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Geoarchaeological insights into the location of Indus settlements on the plains of northwest India

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Abstract

The paper presents a geomorphological and micromorphological study of the locational context of four Indus period archaeological sites – Alamgirpur, Masudpur I and VII, and Burj, all situated on the Sutlej-Yamuna interfluve in northwest India. The analysis indicates a strong correlation between settlement foundation and particular landscape positions on an extensive alluvial floodplain. Each of the analysed sites was located on sandy *levées* and/or river bank deposits associated with former channels. These landscape positions would have situated settlements above the level of seasonal flood water resulting from the Indian Summer Monsoon. In addition, the sandy soils on the margins of these elevated landscape positions would have been seasonally replenished with water, silt, clay and fine organic matter, considerably enhancing their capacity for water retention and fertility, and making them particularly suitable for agriculture. These former landscapes are obscured by recent modification and extensive agricultural practices. These geoarchaeological evaluations indicate that there is a hidden landscape context for each Indus settlement. This specific type of interaction between humans and their local context is an important aspect of Indus cultural adaptations to diverse, variable and changing environments.

Keywords

Geoarchaeology; micromorphology; Indus Civilisation; landscapes; luminescence dating

Introduction

The rise of early cities and states in ancient Egypt and Mesopotamia is interwoven with the proximity of the floodplains and associated landforms of major perennial rivers. South Asia's Indus Civilisation is also typically regarded as being riverine as the cities and settlements of its urban phase (*c*.2500-1900 BC) were distributed throughout much of the Indus River Basin, which is watered by the Indus River and the five major rivers of Punjab. The Nile, Tigris-Euphrates and Indus river basins are all extensive, but it is arguable that of the three, the Indus River Basin is the most complex in terms of hydrology and geomorphology. The settlements of the Indus Civilisation were distributed across a region that is distinctive in having considerable climatic and ecological diversity, in part because the Indus River Basin straddles an environmental threshold where winter and summer rainfall systems overlap, and each have steep gradients (Fig. 1; Petrie *et al*. 2017, 2018; Petrie and Weeks 2018). The distribution of the rainfall from these systems combined with the proximity of the Himalayas to the north, the Suleiman Range to the west, and the Thar Desert to the east place a range of constraints on the hydrology and geomorphology of the intermontane valleys and floodplains of the Indus River Basin, which in turn impacted the ways Indus Civilisation populations inhabited this landscape (Petrie *et al*. 2017, 2018; Petrie 2017).

Between 2008 and 2014, the collaborative *Land, Water and Settlement* project investigated long-term human and environment relationships on the plains of northwest India. These extensive plains are comprised of the interfluve between the Sutlej and Yamuna Rivers, and include the course (or courses) of a major palaeochannel that has been the focus of various research efforts and is often linked to the distribution of Indus Civilisation settlements in the region (e.g. Lal 2002; Valdiya 2002; Saini *et al.* 2009; Danino 2010; Clift *et al.* 2012; Giosan *et al.* 2012; A. Singh *et al.* 2017). The *Land, Water and Settlement* project carried out a combination of extensive archaeological survey and integrated geoarchaeological analysis that demonstrated that there is not a simple correlation between visible palaeochannels and settlement location during the Indus period (Petrie *et al*. 2017; also Singh *et al*. 2008, 2009, 2010a, 2010b, 2011, 2012, 2013, 2015a, 2015b, 2018; Petrie *et al*. 2009, 2016, 2018). This paper presents a geoarchaeological analysis of the location of four rural Indus Civilisation settlements situated in the distinctive alluvial environment of this region. It provides insights into the nature and chronology of landscape morphology and development, soil formation, and the types of decisions influencing populations establishing new settlements in a complex and changing alluvial environment. The analysis presented here suggests that the practices of Indus farmers were well adapted to a dynamic floodplain environment, with limited perennial water availability on the surface. When establishing new settlements, Indus populations made choices that took consideration of elevation, water access, and drainage that assured the agricultural sustainability of those settlements, and also aided their resilience to a mid-Holocene climate that was variable (synchronically) within and between years and changing (diachronically) over time .

Hydrology, geoarchaeology and the Indus Civilisation

During the urban phase of South Asia's Indus Civilisation (*c.*2600/2500-1900 BC), settlements were distributed across an extensive area of the Indus River Basin, which stretches across much of modern Pakistan and parts of western India (e.g. Wheeler 1968; Lal 1997, Kenoyer 1998; Chakrabarti 1999; Possehl 1999, 2002; Agrawal 2007; Wright 2010; Petrie 2013). This extensive region is made up of a range of climate zones and geomorphological units, with the northern areas primarily being comprised of the fertile alluvial plains adjacent to the Indus and the five rivers of Punjab, which stretch to the Ganges-Yamuna catchment to the east (Fig. 1).

There has been a long history of research into the hydrology and associated geomorphology of the Indus River Basin, which has focused on both active rivers (e.g. C.F. Oldham 1893; Pilgrim 1919; Pascoe 1920; Fraser 1958; Mithal 1968; Schroder [ed.] 1993; Meadows and Meadows [eds] 1999), and a number of major dried river channels. Palaeochannels were initially recognised on the ground in the nineteenth century (e.g. C.F. Oldham 1874, 1893; R.D. Oldham 1886), subsequently investigated using remote sensing imagery (e.g. Ghose *et al.* 1979; Yashpal *et al.* 1980; Ramasamy *et al*. 1991; Gupta *et al*. 2004; Bhadra *et al*. 2009) and more recently reconstructed through combinations of remote sensing, coring, provenience analysis and absolute dating (e.g. Bhadra *et al*. 2009; Saini *et al.*

2009; Gupta *et al*. 2011; Clift *et al.* 2012; Giosan *et al.* 2012; van Dijk *et al*. 2016; Orengo & Petrie 2017, 2018; A. Singh *et al.* 2017). The presence of these palaeochannels suggests that these floodplains are highly dynamic, which has major ramifications for human settlement.

The investigation of the relationship between hydrological features and Indus Civilisation settlements also has a protracted history with most attention being devoted to the environmental settings and site formation of the major urban sites of Mohenjo-Daro (e.g. Raikes 1964; Lambrick 1967; Flam 1981, 1993, 1999, 2013; Cucarzi 1984, 1987; Raikes and Dales 1986; Balista 1988; Leonardi 1988; Jorgensen *et al*. 1993; Harvey and Schumm 1999; Jansen 1999) and Harappa (e.g. Amundson and Pendall 1991; Belcher 1997, 1998; Belcher and Belcher 2000; Schuldenrein 2002; Schuldenrein *et al*. 2004, 2007; Wright 2010). The analysis at these two city sites has been carried out at relatively high-resolution, and has detailed the specific relationship between evolving urban settlements and their distinctive and changing local landscapes.

Indus settlements were situated in a range of climatically, ecologically, environmentally distinct locations, including intermontane valleys, on alluvial fans, at the margins or inside what are today arid zones, in areas that lack perennial rivers but are watered by monsoon rainfall, and even on islands (Wright 2010: 33-38; Petrie & Thomas 2012; Petrie 2013, 2017; Petrie *et al.* 2017). It has been argued that Indus farmers were well adapted to diverse and variable environments, and that this helped them be resilient to climate change (Petrie *et al*. 2017; Petrie 2017), but geoarchaeological characterisation of settlements has only been attempted in some of these contexts. In Gujarat, there is evidence for a number of settlements on sand dunes, and the relationship between these settlements and the inter-dune areas suited for agricultural exploitation has been explored in some detail (e.g. Balbo *et al*. 2013; Conesa *et al*. 2014, 2015, 2017).

In the context of the Indus Civilisation, understanding the relationship between settlements and dynamic floodplains is particularly significant, and the relationship between former palaeochannels and archaeological settlement distribution has been examined in Sind (e.g. Flam 1981, 1993, 2013; Jorgensen *et al*. 1993), Cholistan (e.g. Stein 1942; Mughal 1997; also Geyh and Ploethner 1995) and the ancient Beas (Schuldenrein 2002; Schuldenrein *et al*. 2004, 2007; Wright and Hritz 2013) in Pakistan, and northern

Rajasthan (e.g. Raikes 1967; Rajani and Rajawat 2011) and Haryana in northwest India (e.g. Courty 1985, 1990, 1995; Courty *et al*. 1987, 1989). However, with the exception of the work along the Beas, much of this analysis been conducted at a large scale, and has not involved detailed geoarchaeological analysis at specific archaeological settlements.

The Indus Civilisation and the alluvial floodplains of northwest India

There were relatively few Indus settlements large enough to be regarded as cities, and each of these was situated in a different hydrological zone and ecological context. One of these large settlements, the Indus city at Rakhigarhi (Nath 1998; Shinde *et al*. 2013, 2018), was situated in the central part of the extensive alluvial interfluve that lies between the Sutlej, which is the easternmost of the Punjab Rivers, and the Yamuna, which is westernmost of the major Gangetic Rivers (Fig. 1). Today this extensive plain lacks perennial rivers, but there is evidence that it has been traversed by a substantial number of ephemeral watercourses, some of which appear to have been relatively large palaeochannels (van Dijk *et al*. 2016; Orengo & Petrie 2017, 2018).

Today the Sutlej-Yamuna interfluve is an area where winter and summer rainfall systems overlap, and it is characterised by considerable variability and steep gradients in rainfall distribution, such that areas to the west and south receive little direct rainfall, whereas moving to the east and north, areas receive increasing amounts of summer, and in the north in particular, also winter rain (Petrie *et al*. 2017; Petrie 2017). A number of archaeological survey and excavation projects have demonstrated that the alluvial plains of the Sutlej-Yamuna interfluve in north-western India were occupied throughout the late prehistoric and historic periods, including extensive occupation by Indus Civilisation populations (e.g. Suraj Bhan 1975; Suraj Bhan and Shaffer 1982; Joshi *et al*. 1984; Possehl 1999; Chakrabarti and Saini 2009; Dangi 2009, 2011; Kumar 2009; Singh *et al*. 2010b, 2011, 2018; Parmar *et al*. 2013; Pawar *et al*. 2013; Sharan *et al*. 2013; see Green and Petrie 2018). There has been a tendency to associate the distribution of Indus Civilisation archaeological sites with the reconstructed courses of palaeochannels (e.g. Lal 2002; Valdiya 2002; Danino 2010; Giosan *et al.* 2012; A. Singh *et al.* 2017). However, these relationships have not been explored in detail, they have typically been investigated at a very large scale, and the associations between the large urban centre of Rakhigarhi and the settlements in its hinterland, and the local landscape contexts and the palaeochannels that have been identified there, remain unclear.

The *Land, Water and Settlement* project was a collaboration between scholars from the University of Cambridge and Banaras Hindu University (2008 - 2014) that investigated the nature of long-term human and environment relationships on the plains of northwest India (Petrie *et al*. 2017). The project focused on the period from before the appearance of the cities of the Indus Civilisation (Early Harappan: *c*. 3000-2500 BC), through the period of their floruit and decline (Mature Harappan: *c*.2500-1900 BC), and the subsequent periods where rural populations made use of progressively changing assemblages of material culture (Late Harappan: *c*.1900-1600/1500 BC; Painted Grey Ware [PGW]: *c*.1500-700 BC). In addition, it also considered the Early Historic period, during which urban centres reappeared (Northern Black Polished Ware [NBPW]: *c*.700-200 BC; Early Historic *c*.500 BC – AD 500) and the Medieval period, when they continued to flourish (*c*.AD 500-1500). Much of the research carried out by the *Land, Water and Settlement* project focused on the investigation of relatively small rural settlements, which appear to have housed the majority of the settled population during all three Indus periods (Madella and Fuller 2006: Fig. 9; Parikh and Petrie in press). The field and laboratory work included archaeological surveys and excavations, with the latter leading to integrated archaeobotanical, archaeozoological, stable isotope and ceramic analysis. Within the overarching research programme, geoarchaeological analysis was conducted at a number of the Indus sites and their surrounding areas in Haryana and western Uttar Pradesh (Fig. 2).

In contrast to the diversity of the geoarchaeological research undertaken at Indus Civilisation city sites (Mohenjo-Daro and Harappa; see above), there has only been limited research on the geoarchaeology of rural or hinterland sites in Pakistan (e.g. Lahoma Lal Tibba, Chak Purbane Syal; Schuldenrein 2002; Schuldenrein *et al*. 2004, 2007), and northwest India (e.g. Courty 1985, 1990, 1995; Courty *et al*. 1987, 1989). This paper presents the results and interpretations derived from sets of geoarchaeological samples recovered by the *Land, Water and Settlement* project from soil/sediment sequences in the immediate environs of the Indus sites of Alamgirpur (Mature Harappan, Late Harappan, PGW and

Medieval), Masudpur VII (Early Harappan, Mature Harappan, Late Harappan), Masudpur I (Mature Harappan, Late Harappan) and Burj (Early Harappan, PGW, Early Historic). This geoarchaeological investigation set out to gain insight into the location of settlements in the distinctive alluvial environment of northwest India, thereby helping us to understand why the people that established these settlements selected particular locations. In this regard, it was important to establish how the ancient land surfaces developed geomorphologically and pedologically, and to ascertain whether there were any common attributes in terms of natural settings. It was particularly important to understand the nature of 'local'-scale adaptations that Indus populations made to live in these landscapes in the third and second millennium BC.

Material and Methods

Soil profiles from the hinterland landscapes of each of the sites were recorded and sampled for micromorphological studies (Courty et al. 1989) and a suite of basic physical analyses (French 2015: App. 1) (SI.1, Table SI.1). The interpretations of the soil thin sections and associated small bulk samples from individual site areas are presented below, along with the result of OSL dating of samples collected from deposits immediately below the oldest occupation levels at each of these sites. Details of all of the methods used and the descriptions of the soil thin sections and associated small bulk samples are in the Supplementary Information (see SI.1, Table SI.2).

Geoarchaeology

Geoarchaeological approaches are well established and provide very powerful tools for understanding landscape change and associated human adaptation (French 2015), particularly because of their ability to investigate and interpret environmental and cultural signatures that are typically concealed within the landscape itself (French 2003). Geoarchaeological field research is aimed primarily at gathering data with which to understand human-landscape relations (Goldberg and Macphail 2006), and for the study presented here, attention was specifically focused on examining the nature of the land surfaces and the associated soil properties of the plains of northwest India in close proximity to archaeological settlements. The specific aim was to situate Indus archaeological sites in their local environmental contexts. In order to achieve this aim, soil surveys at and around settlement sites were carried out with the use of hand-augering and hand cut-sections to reveal alluvial/occupation/soil/subsoil sequences. At each profile location, the stratigraphy was recorded and sampled for micromorphological and other geoarchaeological analyses (see *SI.1 Methods*).

In total, nine 'mammoth' soil blocks from a total of 15 key soil profiles recorded (Table SI.1) were prepared for thin section analysis at the McBurney Laboratory (Department of Archaeology, University of Cambridge) (after Murphy 1986; Courty *et al*. 1989; Table SI.2). In addition, a suite of basic physical parameters (pH, loss-on-ignition for total organic and carbon contents, magnetic susceptibility, and particle size analysis) were carried out at the Department of Geography (University of Cambridge), on a series of small bulk samples taken in conjunction with the micromorphological block samples (Table SI.3) (Avery and Bascomb 1974; Clark 1996: 99-117; French 2015).

Radiocarbon dating

During the excavations of Alamgirpur, Masudpur I, Masudpur VII and Burj, bulk soil samples were collected for flotation and the recovered material was used for archaeobotanical analysis and dating. Radiocarbon dates from Alamgirpur (Singh *et al*. 2013) and Masudpur I and Masudpur VII (Petrie *et al*. 2016) were analysed at the Oxford Radiocarbon Accelerator Unit (ORAU, RLAHA, Oxford), have already been published, and will be referred to where relevant in the text below. The radiocarbon dates from Burj were also analysed at the ORAU and have not previously been published, but the relevant determination is discussed below.

Luminescence dating

Samples for optically stimulated luminescence (OSL) dating were collected by hammering opaque tubes into the sediment stratigraphy, and were opened and prepared under subdued orange light conditions in the Oxford Luminescence Dating Laboratory (School of Geography and the Environment, Oxford; see SI.1). A standard sediment preparation procedure was applied to isolate a purified quartz fraction suitable for dating. This involved the removal of carbonate and organic material using hydrochloric acid and hydrogen peroxide, followed by sieving and mineral separation using sodium polytungstate. Hydrofluoric acid was used to remove the alpha-irradiated outer layer of quartz grains and samples were re-sieved prior to measurement. The OSL dates from each site are discussed in the individual sections below. Single grain OSL measurements were made using a Risø TL/OSL luminescence reader fitted with a 10 mW, 532 nm focused laser for stimulation and a $^{90}Sr/^{90}Y$ beta source (dose rate of ~4 Gy/min) for laboratory irradiation. Ultraviolet luminescence signals were detected through a bialkali photo multiplier tube fitted with 7.5 mm of U340 filters. Equivalent dose (D_e) values were calculated from single grains of quartz (grain size range 150-180 μm) using the single-aliquot regenerative dose (SAR) protocol (Murray and Wintle 2000), with a pre-heat of 220°C for 10 s and cut-heat of 160°C both for 10 s, selected following combined pre-heat and dose recovery tests. Dose recovery tests were used to assess the suitability of the SAR protocol for D_e determination. Luminescence signals were measured at 125°C for 1 s at 90% laser power and D_es were calculated from the signal measured during the first 0.05 s of stimulation, with the mean background over the last 0.2 s subtracted. Luminescence signals were screened using a standard suite of rejection criteria, and only grains which satisfied the following criteria were accepted for age calculation: i) recycling ratio within 10% of unity; ii) OSL IR depletion ratio (Duller 2003) within 10% of unity; iii) recuperation of less than 5%; iv) test dose signal be at least 3σ greater than background levels (Jacobs *et al*. 2006). Dominance of the fast component was assessed by applying the fast ratio (Durcan and Duller 2011) to multi-grain quartz OSL signals. For the majority of samples, between 1500 and 3800 individual quartz grains were measured, with between 0.8% and 4.1% of grains providing luminescence signals discernible from machine background levels and which satisfied all rejection criteria. Dose distributions are moderately overdispersed (38-47%; Table 4) for this suite of samples and are approximately symmetrical around a central value (Fig. SI.1). This pattern suggests that overdispersion in the distributions is not caused by incomplete bleaching, which can be identified from skewed distributions. Instead, post-depositional factors, such as mild micro-dosimetric variability, as well as intrinsic intra-sample variability of quartz luminescence characteristics are hypothesized to contribute to these spread in data. On this basis, the central age model (Galbraith *et al*. 1999) has been used for sample De calculation, following the approach of Durcan *et al*. (in press).

Radionuclide concentrations were used for dose rate calculations, which were made using the dose rate calculator DRAC (v1.2; Durcan *et al*. 2015). Radioactivity was converted to dose rates using the attenuation factors of Guerin *et al*. (2011), and infinite-matrix dose rates were adjusted for attenuation by grain size, chemical etching and moisture content (5 ± 2%). D_es and dose rates are summarised in Table SI.4, along with the calculated OSL ages. Further details of the methods and the results are presented in Table SI.4.

It is recognized that it is not feasible to directly compare the OSL and radiocarbon determinations (Jones 1999). Nonetheless, the samples for the former were collected immediately below the earliest anthropogenic deposits, while those for the latter were collected from the earliest anthropogenic deposits containing datable material from each site. The OSL dates should thus closely correspond to the latest pre-occupation deposition, and the radiocarbon dates should correspond to the earliest occupation deposits.

Alamgirpur

Site Description

The site of Alamgirpur (Meerut district, Uttar Pradesh; Fig. 2; SI.2.1, Fig. SI.2) is the easternmost excavated Indus site, and it was established in the urban phase of the Indus Civilisation and occupied during the Mature and Late Harappan, PGW and Medieval periods (Ghosh 1958; Singh *et al*. 2013). The settlement is situated in a landscape composed of Quaternary alluvium to the east of the Yamuna River in the Hindon basin, which is part of the Ganges River basin (Singh 1996). Today the humid sub-tropical climate of this region has monsoonal characteristics, and it receives an average annual rainfall of about 800mm (Weatherbase 2017). The modern village of Alamgirpur lies adjacent on the left bank of the Hindon River floodplain, and the archaeological mound is located *c*.2 km east of the current perennial river course (Fig. SI.2).

The earliest deposits exposed in the YD2 and SC trenches at Alamgirpur have both been radiocarbon dated to *c*.4.3-4.0 cal ka BP (Singh *et al*. 2013: 50-51, Tables 10-11). These dates from different locations on the mound are statistically identical and internally consistent, suggesting that the mound was first occupied in the late centuries of the third millennium BC, during the Indus urban period. An OSL date (CAM-9) was obtained from the 'natural' sandy silt deposit immediately beneath the archaeological deposit in the SC trench from which the radiocarbon date was obtained. The date of 4.47 ± 0.40 ka pre-dates the radiocarbon dates, and suggests that the basal deposits upon which the site was established were laid down in the period immediately before it was occupied.

Sampling

During a survey conducted in December 2010, a series of five profiles were observed in and around the mound and soil block sampling was carried out (see SI.2.1; Figs SI.2-3, Tables SI.1-SI.2). The positions of the profiles were chosen to characterise the geomorphological setting and development of the archaeological site. Samples for micromorphological analysis were collected from Profiles 1 and 3 (434-454 and 143-153cm below the modern ground surface, respectively), as these locations were the most likely to reveal information on the environmental conditions prior to the occupation on this mound.

Analytical Results

Schematic soil columns that reconstruct the stratigraphic profiles are shown in Figure 3. Sample 1/1 (434-454cm) is mainly an apedal sandy soil, becoming a moderately well-developed sub-angular blocky silty clay loam with depth (Fig. 4; Table SI.2). The few fragments of clay included in this soil are likely to be the products of recycling of the much older and pre-existing 'B' horizon material, which further indicates disruption, local reworking, erosion and local deposition by biological and geomorphological agents (*cf*. Brewer 1960; Kuhn *et al*. 2010). Nonetheless, the oriented pure and dusty (silty) clay coatings present in the groundmass and voids as pedofeatures and some blocky ped soil structural evidence suggest that this was a palaeosol with a reasonably well-developed clay-enriched (or Bt) horizon (*cf*. Fedoroff 1968; Kühn *et al*. 2010; Retallack 1990), indicative of at least some stabilisation and pedogenesis in the past. In particular, the common illuvial features of micro-laminated pure and dusty clay striae and void coating features suggests that this soil was originally formed in a well-vegetated and stable environment (*cf*. Fedoroff 1968; Kühn *et al*. 2010; Retallack 1990), but the oxidation/gleying features suggest that this soil was seasonally wet (*cf*. Lindbo *et al*. 2010). The high organic content also suggests that this soil once supported a better surface vegetation (*cf*. Stolt and Lindbo 2010), although the organic remains have been largely replaced by amorphous iron (Fig. 5), as a result of oxidization caused by the seasonal rise and fall of the groundwater table (*cf.* Lindbo *et al*. 2010). These soil properties indicate that there was some initial soil development during the earlier Holocene, which then became dominated by much wetter soil conditions. In contrast, Sample 3 (143-153cm) showed a very fine sand interfacing with horizontally bedded white micaceous river sand. It is suggested that the 'soil horizon' observed in this profile is a former weathered surface of a *levée* formed from riverine deposition of the nearby River Hindon. The ancient mound, and the modern villages of Alamgirpur and Nandapura are all situated along a *levée* at the eastern edge of the Hindon floodplain (see Fig. SI.2).

Interpretation

From the general landscape survey and detailed micromorphological analyses, it can be suggested that the current floodplain/valley edges of the Hindon River are defined by irregular but linear arrangements of sand dunes (*c*. 6-8m high), the origin of which are *levées*. The spatial configuration of these geomorphological features indicate that *levée* formations probably began to develop during the Late Quaternary, followed by cycles of soil formation and flooding. The latter process is evidenced in Sample 1/1 which shows some disruption through the inclusion of fragments of a pre-existing palaeosol in the form of well-developed clay fragments (Table SI.2). Sample 3 represents a fluvisolic palaeosol formed from the deposition of alluvial sediments by the river. Indus period pottery fragments were found within the soil matrix, suggesting that soils were being worked in this period.

These geoarchaeological analyses highlight the formation sequence and post-depositional transformations of the early Holocene palaeosol and the alluvial sequence in the Hindon basin, adjacent to Alamgirpur. The indications of soil formation seen in the micromorphological analysis indicate that this process occurred well before the Indus populations targeted this location for permanent settlement (Fig. 3). Thus this particular location may well have been chosen for establishing a settlement because it remained above the flooded zone and/or it had soils suitable for agricultural use.

Masudpur I and Masudpur VII

Site descriptions

The mound sites of Masudpur I and Masudpur VII (Fig. 2; SI.2.2, Fig. SI.4) are situated in a part of the Sutlej-Yamuna interfluve that today has a semi-arid climate and is characterised by scanty and irregular rainfall, hot summers, dry cold winters, prevalent aridity and desert and saline soils (Kottek *et al*. 2006; Petrie *et al*. 2017; Petrie and Bates 2017). Masudpur I was a large village or town sized settlement (6-8 ha) occupied in the Mature and Late Harappan periods, while Masudpur VII was a small village sized settlement (1 ha) occupied in the Early, Mature and Late Harappan periods (Petrie *et al*. 2009, 2016; Parikh and Petrie 2016, in press).

Today, the area around these settlement sites consists of a flat to undulating plain partly covered with intermittent sand dunes (Petrie *et al*. 2009). Sediments have been characterised as mainly fine alluvium derived from the Himalayas with an admixture of wind-blown sand from the Thar Desert of Rajasthan, to the southwest (Courty 1985; Bhatia and Kumar 1987). It has long been argued that the alluvium was primarily deposited during the Quaternary by large rivers that have since dried up (Ahuja *et al*. 1980), but rainfall and hydrological activity during the earlier Holocene have also had a major impact on the distribution of sediments on the floodplain.

The earliest radiocarbon dates from the deposits exposed in the XA1 and XM2 trenches at Masudpur I have been radiocarbon dated to *c*.4.4-4.1 cal ka BP (Petrie *et al*. 2016: Table S7), suggesting that the mound was first occupied during the Indus urban period. OSL dates obtained from the 'natural' sandy silt deposit immediately beneath the archaeological deposits in each of these trenches were obtained, and their ranges are 4.89 ± 0.37 ka for sample CAM-1 (Trench XA1/XM2) and 4.01 ± 0.31 ka for sample CAM-3 (Trench XA1/XM2), with the range of the latter overlapping with the earliest radiocarbon dates. The closeness of these dates suggest that the final phase of basal deposits upon which the site was established were laid down shortly before that process took place.

The earliest radiocarbon date from the deposits exposed in the YA2 and YB1 trenches at Masudpur VII have been radiocarbon dated to *c*.4.9-4.6 cal ka BP (Petrie *et al*. 2016: Table S6), suggesting that the mound was first occupied before the Indus urban period. OSL dates obtained from the 'natural' sandy silt deposit immediately beneath the archaeological deposits in each of these trenches date were obtained, and their ranges are 7.32 ± 0.59 ka for sample CAM-5 (Trench YA2) and 6.47 ± 0.52 ka for sample CAM-3 (Trench YB1). The luminescence and radiocarbon taken together suggest that the basal deposits upon which this site was established were laid down several millennia before the settlement was founded, assuming that no later sediments had been removed by natural or anthropogenic processes.

Sampling

Geoarchaeological survey of the environs of these sites was undertaken in March 2010, with one profile being recorded near Masudpur VII (Profile 15) and a series of four profiles (Profiles 10, 11, 12 and 13) being investigated to the north, south and southeast of the surviving mound of Masudpur I (Fig. SI.4; Tables SI.1 and SI.3). These locations were chosen with the aim of characterising the geomorphological development of the respective archaeological sites. MSD Profile 15 was observed within the exposed archaeological section of trench YB1 at Masudpur VII (Table SI.1). The profile shows that the site was established on a sand dune at the terminal end of a north-south oriented chain of dunes, and there are no modern water courses flowing in the vicinity.

Analytical Results

Schematic soil columns that reconstruct the stratigraphic profiles are shown in Figure 6. Profile 10 was exposed 100m to the north of excavation trench XA1 at Masudpur I (see Petrie *et al*. 2009, 2016). Underneath *c*.1m depth of Indus period archaeological deposits at Profile 10 there was a 35cm thick older land surface comprising of organic, dark greyish brown very fine sandy silt over pale brown very fine sandy silt (Fig. SI.5). This stratum developed on a substrate of pale yellowish brown, and calcitic very fine sandy silt with frequent calcitic nodules. Profile 11 was exposed 350m further to the north of Profile 10 and was characterised by 1m of brown silt over 1.5m of yellowish/greyish brown fine sandy silt to fine-medium sand with depth. Here, no old surface or soil development was evident. Profile 12 was a well-cutting, 50m to the south of the farmstead adjacent to the settlement mound, and revealed a depth of >1.7m of homogeneous brown very fine sandy silt with frequent pottery sherds. Profile 13, a dry well 200m to the southeast of the farmstead recorded 2.15m of similar of homogeneous brown very fine sandy silt above a yellowish brown fine sandy silt. Samples for micromorphological analysis were collected from Profiles 10 and 13 (see SI.2.2).

There is relatively little textural difference between Profiles 10 and 13, with sand predominating along with a considerable silt content, but relatively low values of clay present (see SI.2.2; Table SI.3). The physical characteristics of the Masudpur profiles exhibited strongly alkaline conditions (pH of 8.61-9.36), as well as relatively low percentages of organic (0.95-1.26%) and calcium carbonate (2.6-7.2%) contents, and low magnetic susceptibility values (<20.3 SI) (Table SI.3). Nonetheless, this soil exhibits illuvial clay and dusty clay that formed coatings and striae in the sub-soil horizon (Fig. 7; see SI.2.2), much like that observed in Profile 1 at Alamgirpur, thus suggesting that this soil developed under stable, well-vegetated and well-drained conditions for a length of time prior to the combined effects of groundwater rise and fall and burial by Harappan occupation deposits.

The surficial geology beneath Masudpur I appears to be composed of finely bedded sands that are suggestive of former channel fill deposits now surviving as low sinuous ridges (Fig. 6, also SI.2.2). The lower-lying areas of the adjacent plain were probably more or less continually affected by the slow, seasonal deposition of alluvium from overbank flooding, presumably associated with monsoonal rains (*cf*. Gibling *et al*. 2005; French *et al*. 2017). Subsequent stability in this system appears to have led to the development of a well-developed soil with organic Ah, eluvial Eb and illuvial clay-enriched Bt horizons present (see SI.2.2). This type of former soil (or Luvisol) would have provided excellent cultivable land for people who appear to have settled on the well-drained higher ground of the former sand bars/ridges.

Interpretation

The surrounding, more low-lying areas are likely to have received alluvial silt deposition seasonally, which would have provided both moisture and nutrients to the soil. This process might have significantly improved the fertility of these *levée* margin soils, by adding both humic, silt and clay contents to the fine sandy soils, thereby helping to maintain soil structure and the productive capacity of farming in this landscape. However, real improvements in fertility and crop yields would have probably required sustained additions of organic waste, minimal tillage, and multi-cropping regimes (Berner *et al*. 2008; Weber *et al*. 2007), and there is palaeo-botanical evidence for multi-cropping practices at these sites (Petrie and Bates 2017). Nonetheless, the degree of development of the soil properties shows that the soil system was stable for a relatively long period, and this could have coincided with the Indus occupational phases.

In general, the textures of the soils around the Masudpur I mound are very sandy, and they are therefore very well drained (Fig. 6). However, the micromorphological analysis at Masudpur VII suggests that the soil in that area is comparatively less sandy with a slightly loamier texture. The down-profile illuvial movement of clay and silty clays are evident in almost every thin section, albeit in relatively small amounts, indicating both phases of relative stability and some soil formation as well as the continuing seasonal influence of alluvium additions at both of these sites.

Burj

Site description

The site of Burj (see Fig. 2; SI.2.3, Fig. SI.6) is situated on the Sutlej-Yamuna interfluve some distance to the north of Masudpur, and sits adjacent to the Ghaggar palaeochannel on the opposite side to the well-known Indus site of Kunal. Today, this region has a semi-arid climate, and appears to be drier than the area around Masudpur (Courty 1990; Kottek *et al*. 2006; Petrie *et al*. 2017; Petrie and Bates 2017).

The earliest deposits exposed at the site were in the ZG9 trench at Burj (Singh *et al*. 2010a), and the earliest radiocarbon determinations from there have been dated to *c*.4.8-4.5 cal ka BP (Context 216: OxA-26475 – 4031±34 BP), which suggests that the mound was first occupied during the Indus pre-urban period, though there was also evidence for occupation during the PGW period. One optically stimulated luminescence date was obtained from the 'natural' sandy silt deposit immediately beneath the archaeological deposits in a neighboring trench, and its range was 5.48 ± 0.42 ka for sample CAM-11 (Trench ZA2). The OSL and radiocarbon dates taken together suggest that the basal deposits upon which the site was established were laid down up to a millennium before the settlement was founded.

Sampling

Five profiles (Profiles 1, 2, 3, 72 and 73) were recorded on and around the surviving mound at Burj, which is partially overlain by the modern village (SI.2.3; Fig. SI.6; Tables SI.1-SI.3). These profiles were selected in order to characterise the geomorphological context of soils associated with the archaeological site.

Analytical Results

Schematic soil columns that reconstruct the stratigraphic profiles are shown in Figure 8. Profile 1 was located *c*. 30m northeast of the present-day edge of the mound and revealed that 40-65cm of modern ploughsoil, which had recently been removed by villager quarrying, overlying a 50cm thick horizon of yellowish brown, very fine sandy-silt, containing occasional bivalve shells, developed on a pale yellowish brown calcitic silt with irregular calcitic nodules (Fig. SI.7). The bivalves have not been assessed in detail, but their presence is interesting given the settlement's proximity to the Ghaggar palaeochannel, and suggests that ponding may have resulted from the flooding of parts of the surrounding landscape during periods of seasonal rain. This entire profile was cut by a substantial pit containing PGW period pottery. Profile 2 (Fig. SI.8) was exposed on the northern edge of the settlement mound and had similar properties to that of Profile 1, without the intrusive pit. Profile 3 was exposed 100m to the east of the modern Sikh temple that is situated on the highest point on the mound. The upper 75cm of this profile was composed of an homogeneous, pale brown silt with occasional pottery sherds, which developed on a 50cm thick horizon of horizontally banded archaeological levels of alternating dark reddish brown and pale grey silt. This deposit had in turn accumulated on a pale yellowish brown calcitic silt similar to that already seen in Profiles 1 and 2. Profile 72 was cut 120m east of trench ZA2. Archaeological deposits were found to a depth of 120cm, and overlay pale yellowish brown sandy silt with concentrations of calcium carbonate, which may indicate the presence of a channel fill deposit. Profile 73 was located 600m southwest of the archaeological trench of ZA2, amidst a field that was reported as being 80cm higher some ten years earlier, after which time it had been levelled to reach the elevation of the surrounding fields. The profile showed 30cm of modern topsoil over 30-60cm of dark greyish sandy silt. Very few sherds of pottery were found from the dark greyish sandy silt, and it was situated on pale yellowish sandy silt with concentrations of $CaCO_3$, again possibly indicative of the presence of channel fill deposits.

A representative set of three block samples from different depths in Profile 1 were selected for micromorphological analysis (Fig. 9; SI.2.3). The micromorphological analysis clearly exhibits the illuvial movement down-profile and the formation of pure clay and silt coatings which suggests that pedogenesis was taking place, more or less coincident with the Indus occupation. In particular, the illuviation of pure and dusty clays is only possible when the soil pH is circum-neutral to slightly acidic, and there are stable, moist and well vegetated conditions over a considerable length of time, allowing an argillic (or Bt) horizon to develop (Fedoroff 1968, 1972; Bullock and Murphy 1979; Kühn *et al*. 2010; W.R.B. 2014). In contrast, the dominant soil forming process in the region today is calcification and high alkaline pH levels, with concomitant seasonally very severe aridity and strong evaporation of soil water in the near surface soil system. These two different processes are unlikely to have developed at the same time (*cf*. Srivastava and Parkash 2002). It therefore it seems that the soil at Burj was in a unique state of development during the Indus period (Fig. 8), which was not analogous to today, just as has been observed at Alamgirpur and Masudpur.

Interpretation

These relatively well-developed soils existing in river edge locations associated with several Indus sites implies a certain level of stability in the floodplain margins and a moister palaeo-environmental regime. Additionally, the proximity of the river channels and fine overbank flooding from time to time would have continued to benefit agricultural exploitation.

Discussion

This analysis of the buried soils and underlying geomorphological features related to Alamgirpur, Masudpur I, Masudpur VII and Burj provides a number of important insights into landscape development and geomorphology on an extensive alluvial floodplain in northwest India, and particularly the importance of this environment for Indus settlements and their hinterlands. These environments are distinct from those occupied by populations in ancient Egypt and Mesopotamia, most particularly due to the influence of both winter and summer rainfall systems, and also the combination of an extensive floodplain watered by a combination of perennial and ephemeral river channels. This study highlights the fact that farmers occupying seasonally inundated alluvial plains subject to flooding are constantly faced with risks that they must adapt to. Analysis of the archaeobotanical evidence from these sites have shown that farmers made use of strategies that enabled them to exploit combinations of summer and winter crops that required differing quantities of water, suggesting a careful awareness of the nuances of living and farming in such landscapes (Petrie and Bates 2017).

With the exception of two sites located close together (Masudpur I and VII), the ancient settlements being considered in this paper were situated considerable distances apart. In principle, the landscape information from each site should be treated as being relatively discrete, but importantly, they share a number of similarities. For instance, all four of these Indus settlement sites were situated on former sandy *levées* or river bank deposits of Quaternary river systems, which also appear to have been active during the early Holocene. These features are evident in the geomorphic sampling locations (Fig. 10) and also in processed digital elevation models that highlight micro-relief (Fig. 11). These locations were both slightly higher in elevation and also better drained than the surrounding lower-lying alluvial plain landscapes, and were more likely to have remained above the flood water levels and associated disruption during the wet season. These *levées* appear to have been widely targeted for both settlement and agricultural exploitation, as it is notable that this has also been observed at Harappa, which is situated in a difference part of the Indus River Basin (Belcher and Belcher 2000; Schuldenrein *et al.* 2004, 2007). Importantly, these slightly elevated areas had relatively well-developed soils, unlike those in the area today, which would have been significant beneficial factor for these settlements. In contrast, the adjacent lower lying parts of the landscape were characterised by much finer textured soils derived from silts and clays, indicating the continuing seasonal input of fine overbank alluvial material into an aggrading floodplain system. These patterns are distinct from those seen in the lower parts of the Indus River Basin, where the major river channels of Punjab have consolidated into larger channels, which produced sizable meanders and show evidence of pronounced migration over the last 4000 years (Flam 1993, 1999; Schuldenrein *et al.* 2007).

The micromorphological analysis presented here demonstrates that the former land surfaces on *levées* and their margins in different parts of northwest India exhibited reasonably well-drained and structured soils that had undergone some pedogenesis. Importantly, these soils all contain a relatively minor but significant, fine illuvial silt and clay content in the voids and groundmass, unlike the sandy subsoils beneath. The consequent silty clay 'argillans' that occur in semi-desert soils in this region have been interpreted as a result of *in situ* weathering (Kooistra 1982), or derived from the breakdown of fine particles related to surface crusting and seasonal floods (Courty and Fedoroff 1985). As vegetation cover is often poor/degraded in semi-arid areas, surface crusts may modify the easy downward translocation of fines into deeper horizons. Sandy soils with a single grain structure also act as a very favorable porous medium for water infiltration and percolation, especially under semi-arid conditions. Suspended clay and silt are deposited in water films and preferentially deposited around sand grains by capillary action. Also, the strong adherence of clay particles to the sand grains explains the persistence of clay when these soils have been partly re-worked by the wind (Wieder and Yaalon 1978).

These soils also exhibit more ubiquitous gleyic properties, which are normally a consequence of seasonal wetting and drying, and proximity to the groundwater table (*cf.* Lindbo *et al*. 2010). It is difficult to be sure whether this relates to modern and/or past monsoonal flooding and alluviation, but given today's extensive network of pump irrigation and control of groundwater levels, it is unlikely that it can be ascribed solely to past causes.

Importantly, the buried palaeosols with more well-developed, silt and clay enriched B horizons that have been observed do not show the accumulation of calcium carbonate ($CaCO_3$), which is ubiquitous in most modern soils of this region. This signals that transpiration and evaporation did not outweigh precipitation (Durand *et al*. 2010). The absence of these properties in the palaeosols associated with the well-developed Bt horizons at Alamgirpur, Masudpur and Burj suggests that the climatic and vegetational conditions at these sites were somewhat different in the past than today. These soils must therefore have been better vegetated and more moist, and consequently under a different precipitation and groundwater regime, and therefore potentially more fertile. This observation is notable as significant shifts to drier conditions in this region have been identified at different points during the Holocene (Dixit *et al*. 2014a, 2014b, 2018). Climate models for the region around Harappa (Bryson *et al*. 2008) and palaeoclimatic proxy records from various locations in northwest India (Dixit *et al*. 2014b, 2018) suggest that the mid-Holocene was characterized by relatively stronger winter and summer rainfall, and a reassessment of a sediment core off the Pakistani coast has indicated that both rainfall systems were weaker from 4.2 ka BP (Giesche *et al*. 2019; also Dixit 2014b). The weakening of these precipitation regimes occurred during the mid-late phases of the Indus urban period, during which Masudpur I and VII and Alamgirpur were all occupied.

The slow-moving flood waters associated with seasonal inundation and overbank flooding through monsoonal run-off appear to have contained clay, silt and fine organic matter which would have replenished the soils annually. In turn, these fine alluvial additions would have gradually altered soil textures to be finer and more moisture retentive, counteracting the detrimental effects of the free-draining sandy parent material (*cf.* Moody 2006), and thus affecting fertility positively. Furthermore, these soils could have been easily worked (*cf.* Greenman *et al*. 1967), even without the need for ploughing, which would facilitate simple forms of agriculture (*cf.* Hillel 2004). Seasonal flooding would have also mitigated against water stress, especially for moisture-hungry cereal crops. Consequently, these soils which were associated with Indus urban period settlements had a degree of stability and resilience supported by annual replenishment. Thus both the *levées* and their floodplain margins could have been relied upon to support annually successful arable crops. It is also possible that the association of these alluviated 'good' soils with large artefact scatters around these settlements may imply a form of fertilisation with domestic refuse to additionally enhance the properties of these *levée* soils (*cf.* Wilkinson 2003: 117-8).

The associated river systems and their lower-lying floodplains adjacent to the settlement sites were regularly affected by the seasonal aggradation of overbank flood deposits. These were mainly composed of fine sand and silt as soil run-off associated with monsoonal rains and riverine flooding, and gradually encroached onto the soils on the margins of the higher areas of the *levées*. This lead to some new soil processes occurring such as gleying and the secondary formation of calcium carbonate and amorphous oxides as well as soil thickening and textural alterations with sand/silt alluvial sediments, and/or the re-working and secondary deposition of channel bed derived sands. These potentially extensive 'skirtland' alluviated areas around every site would have initially also provided a naturally and seasonally replenishing soil and groundwater system available for agricultural use with both nutrient and fine soil additions and a seasonally high groundwater table. Over time, these areas would have become seasonally very dry, calcitic Fluvisols and would therefore have been 'too risky' for maintaining a viable cropping regime until more recent times without drainage and/or nutrient additions.

Other studies of the pre-Indus Civilisation soil complexes are relatively few and far between, with the investigation of the Upper Beas palaeo-channel and associated floodplain margin soils associated with the sites of Harappa, Lahoma Lal Tibba and Chak Purbane Syal offering the most comparable analytical detail (Schuldenrein *et al.* 2004, 2007). Essentially three phases of pre- Indus Civilisation soil formation have been recognized that exhibit remarkable similarities to the picture that has emerged from our study of sites much farther to the east in the Ghaggar-Hakra valley zone of northern India. These Upper Beas soils are typically preserved on the margins of slightly higher areas of ground on channel/floodplain margins. The earlier Holocene phase (*c*.10-7 ka BP) saw the development of weakly developed A-B horizon soils, which show some signs of clay illuviation, and overlay either Bk and/or Ck horizons with carbonate nodules, and often with thick, late Quaternary alluvial or wind-blown deposits beneath. In the second period between *c*.7 and 4 ka BP, these soils developed further into A-B-Bwt profiles with the argillic Bt horizon exhibiting particular development. Then, just before the settlement mounds were established by about 2400-2200 cal BC, there was a more mixed and increasingly unstable picture with the first signs of overbank alluviation and channel avulsion.

Thus, there again appears to be clear evidence of the stabilization of floodplain margin landscapes with optimal climatic conditions with a stable rainfall regime and moderate evapotranspiration which enables good soil development during the early-mid-Holocene. This was followed by some de-stabilisation of the environment and the development of thinner soils with channel migration just before the urban phase of the Indus Civilisation.

Conclusions

This geoarchaeological study has shown that at least some and perhaps many Indus populations living on the Sutlej-Yamuna interfluve had a preference for targeting low terraces and sandbar/ridges on the margins of the ancient floodplains for the establishment of their settlements. Although the immediate environs of only four sites have been investigated, their floodplain edge locations would have reduced the risk of settlements being inundated, which would certainly have been affecting the adjacent alluvial plains throughout the Holocene, and are documented up to the present. Significantly, the combination of relatively good soils on these areas of higher ground and the associated naturally and seasonally replenishing alluvial soil system adjacent combined to provide a most important resource that assured agricultural sustainability. Moreover, this earlier-mid-Holocene soil development can only have been associated with a better moisture regime with less risk of drought, and relative landscape stability, which is mirrored by geoarchaeological and soil analytical studies in the Upper Beas (Schuldenrein *et al*. 2004). This combination of factors is probably the essence of the establishment and sustainability of the agricultural system in this region during the Indus periods. This type of relationship between humans, their locale, and good soil development, is an important aspect of Indus cultural adaptations to diverse, variable and changing environments through time, and it is likely that many variations on such adaptations were widespread across the Indus River Basin (Petrie *et al*. 2017, 2018; Petrie 2017).

Our knowledge of these landscapes will only increase with further research, and it is notable that additional samples for geoarchaeological analysis and OSL dating have been collected from buried landscapes and palaeochannels in various locations across this region (Durcan *et al*. 2019). Significantly, it appears that the more favorable and stable landscape regimes that had existed throughout much of the earlier-mid-Holocene, had begun to change by *c*.4.2 ka BP, when Indus Civilisation settlement sites were distributed across an extensive area. In the past, the landscape was more undulating, with variable soil development on the floodplain margins and *levées* versus the wet alluvial zones alongside former channels. The wide floodplain areas have gradually aggraded with alluvial material, and this process continued during the post-Indus and historic periods. In combination with modern leveling activities, this process has created the ostensibly flat to gently undulating surface topography that is evident today.

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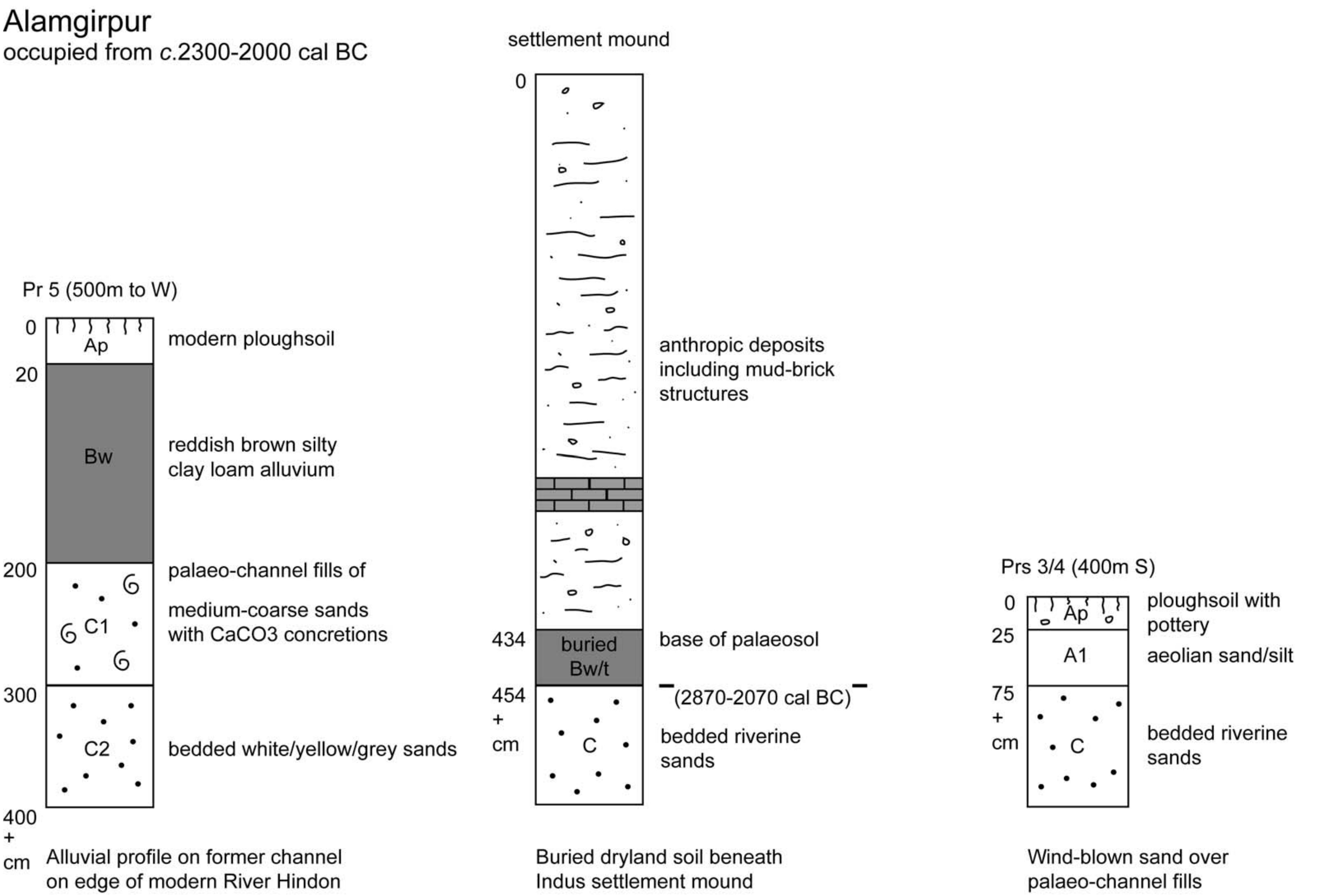
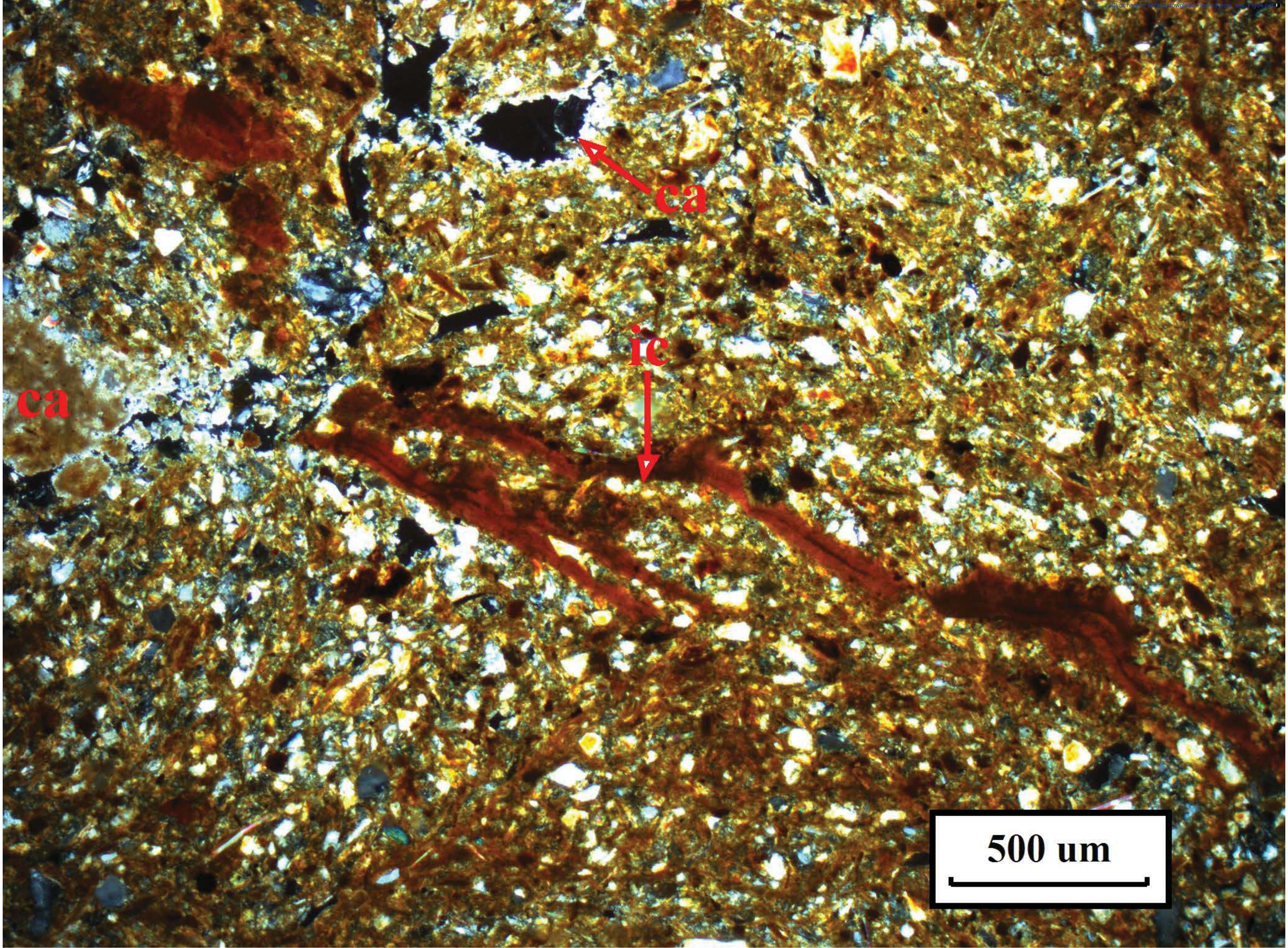
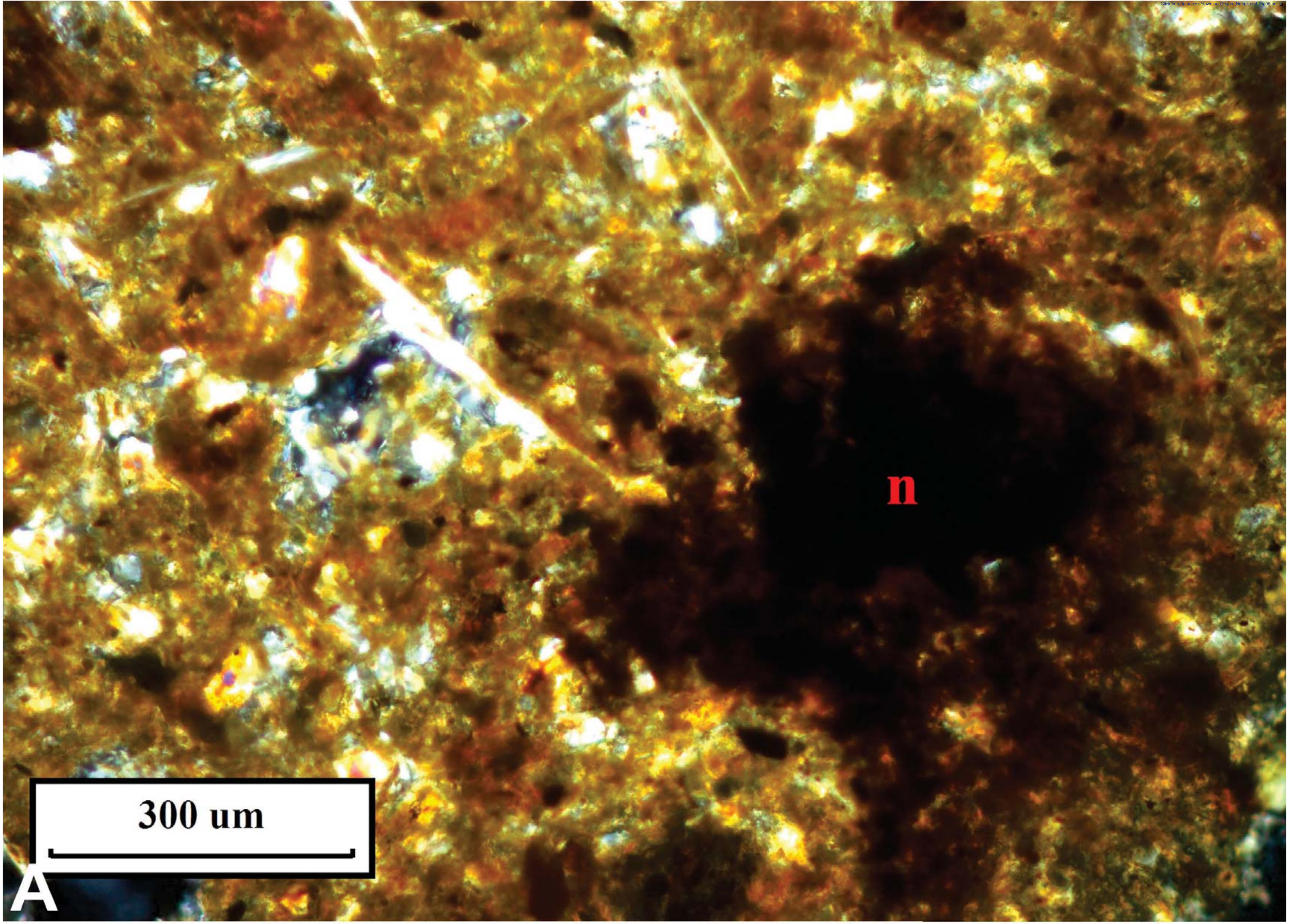
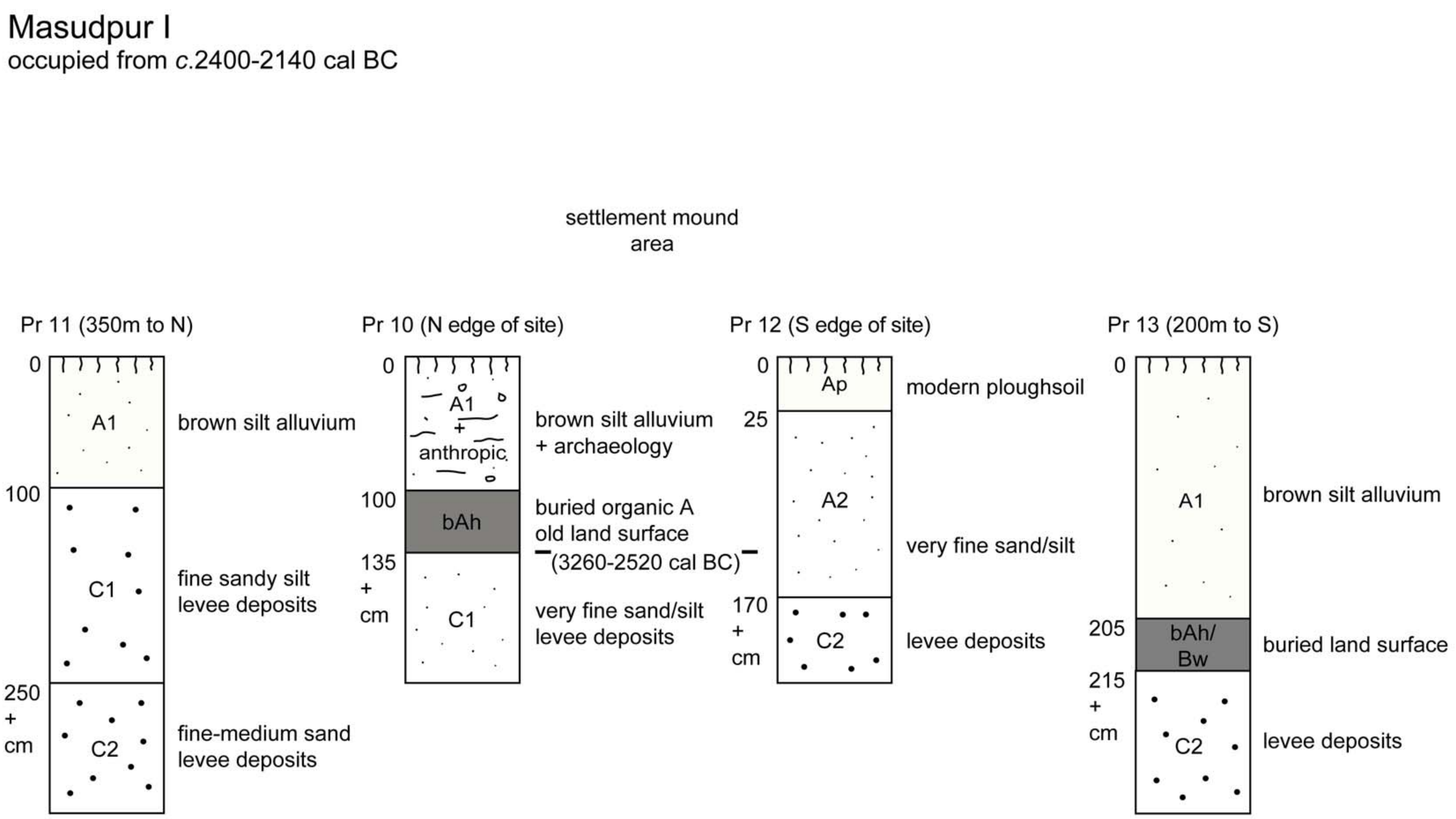
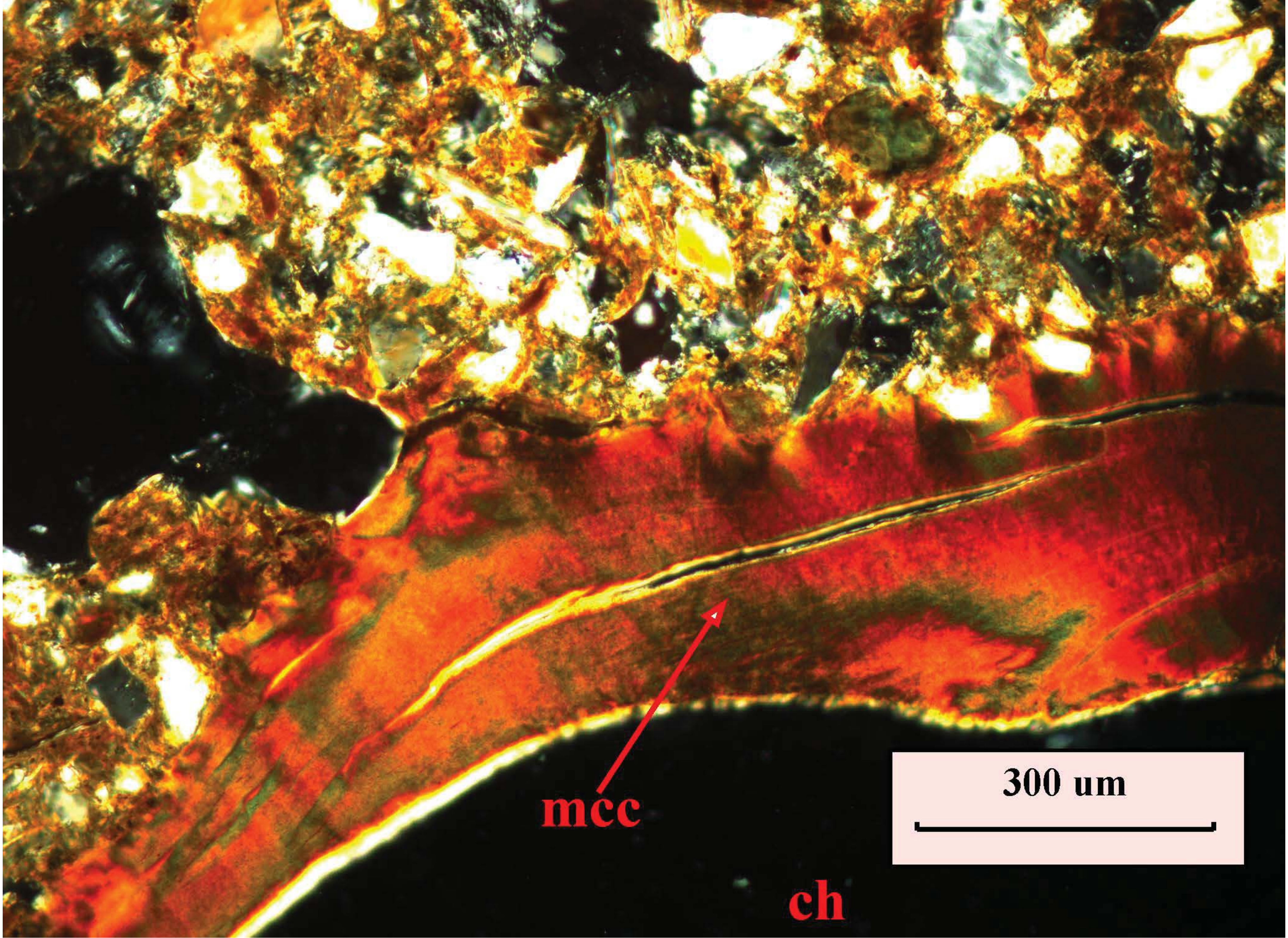

Alamgirpur
occupied from c.2300-2000 cal BC
Pr 5 (500m to W)
0
Ap
modern ploughsoil
20
Bw
reddish brown silty clay loam alluvium
200
C1
palaeo-channel fills of
medium-coarse sands with CaCO3 concretions
300
C2
bedded white/yellow/grey sands
400
+
cm
Alluvial profile on former channel on edge of modern River Hindon
settlement mound
0
anthropic deposits including mud-brick structures
434
buried Bw/t
base of palaeosol
454
+
cm
(2870-2070 cal BC)
C
bedded riverine sands
Buried dryland soil beneath Indus settlement mound
Prs 3/4 (400m S)
0
Ap
ploughsoil with pottery
25
A1
aeolian sand/silt
75
+
cm
C
bedded riverine sands
Wind-blown sand over palaeo-channel fills

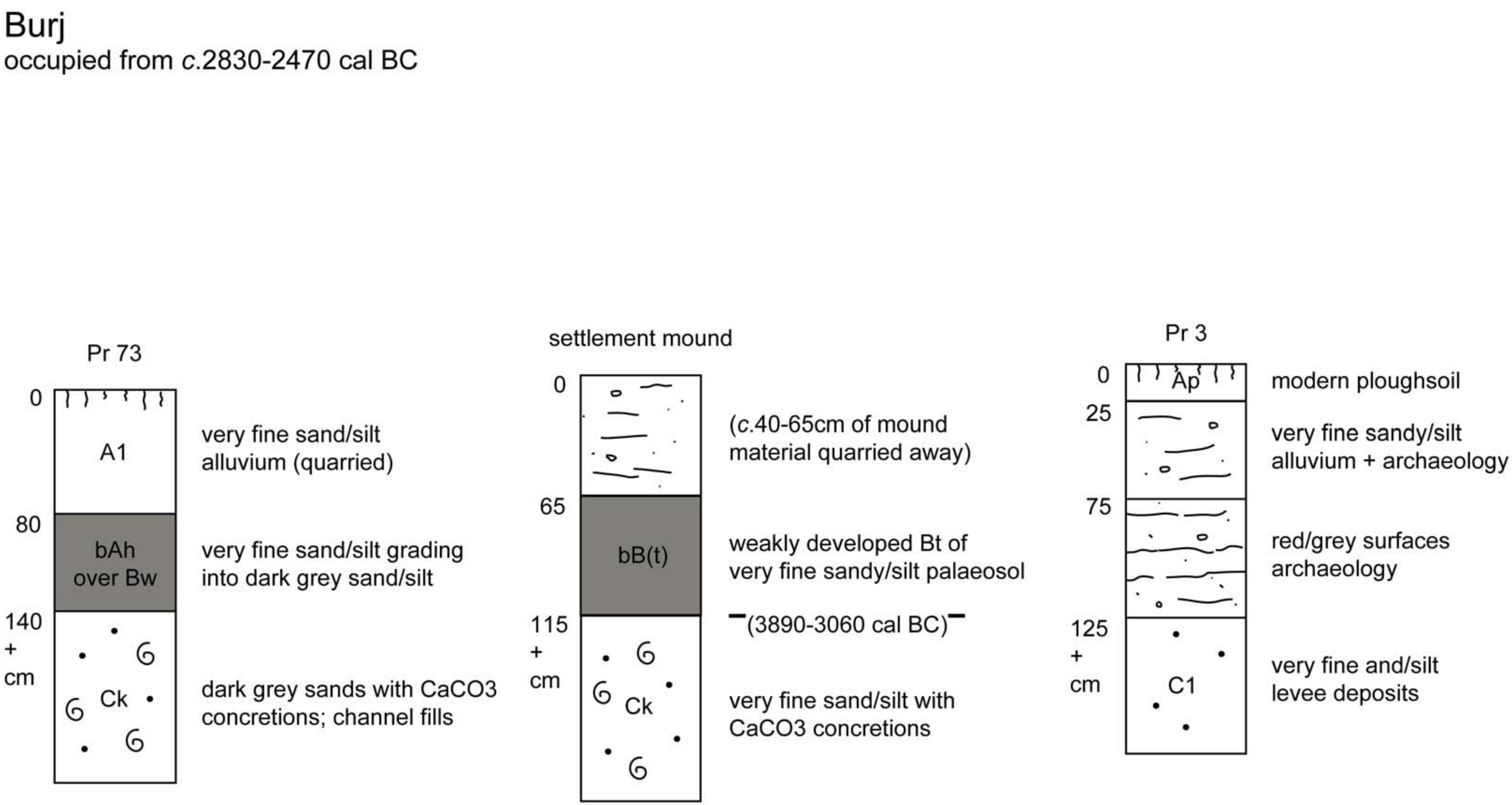

ca
ic
ca
500 um

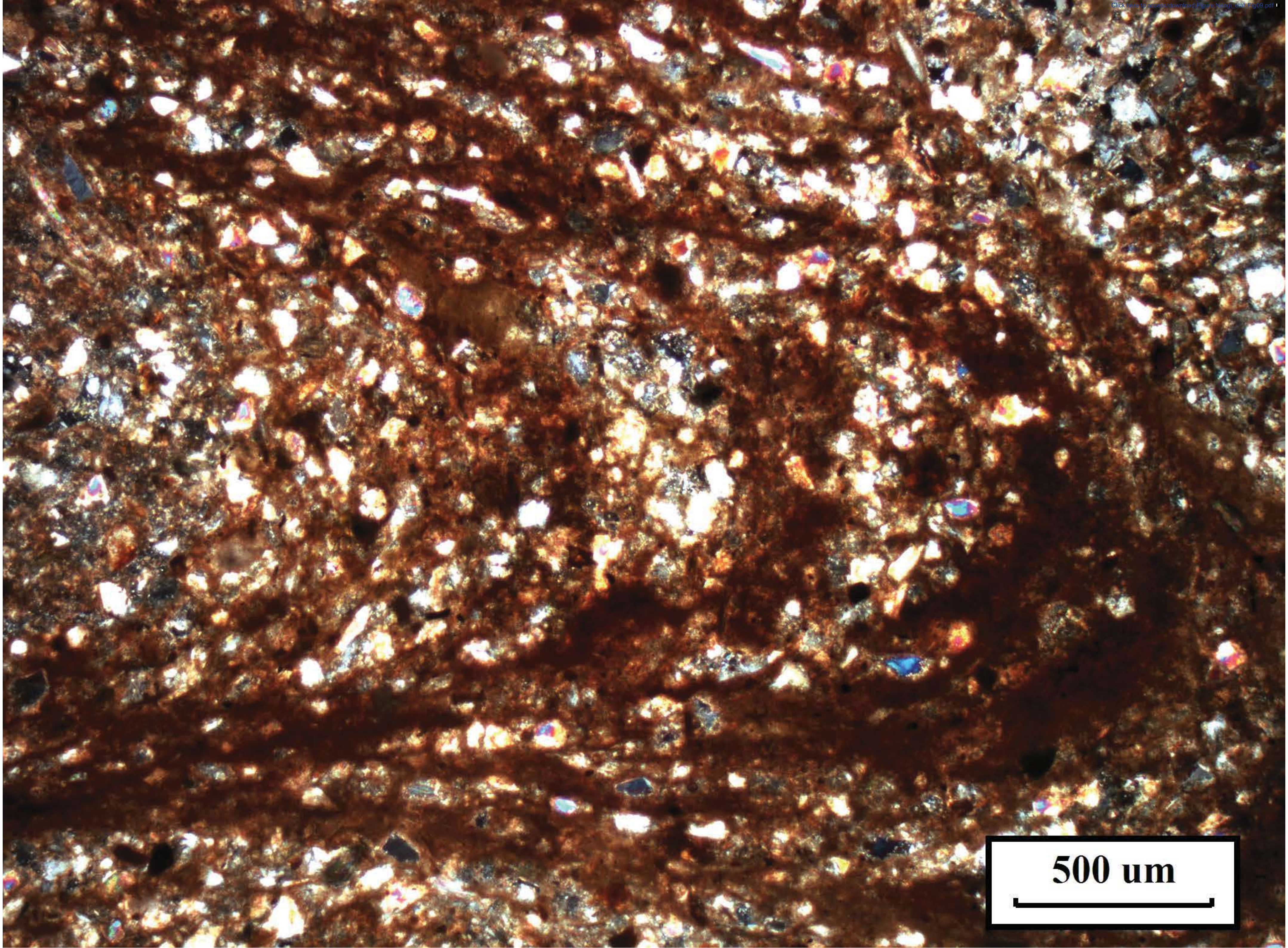

n
300 um
A


Masudpur I
occupied from c.2400-2140 cal BC
settlement mound
area
Pr 11 (350m to N)
0
A1
brown silt alluvium
100
C1
fine sandy silt
levee deposits
250
+
cm
C2
fine-medium sand
levee deposits
Pr 10 (N edge of site)
0
A1
+
anthropic
brown silt alluvium
+ archaeology
100
bAh
buried organic A
old land surface
(3260-2520 cal BC)
135
+
cm
C1
very fine sand/silt
levee deposits
Pr 12 (S edge of site)
0
Ap
modern ploughsoil
25
A2
very fine sand/silt
170
+
cm
C2
levee deposits
Pr 13 (200m to S)
0
A1
brown silt alluvium
205
bAh/
Bw
buried land surface
215
+
cm
C2
levee deposits

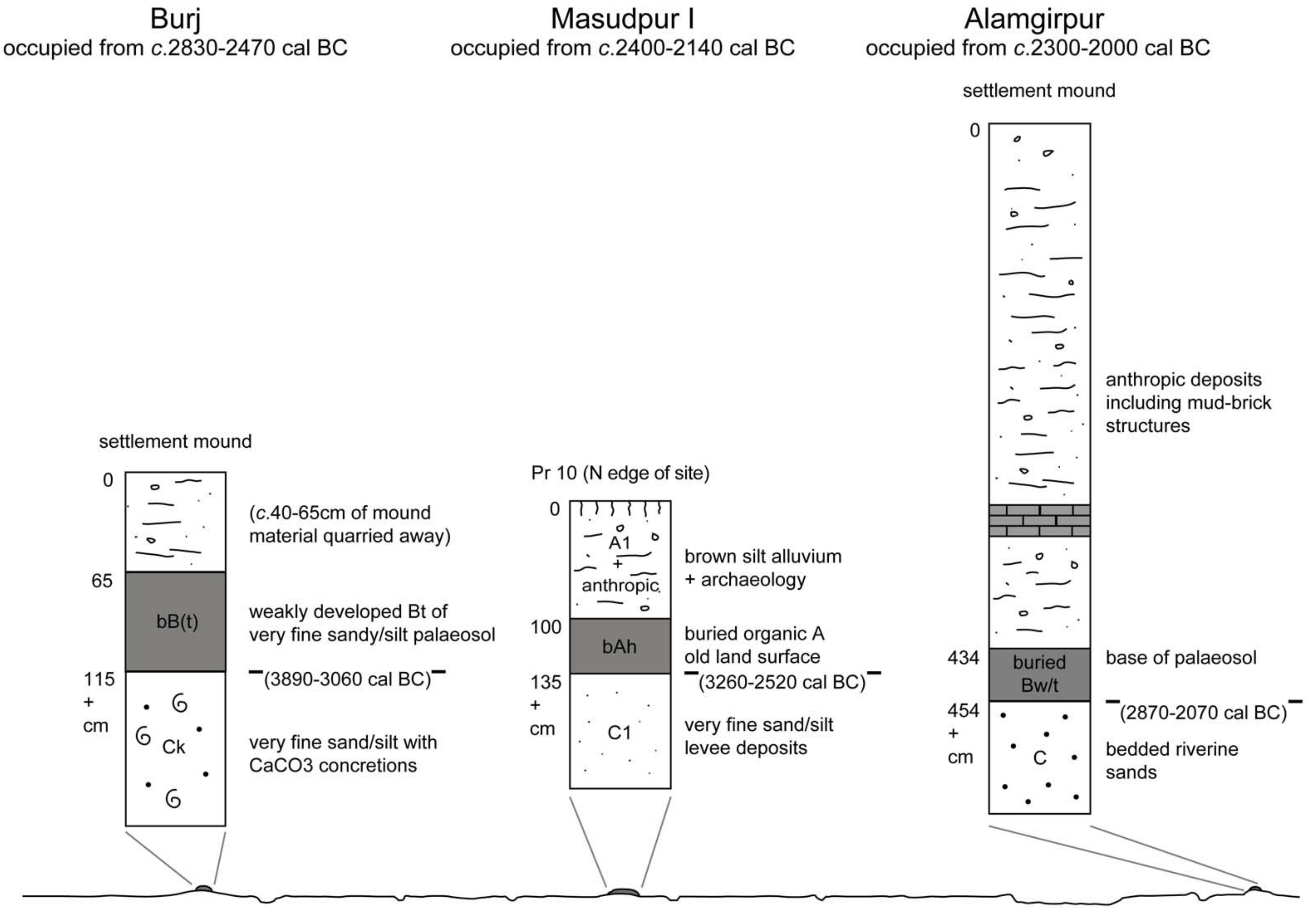
Figure




Burj
occupied from c.2830-2470 cal BC
Pr 73
0
80
140
+
cm
A1
bAh
over Bw
Ck
very fine sand/silt
alluvium (quarried)
very fine sand/silt grading
into dark grey sand/silt
dark grey sands with CaCO3
concretions; channel fills
settlement mound
0
65
115
+
cm
bB(t)
Ck
(c.40-65cm of mound
material quarried away)
weakly developed Bt of
very fine sandy/silt palaeosol
(3890-3060 cal BC)
very fine sand/silt with
CaCO3 concretions
Pr 3
0
25
75
125
+
cm
Ap
C1
modern ploughsoil
very fine sandy/silt
alluvium + archaeology
red/grey surfaces
archaeology
very fine and/silt
levee deposits


500 um

Figure


Burj
occupied from c.2830-2470 cal BC
Masudpur I
occupied from c.2400-2140 cal BC
Alamgirpur
occupied from c.2300-2000 cal BC
settlement mound
0
65
115
+
cm
bB(t)
Ck
(c.40-65cm of mound material quarried away)
weakly developed Bt of very fine sandy/silt palaeosol
(3890-3060 cal BC)
very fine sand/silt with CaCO3 concretions
Pr 10 (N edge of site)
0
100
135
+
cm
A1
+
anthropic
bAh
C1
brown silt alluvium + archaeology
buried organic A old land surface
(3260-2520 cal BC)
very fine sand/silt levee deposits
settlement mound
0
434
454
+
cm
buried Bw/t
C
anthropic deposits including mud-brick structures
base of palaeosol
(2870-2070 cal BC)
bedded riverine sands

Figure

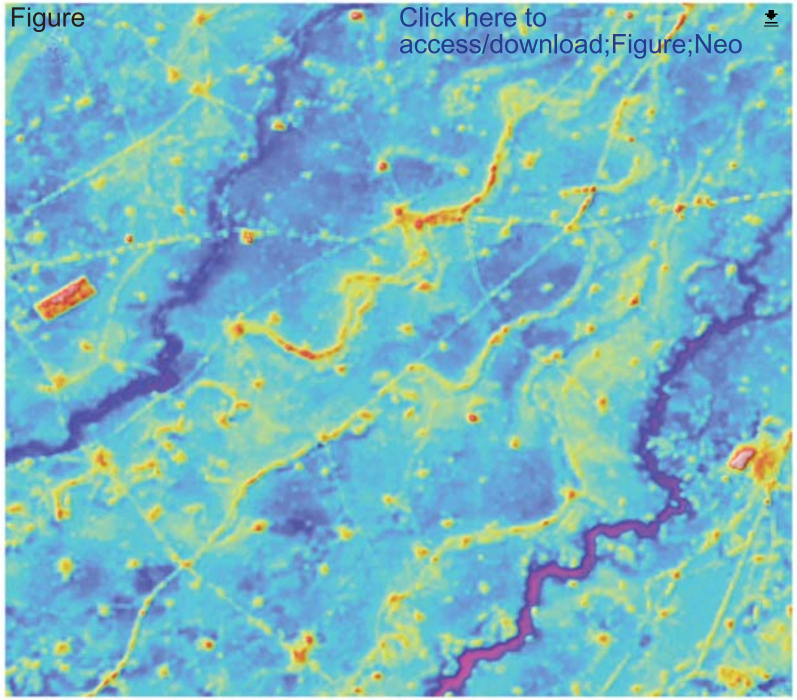


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Figure

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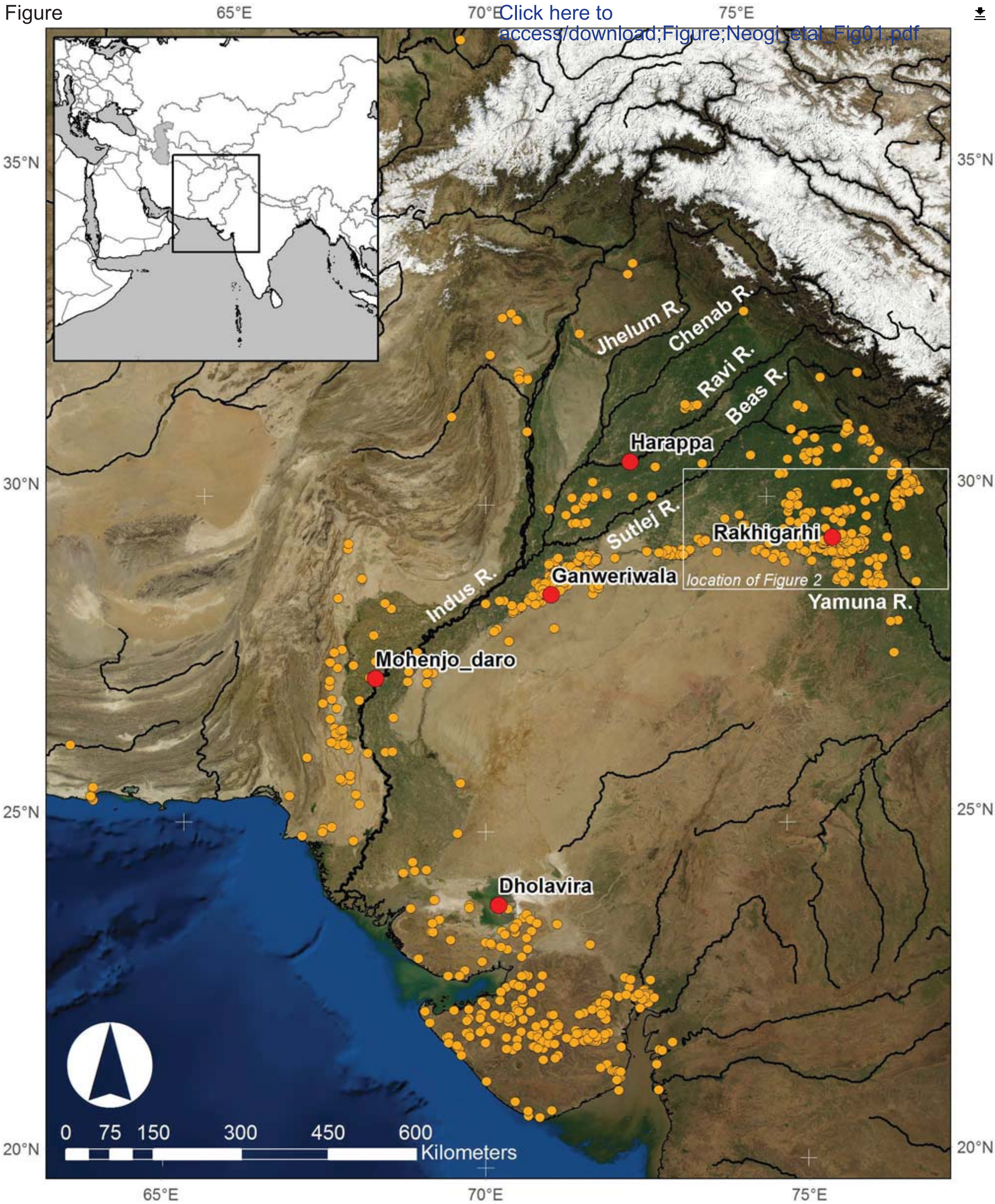
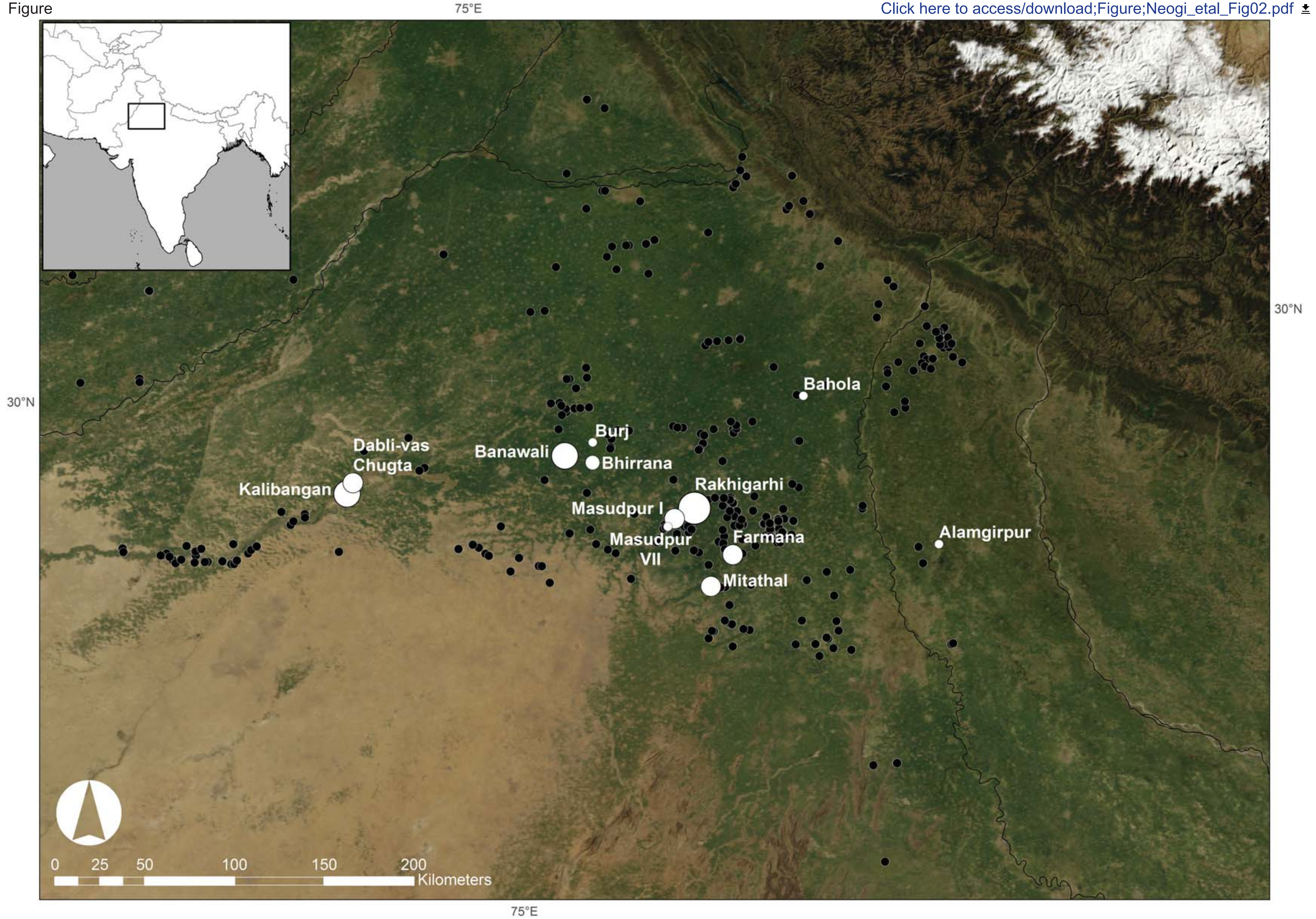


Figure


75°E
30°N
Dabli-vas
Chugta
Kalibangan
Banawali
Burj
Bhirrana
Rakhigarhi
Masudpur I
Masudpur
VII
Farmana
Mitathal
Bahola
Alamgirpur
0 25 50 100 150 200
Kilometers

Supplementary information

S. Neogi, C.A.I. French, J.A. Durcan, R.N. Singh, & C.A. Petrie

Geoarchaeological insights into the location of Indus settlements on the plains of northwest India

SI.1. Methods

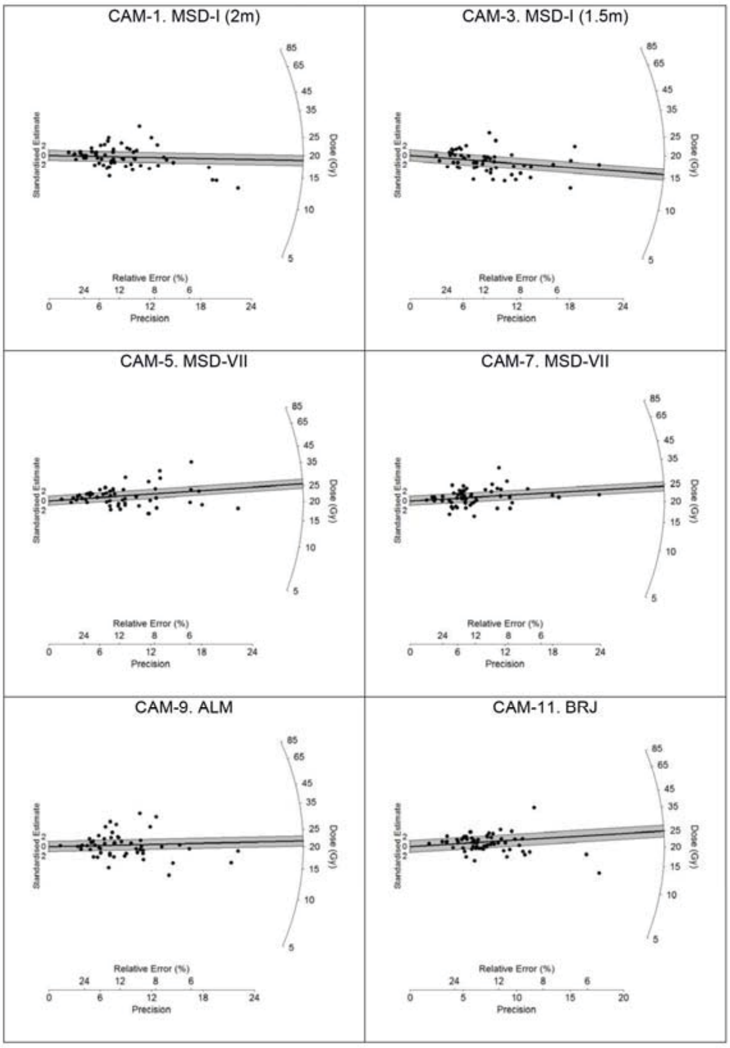
Geoarchaeology

The technique of soil micromorphology is adept at investigating soil texture, properties, processes and their inter-relationships in soils and sediments (Kubiëna 1970; Courty *et al*. 1989; Goldberg and Macphail 2006). Soil sampling for micromorphology removed intact soil blocks from vertical sections, which were impregnated with a crystic resin under vacuum, and when cured were then cut, mounted on large glass slides and polished to a thickness of *c*. 25-30um using a Brot multi-plate grinding machine following the method described by Murphy (1986; French 2015, App. 3) at the McBurney Laboratory, Department of Archaeology, University of Cambridge. Thin sections were analysed using a Leica 12 PolS and Wild M40 wide-view polarizing microscopes. The sections were all described using the accepted terminology of Bullock *et al*. (1985), Stoops (2003) and Stoops *et al*. (2010) (Table SI.2).

pH measurements were determined using a 10g to 25ml ratio of <2mm air-dried soil to distilled water with an Hanna HI8314 pH metre. Determining loss-on-ignition followed the protocol of the Department of Geography, University of Cambridge, to record the percentages of calcium and carbon in the soil (www.geog.cam.ac.uk/facilities/laboratories/techniques/psd.html). For loss-on-ignition, weighed sub-samples were heated to 105˚C for 6 hours to measure water content, then heated to 400˚C for 6 hours to measure carbohydrate content, then to 480˚C for 6 hours to measure total organic matter content, and finally heated to 950 ˚C for 6 hours to measure CO_2 content lost from Ca CO_3 within the sediment (Bengtsson and Ennell 1986). The calcium carbonate content can then be calculated by stoichiometry (Boreham *et al*. 2011). A Malvern Mastersizer was used for the particle size analysis (Table SI.3) using the same Geography facilities at Cambridge. For magnetic susceptibility measurements (Table SI.3) a Bartington MS2B metre was used, giving mass specific calculations of magnetic susceptibility for weighed, 10cm^3 subsamples (English Heritage 2004: 27).

Luminescence dating

Figure SI.1. Radial plots of equivalent dose (De) distributions (in Gy) for each sample. The closed symbols show Individual De determinations, and the solid black line shows the central age model calculated sample De and the associated ±2σ uncertainty (grey shaded area).



SI.2. Profile descriptions, micromorophological observations and geochemical results

SI.2.1. Alamgirpur

The site of Alamgirpur (Meerut district, Uttar Pradesh) was first excavated under the direction of Y.D Sharma in 1958-1959 (Ghosh 1958) and was reinvestigated under R.N Singh in 2008 (Singh *et al*. 2013). The occupation of the site has been dated by a combination of material culture analysis and radiocarbon dating. Five profiles were exposed in the vicinity of Alamgirpur in order to characterize the local geomorphology, and samples for micromorphological analysis were collected from Profiles 1 and 3 (434-454 and 143-153cm below the top of the profile, respectively; Fig. SI.2-3, also Fig. 3). It was ascertained that these locations were the most likely to reveal information on the environmental conditions prior to the occupation on this mound.

Profile 1 was located at the basal part of the much dissected settlement mound on its southern side (Fig. SI.3). A buried soil was observed here as a 24cm thick pale yellowish brown sandy silt, developed on a substrate of yellow silt with abundant $CaCO_3$ concretions. Profile 2 was located close to Profile 1, but at a higher elevation (1m above the base). It had similar characteristics to Profile 1, but the deposits were overlain by 20cm of archaeological deposits. Profile 3 was observed 400m towards the south of the settlement mound, and comprised 75cm of very fine sand over horizontally bedded white micaceous river sands. This profile was at the edge of a sand dune that had distinctive Indus period pottery sherds eroding from it. Profile 4 was very similar to Profile 3, and located on the western edge of the same dune. Profile 5 was dug 500m west of the archaeological mound on the flat alluvial plain of the Hindon River.

In terms of physical parameters (Table SI.3), these profiles were strongly alkaline (pH 8-9.8) with a low total organic content (0.4-2.175%). A high calcium carbonate value (11.21%) was only present at the base of the profile. Magnetic susceptibility values were relatively not enhanced at 16.6-28.6SI. Although the textures of the soil samples vary considerably from sand/silt dominated to silt/clay domninated, these are probably determined as much by variation in the parent material as by pedogenic processes. Overall the range of particle size results confirms the presence of very fine soil materials indicative of deposition and sorting in low energy environments, especially in sample Profile 1 where silt and clay predominate, leading to a perched groundwater table and gleyic properties.

Sample 1/1 (434-454cm; Table SI.2; Fig. 4) was collected from the base of Profile 1. It is mainly an apedal sandy soil, becoming a silty clay loam with depth. There are hints of a weakly developed sub-angular ped structure associated with fragments of highly oriented, birefringent, allochthonous and autochthonous micro-laminated pure (or limpid) clay throughout the groundmass as well as impure or dusty/silty clay pedofeatures increasing down-profile (Table SI.2; Fig. 4). This suggests that the fragments of clay are the products of recycling of the much older and pre-existing 'B' horizon material (*cf*. Brewer 1960; Kuhn *et al*. 2010). The other, less frequent, impure clay textural pedofeatures suggest several episodes of clay movement and re-deposition down-profile (*cf*. Usai and Dalrymple 2003), possibly associated with the movements of groundwater and brief periods of alluvial aggradation and disturbance (*cf*. Fedoroff 1972).

High organic content indicates the presence of thick vegetation, though there has been replacement by amorphous iron. The fine fabric is also masked to a great degree by amorphous sesquioxides (iron oxides/hydroxides) (Fig. 5). These features are suggestive of repeated waterlogging conditions, but with fluctuations in the groundwater table and resultant alternating wetting and drying conditions. Wetter soil conditions after a period of soil development are indicated by these soil properties. Superimposition of one or more pedofeatures indicates the polygenetic nature of the soil, and the lack of $CaCO_3$ exhibited by the rare crystalline pedofeatures is further evidence of this enhanced moist environment.

Sample 3 (143-153cm) was collected from the middle of Profile 3, where very fine sand interfaced with horizontally bedded white micaceous river sand. Microscopic observation (Table SI.2) indicates that the underlying parent material is a fine to medium quartz sand. The soil horizon above was predominantly a coarse quartz sand, but it exhibited a bridged grain to striated appearance with dusty or impure clay. These features suggest a possible fluvial component to this deposit. Therefore, it is likely that the 'soil horizon' observed in this profile is instead the former weathered surface of a *levée* formed from riverine deposition of the nearby River Hindon, but which did enjoy some measure of stability and weak pedogenic development in the past as an old ground surface. Indeed the presence of a few crystalline pedofeatures and nodules of $CaCO_3$ suggest some periods of surface drying (*cf*. Durand *et al*. 2010).

Figure SI.2. Map showing the location of the profiles around Alamgirpur (Map: C.A. Petrie)

Figure SI.3. The sampling procedure at Alamgirpur Profile 1 (Photo: A.K. Pandey)

SI.2.2. Masudpur I

The mound sites of Masudpur I (locally known as *Sampolia Khera*) and Masudpur VII (locally known as *Bhimwada Jodha*) were excavated by the *Land, Water and Settlement* team in 2009 (Petrie *et al*. 2009, 2016; Singh *et al*. 2009, 2015a, 2015b). The occupation of both sites has been dated by a combination of material culture analysis and radiocarbon dating.

Samples for micromorphological analysis were collected as follows: Sample 10/2, Sample 10/3 from Profile 10, and Sample 13 from Profile 13 (Fig. SI.4, see also Fig. 6).

Sample 10/2 (105-113cm) is a fine sandy loam with an apedal soil structure that overlies another soil identified in Sample 10/3 (see below). The parent material is well-sorted fine sand and silt quartz and mica. Bridged grain and pellicular microstructures of the fabric reflect the homogeneous sandy nature of the soil. There were some included potsherds and fine bone fragments within the sandy matrix, and humified plant tissues were common. At least for part of the year a fluctuating groundwater table has led to some gleying resulting in some iron oxide mottling (*cf*. Schwertmann 1993; Lindbo *et al*. 2010), despite sandy soils generally being well drained (Vinther *et al*. 2006). Nevertheless, there is some secondary $CaCO_3$ formation in the form of micrite which suggests that there has been some evapo-transpiration and surface drying, possibly as a consequence of semi-arid climatic conditions (*cf*. Courty *et al*. 1987; Durand *et al*. 2010). Sandy soils are generally free draining and leached, thus often preventing the accumulation of much of an organic-rich topsoil horizon (Moody 2006; Hassink *et al*. 1993), and this was probably the case here.

Sample 10/3 was collected at 113-122cm, and was thus slightly deeper than within Profile 10. This sample exhibits a crumb to pellicular grain microstructured, fine sandy loam composed of well-sorted quartz and mica. There is minor evidence of the inclusion of fine anthropogenic material of fragments of bone and potsherds. The organic content increases considerably from the MSD Sample 10/2 thin section and includes organic fines and plant tissue fragments. These soil properties indicate that this was probably a buried topsoil acting as a former land surface (*cf*. Liversage and Robinson 1993). In addition, the soil shows polygenetic properties and there is evidence for the accumulation of carbonates in the form of micrite, suggesting phases of surface drying, as well as gleying resulting in grey/brown mottling throughout the soil profile.

Sample 13 (205-212cm) was also a fine sandy loam, but there are very striking differences between this thin section and MSD Samples 10/2 and 10/3. The fine sand and silt components are very well-sorted, and the organic content is high and includes melanised fines and larger plant tissues. A channel microstructure is predominant. There are coatings of illuvial clay within many of the channels indicating that clay has moved downward through the soil profile by the action of water. Amorphous sesquioxide mottling indicates that gleying has been underway, associated with a fluctuating groundwater table. The features suggest that this part of the soil profile was a 'B' horizon, but it exhibits polygenetic properties that have developed at different soil forming stages. The sandy parent material suggests initial fluvial deposition, perhaps as part of an alluvial braid plain complex. Within this aggrading system, a cumulic topsoil developed which contained large amounts of organic material with a channel microstructure resulting from plant rooting (*cf.* French *et al*. 2009).

The micromorphology of Profile 10/2 shows that at a depth of 105-113cm, sedimentary aggradation was the dominant geomorphological process. Beneath this, at a depth of 113-122cm in MSD Profile 10/3, a buried organic Ah horizon was recognised with characteristic crumb aggregates, and evidence for soil fauna and incorporation of organic matter (Emerson 1959). Beneath at a depth of 205-212cm, as observed in MSD Profile 13, there was a buried 'B' horizon present with argic properties as defined by the presence of illuvial clays.

Figure SI.5. Map showing the profile locations at Masudpur I (Map: C.A. Petrie)

Figure SI.5. Photograph of cut section at Masudpur Profile 10 (Photo: C.A.I. French).

SI.2.3. Burj

The small-village sized site of Burj is located in the Fatehabad district of Haryana and was excavated by the *Land, Water and Settlement* team in 2010 to understand the nature and chronology of the transition between Late Harappan and Painted Grey Ware periods, which is much debated (Singh *et al*. 2010a). Although Late Harappan pottery was reported from the surface, excavations only revealed occupation during the Early Harappan and Painted Grey Ware (PGW) periods (Singh *et al*. 2010a).

Samples for micromorphological analysis were collected as follows: Sample 1/1, Sample 1/2, Sample 1/3 from Profile 1 (Fig. SI.6-8). The physical characteristics of the Burj profiles exhibited very strong alkaline conditions (10.2-10.28), with low percentages of organic content (<1.24%) but high calcium carbonate content (12.56-21.47%) and low magnetic susceptibility values (Table SI.3). Texturally the samples were similar, with sand predominating (*c*. 50-65%)

along with a considerable silt content (*c*. 30-43%), but relatively low values of clay present (<5.9%) (Table SI.3).

Sample 1/1 (24-37cm) was collected from near the top of Profile 1, and micromorphological observations showed a generally apedal, porous, fine sandy silt loam with granular soil aggregates and channel microstructures (*cf.* Day and Holmgren 1952; Kooistra and Pulleman 2010; Stolt and Lindbo 2010; Stoops *et al*. 2010) with infrequent anthropogenic inclusions of bone. This suggests that this is a former organic Ah horizon with significant rooting and turbation of the soil (Fig. 9). Secondary calcium carbonate has accumulated within the soil as well as amorphous iron oxides in the form of mottles and amorphous iron compounds giving the soil a brownish colour. The latter properties developed because of seasonal wetting and drying, as calcium carbonate forms when transpiration outweighs precipitation in a semi-arid environment (Durand *et al*. 2010). The parent material was fluvial sands and silts which formed a complex of sedimentary deposition and channels.

Sample 1/2 (50-62 cm) has properties similar to the previous thin section (Sample 1/1) of the profile. The soil is an apedal fine sandy silt loam with a decrease in porosity. The coarse minerals include very well-sorted quartz silt and fine quartz sands. There is very little evidence of included anthropogenic material. The part of the profile represented by this sample can be interpreted as a fluvial sedimentary deposit of fine sand and silt, which has been laid down relatively quickly. Subsequently, plant roots developed a channel microstructure. Bioturbation was a dominant process and has destroyed much of the evidence for sedimentation. During a later soil forming period, there was an accumulation of calcium carbonate within this part of the soil profile. Monsoonal climatic conditions and cycles of wetting and drying appear to have developed iron mottling and fine amorphous iron compounds throughout the fine fabric characterised by brown colours.

Sample 1/3 (75-90cm) was collected from the lower part of Profile 1. This is an apedal fine sandy silt loam with very well-sorted quartz particles and a vughy microstructure with channels. Again, there is a low organic content comprising amorphous fine material and humified plant tissue residues. As with the other samples from Burj, the micromorphology of the soil indicates that organic content has previously been much higher. It is through the oxidation and biological diagenesis of the organics during subsequent soil forming periods that the organic component was transformed into secondary compounds. The soil at this depth has been subject to gleying processes through the repeated fluctuation of the groundwater table. Perhaps the most interesting defining characteristic of this part of the soil profile, despite the particle size analysis suggesting that were a low clay content, is the significant evidence of clay textural pedofeatures, including common coatings, infillings and fragments of micro-laminated pure and dusty clay in the groundmass and voids. This relatively clay enriched horizon suggests that this was an argillic Bt horizon, and based on the degree of development it must have been part of a soil sequum of some considerable age. The presence of a few anthropogenic markers, such as potsherds and bone fragments, suggests that the associated land surface was under human occupation (*cf*. Adderley *et al*. 2010). The evidence for precipitation of $CaCO_3$ diminishes at this depth in the Bt horizon, and there is the scant presence of micrite within the fine fabric. This could indicate the later precipitation of carbonate-rich water as a result of drying of the environment during the later Holocene (*cf*. Sehgal and Stoops 1972).

Figure SI.6. Map showing the Profile locations at Burj (Map: C.A. Petrie)

Figure SI.7. Photograph of the cut section at Burj Profile 1 with the location of soil blocks indicated (Photo: C.A.I. French).

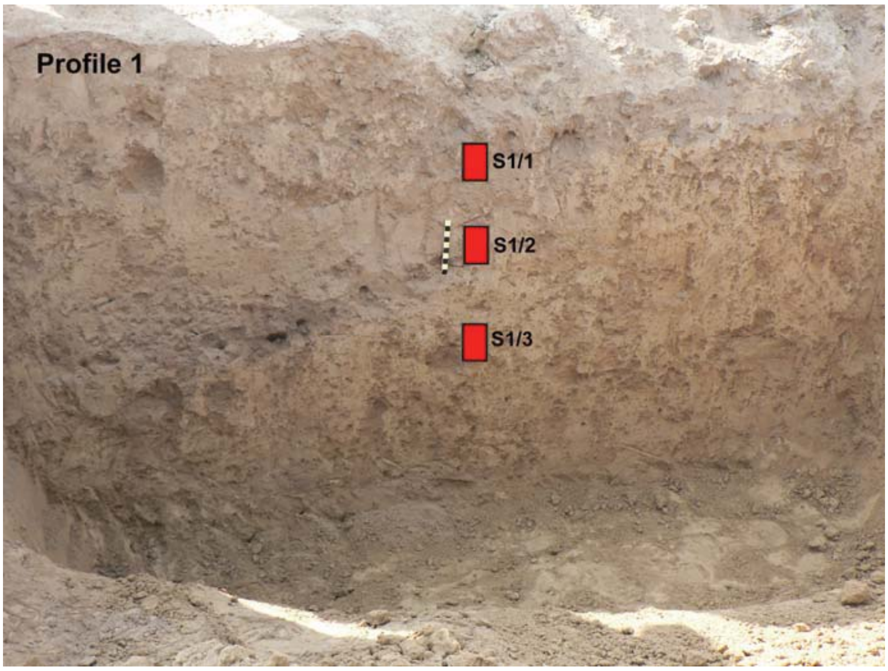


Figure SI.8 Photograph of the cut section at Burj Profile 2 (Photo: C.A.I. French).

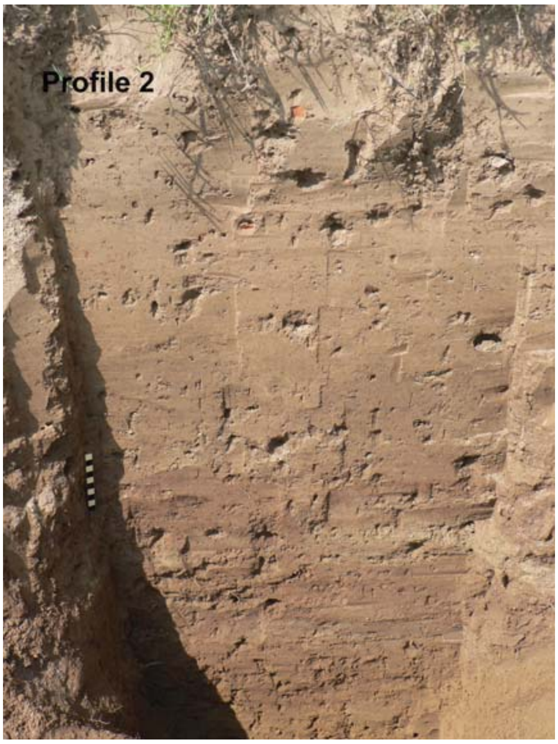


Table SI.1. Profile descriptions for Alamgirpur, Masudpur I, Masudpur VII, and Burj

Site/Profile	Depth below modern ground surface (cm)	Field description
Alamgirpur:		
Profile 1	0-24	pale yellowish brown silt; *c*. 30cm removed; modern ploughsoil (Ap)
	24-75	yellowish fine sandy silt with frequent calcitic nodules; B/C
Profile 2	0-20	pale brown silt with pottery sherds; modern ploughsoil (Ap)
	20-40	pale yellowish brown sandy silt
	40+	yellowish brown sandy silt with frequent calcitic nodules; B/C
Profile 3	0-25	homogeneous fine sand; modern ploughsoil (Ap) with pottery sherds
	25-100	very fine sand/silt; aeolian deposit
	100+	white, laminated, micaceous riverine sand
Profile 4	0-25	homogeneous fine sand; modern ploughsoil (Ap) with pottery sherds
	25-100	very fine sand/silt; aeolian deposit
	100+	white, laminated, micaceous riverine sand; B/C
Profile 5	0-20	pale brown fine sandy loam; modern ploughsoil (Ap) with pot sherds
	20-200	reddish brown silty clay loam; alluvium
	200-300	brown silty clay loam with some sand and calcium carbonate concretions; alluvium
	300-330	very fine and soft, pale brown micaceous fine sand with some calcium carbonate concretions; riverine sands
	330-360	highly micaceous, yellowish brown fine sand with lesser/almost no concretions; riverine sands
	360-390	dark grey fine-medium sand with occasional yellowish/orange mottles; gleyed riverine sands
	390-400	grey/bluish grey, highly micaceous, fine-medium sand; wet/gleyed riverine sands
	400+	groundwater table
Masudpur I:		
Profile 10	0-100	horizontally banded pale yellowish brown fine sandy silt; modern ploughsoil (Ap) with frequent pot sherds
	100-107	dark grey very fine sandy silt; buried Ah horizon
	107-135	pale brown very fine sandy silt; buried B horizon
	135+	pale yellowish brown very fine sandy silt with frequent calcitic nodules; B/C
Profile 11	0-45	pale brown silt; modern ploughsoil (Ap)
	45-155	brown silt; alluvium
	155-170	yellowish/greyish brown very fine sandy silt; upper channel fill deposits
	170-292	yellowish brown very fine-fine sand, becoming coarse with depth; channel fill deposits

	292+	yellow fine-medium sand with frequent calcitic nodules; B/C
Profile 12	0-75	pale brown silt; modern ploughsoil (Ap)
	75-170+	dark greyish brown very fine sandy silt with irregular to columnar blocky ped structure; alluvium; not bottomed
Profile 13	0-185	dark brown silt with irregular to columnar blocky ped structure; modern ploughsoil (Ap) in alluvium
	185-215	as above with orange mottling; part oxidized/gleyed alluvium
	215+	yellowish brown very fine sandy silt; upper channel fill deposits
Masudpur VII:		
Profile 15	0-193	pale brown very fine sand; modern ploughsoil (Ap) with Indus archaeological levels
	193-213	yellowish brown fine sand; upper B/C
	213-268	sterile pale yellowish brown fine sand; B/C
	268+	pale yellow very fine-medium sand with frequent calcitic modules; dune C
Burj:		
Profile 1	0-24	pale brown silt; *c*. 40cm removed; base of modern ploughsoil (Ap)
	24-75	yellowish brown very fine sandy silt with occasional freshwater bivalve; alluvium/reworked channel bed deposits acting as a B horizon
	75+	yellowish brown very fine sandy silt with frequent calcitic nodules; B/C
Profile 2	0-20	pale brown silt with pottery sherds; modern ploughsoil (Ap)
	20-60	yellowish brown very fine sandy silt; B horizon
	60+	yellowish brown very fine sandy silt with frequent calcitic nodules; B/C
Profile 3	0-75	homogeneous pale brown silt; modern ploughsoil (Ap) with pottery sherds
	75-125	horizontally banded archaeological levels of alternating dark reddish brown and pale grey silt; repeated stop/start alluvial deposition and surface drying out
	125+	pale yellowish brown calcitic silt; B/C
Profile 72	0-120	sandy silt; modern ploughsoil (Ap) with Indus archaeological material
	120-145+	pale yellowish brown sandy silt; B/C
Profile 73	0-30	pale yellowish brown sandy silt; modern ploughsoil (Ap)
	30-60	dark greyish brown sandy silt; gleyed B horizon
	60-100	pale yellowish sandy silt with calcitic nodules; B/C

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Table SI.2. Summary micromorphological observations for Alamgirpur, Masudpur I, and Burj

Site/sample	Main fabric	Other features and inclusions	Interpretation
Alamgirpur:			
1/1 upper, 434-444cm	very fine-fine sandy loam exhibiting weakly developed sub-angular blocky microstructure superimposed on channel microstructure	common dark brown amorphous organic fine material & abundant humified plant tissues; groundmass abundantly striated with pure/dusty clays; voids coated with pure/dusty clay; few fragments of highly oriented micro-laminated pure clay; common dense infillings of voids with aggregates of same fine groundmass fabric; frequent amorphous sesquioxide staining of groundmass & replacing plant remains; few $CaCO_3$ nodules	humic sandy loam soil with illuvial fines indicative of former stability & some soil formation; subsequent secondary formation of iron & calcium carbonate through strong drying conditions
1/1 lower, 444-454cm	silty clay loam exhibiting moderately well-developed sub-angular blocky microstructure with abundant channels & vughs	common dark brown amorphous organic fine material & abundant humified plant tissues; groundmass abundantly striated with pure/dusty clays & voids commonly coated with pure/dusty clay; common dense infillings of voids with aggregates of same groundmass fabric; frequent amorphous sesquioxides around pore space & as nodules; common micritic coatings of voids; few $CaCO_3$ nodules	humic silty clay loam with organised clay component & some structural development indicative of argillic B horizon, which becomes strongly gleyed and subject to wetting/drying episodes
3/1, 143-153cm	coarse sandy/silty clay loam with channel microstructure superimposed on single to bridged grain; developed on fine-medium quartz sand	few fragments of pottery, bone & mud-brick; common dark brown amorphous organic fine material & humified plant tissues; groundmass abundantly striated with pure/dusty clays; voids coated with pure/dusty clay; common dense infillings of voids with aggregates of same groundmass fabric; common amorphous sesquioxides around pore space & replacing plant remains; common micritic coatings of voids; few $CaCO_3$ nodules; few silt crusts	weathered surface of levee with fine anthropogenic and overbank alluvial inputs
Masudpur I:			
10/2: 105-113cm	apedal to bridged grain, fine sandy loam	few fragments of pottery & bone; few to common amorphous organic fine material & humified plant tissues rare aggregates of same groundmass fabric; rare dusty clay coatings of voids;	weakly developed sandy loam soil with some input of anthropogenic material, minor illuviation of fines, &

		some secondary amorphous sesquioxide mottling; some secondary micrite formation	secondary formation of iron & calcium carbonate through seasonal wetting/drying
10/3, 113-122cm	crumb to pellicular grain structured, fine sandy loam	few fragments of pottery, bone & mud-brick; common dark brown amorphous organic fine material & humified plant tissues; few phytoliths; common void coatings with pure & dusty clay; few fragments of pure clay; common infillings of voids with aggregates of same groundmass fabric; common amorphous sesquioxides around pore space & replacing plant remains; few $CaCO_3$ nodules; few silt crusts	weakly developed sandy loam soil with gleying & surface drying
13, 205-212cm	single to bridged grain structured fine sandy loam with few channels	common dark brown amorphous organic fine material & humified plant tissues; few phytoliths; common void coatings with pure & dusty clay; common fragments of pure clay; frequent infillings of voids with aggregates of same groundmass fabric; common amorphous sesquioxides around pore space & replacing plant remains; few $CaCO_3$ nodules	sandy loam soil with strong illuvial fines component suggesting longer-term pedogenesis
Burj:			
1/1, 24-37cm	finely aggregated, channelled & vughy, fine sandy silt loam	few dusty clay around grains and lining pore space; occasional zones/nodules of $CaCO_3$; few sesquioxide nodules & mottles; few fragments of bone	bioturbated & rooted A horizon with secondary formation of iron & calcium carbonate
1/2, 50-62cm	finely aggregated, channelled & vughy, fine sandy silt loam	few humified plant tissues; few dusty clay around grains and lining pore space; common zones/infills/coatings/nodules of micritic $CaCO_3$; few sesquioxide nodules & mottles; few fragments of bone	bioturbated & rooted A horizon with strong secondary formation of calcium carbonate indicating surface drying
1/3, 75-90cm	channelled & vughy, fine sandy silt loam	few humified plant tissues; common micro-laminated pure & dusty clay around grains and lining pore space; few nodules of micritic $CaCO_3$; common sesquioxide nodules & mottles; few fragments of pot & bone	clay-enriched Bt horizon implying more moist, vegetated and stable conditions in the past

Table SI.3. Selected pH, loss-on-ignition organic and calcium carbonate contents, magnetic susceptibility, and summary particle size analysis results for Alamgirpur, Masudpur I and Burj

Site/sample number	*pH*	*% organic content*	*% calcium carbonate*	*Magnetic susceptibility ($x10^{-8}$ SI)*	*% sand*	*% silt*	*% clay*
Alamgirpur:							
3, 143-153cm	8.07	0.415	1.68	23	88.89	10.34	0.77
1, 444-454cm	8.43	2.175	3.89	16.6	4.09	53.9	41.93
6, 460-470cm	9.81	1.735	11.2	28.7	37.43	55.35	7.19
Masudpur I:							
10/2, 105-113cm	9.16	1.07	7.2	20.3	73.55	22.16	4.29
10/3, 113-122cm	9.36	0.95	4.1	16.2	74.38	21.19	4.43
13, 205-212cm	8.61	1.26	2.6	13.4	52.2	41.29	6.51
Burj:							
1/1, 24-37cm	10.2	0.945	12.56	24.0	60.03	34.89	5.08
1/2, 50-62cm	10.24	1.24	21.47	18.5	64.44	30.56	5.02
1/3, 75-90cm	10.28	0.88	16.7	11.4	50.75	43.35	5.9

Table SI.4. Equivalent dose (D_e), dose rate ($\dot{D}$) and OSL age summary. D_es, $\dot{D}$ and ages are shown to two decimal places, with all calculations made prior to rounding.

Site	*Depth (m)*	*# Grains accepted (measured)*	*Over-dispersion (%)*	*CAM D_e (Gy)*	*Beta (Gy.ka^{-1})*	*Gamma (Gy.ka^{-1})*	*Cosmic (Gy.ka^{-1})*	*Dose rate (Gy.ka^{-1})*	*Age (ka)*
ALM	1	55 (6600)	46.9 ± 3.7	21.43 ± 1.49	2.88 ± 0.23	1.85 ± 0.12	0.14 ± 0.01	4.87 ± 0.26	4.47 ± 0.40
MSD I	2	61 (1500)	38.6 ± 2.8	18.64 ± 1.06	2.18 ± 0.17	1.48 ± 0.10	0.16 ± 0.02	3.82 ± 0.20	4.89 ± 0.37
MSD I	1.5	56 (2000)	37.7 ± 2.9	15.69 ± 0.91	2.25 ± 0.18	1.50 ± 0.10	0.17 ± 0.02	3.91 ± 0.20	4.01 ± 0.31
MSD VII	3	55 (2600)	38.8 ± 3.0	25.79 ± 1.55	2.05 ± 0.17	1.34 ± 0.09	0.14 ± 0.01	3.53 ± 0.19	7.32 ± 0.59
MSD VII	3	59 (3800)	40.1 ± 3.0	24.24 ± 1.44	2.26 ± 0.18	1.36 ± 0.09	0.14 ± 0.01	3.75 ± 0.20	6.47 ± 0.52
BRJ	1	62 (3300)	38.3 ± 2.8	24.91 ± 1.40	2.67 ± 0.22	1.69 ± 0.11	0.18 ± 0.02	4.54 ± 0.24	5.48 ± 0.42

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