.al., 2013, Radiocarbon55(4).

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BetaCal 3.21

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -25.0 o/oo)

Laboratory number **Beta-517844**

Conventional radiocarbon age **1220 ± 30 BP**

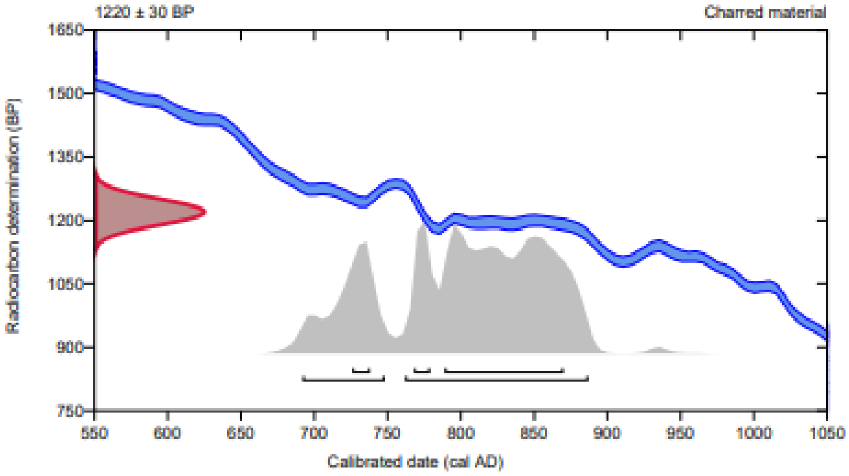
95.4% probability

(74.5%)	762 - 887 cal AD	(1188 - 1063 cal BP)
(20.9%)	692 - 748 cal AD	(1258 - 1202 cal BP)

68.2% probability

(53%)	789 - 870 cal AD	(1161 - 1080 cal BP)
(7.9%)	768 - 779 cal AD	(1182 - 1171 cal BP)
(7.3%)	726 - 738 cal AD	(1224 - 1212 cal BP)

HI-3/57075



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

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BetaCal 3.21

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -23.5 o/oo)

Laboratory number **Beta-517343**

Conventional radiocarbon age **1220 ± 30 BP**

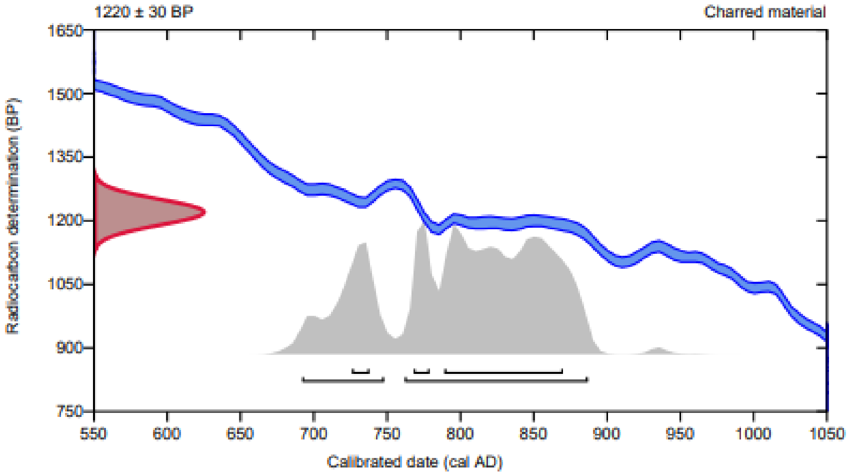
95.4% probability

(74.5%)	762 - 887 cal AD	(1188 - 1063 cal BP)
(20.9%)	692 - 748 cal AD	(1258 - 1202 cal BP)

68.2% probability

(53%)	789 - 870 cal AD	(1161 - 1080 cal BP)
(7.9%)	768 - 779 cal AD	(1182 - 1171 cal BP)
(7.3%)	726 - 738 cal AD	(1224 - 1212 cal BP)

LMBA/YW/2018/EX02 Sample No.78



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

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BetaCal 4.20

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL20)

(Variables: d13C = -24.8 o/oo)

Laboratory number **Beta-621697**

Conventional radiocarbon age **1270 ± 30 BP**

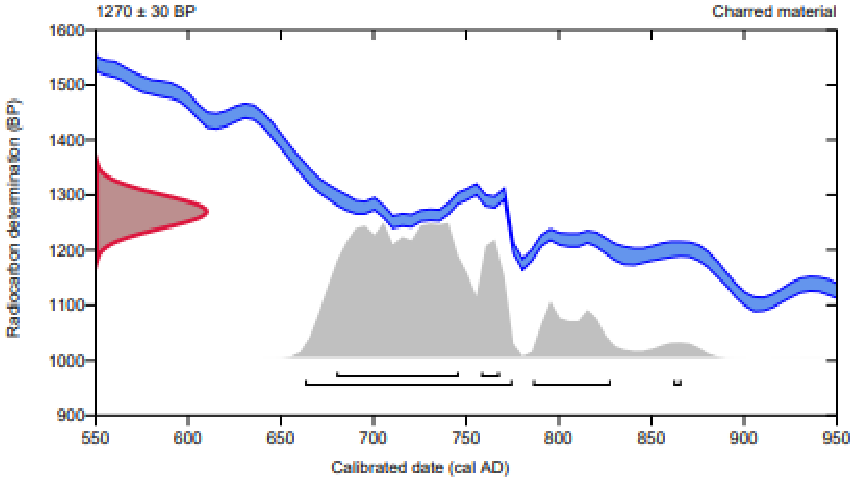
95.4% probability

(83.7%)	663 - 775 cal AD	(1287 - 1175 cal BP)
(11.2%)	786 - 828 cal AD	(1164 - 1122 cal BP)
(0.4%)	862 - 866 cal AD	(1088 - 1084 cal BP)

68.2% probability

(60.5%)	680 - 746 cal AD	(1270 - 1204 cal BP)
(7.7%)	758 - 768 cal AD	(1192 - 1182 cal BP)

Y18SL/65630



Database used

INTCAL20

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL20

Reimer, et al., 2020, Radiocarbon 62(4):725-757.

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BetaCal 3.21

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -24.0 o/oo)

Laboratory number **Beta-517842**

Conventional radiocarbon age **1880 ± 30 BP**

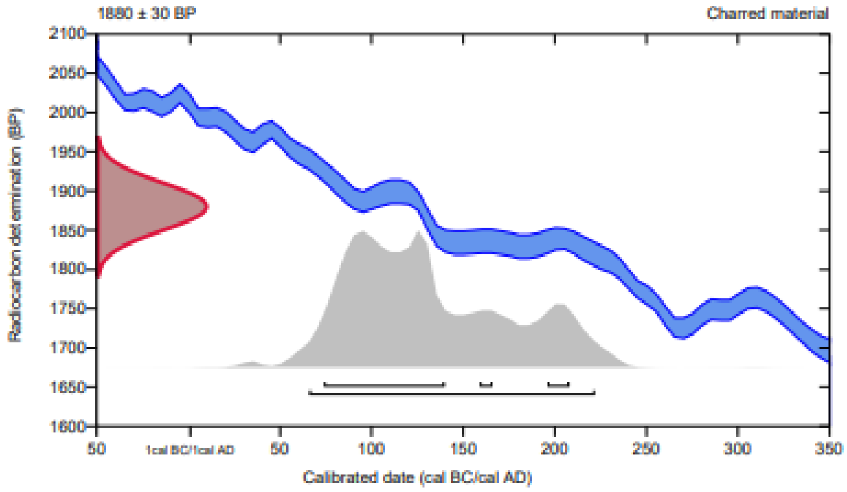
95.4% probability

(95.4%)	66 - 222 cal AD	(1884 - 1728 cal BP)

68.2% probability

(59.3%)	74 - 140 cal AD	(1876 - 1810 cal BP)
(5.9%)	196 - 208 cal AD	(1754 - 1742 cal BP)
(3%)	159 - 166 cal AD	(1791 - 1784 cal BP)

HI-1/57073



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

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BetaCal 3.21

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -24.0 o/oo)

Laboratory number **Beta-517842**

Conventional radiocarbon age **1880 ± 30 BP**

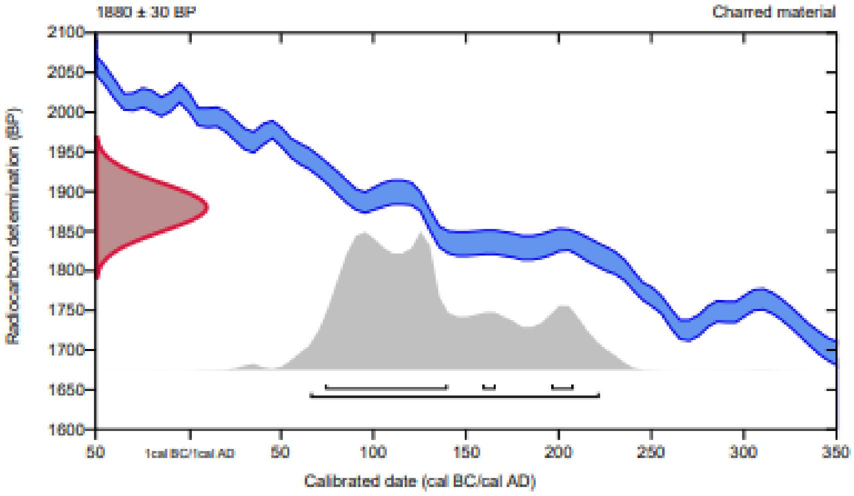
95.4% probability

(95.4%)	66 - 222 cal AD	(1884 - 1728 cal BP)

68.2% probability

(59.3%)	74 - 140 cal AD	(1876 - 1810 cal BP)
(5.9%)	196 - 208 cal AD	(1754 - 1742 cal BP)
(3%)	159 - 166 cal AD	(1791 - 1784 cal BP)

HI-1/57073



Database used
INTCAL13

References
References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

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