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The dry tank: development and disuse of water management infrastructure in the Anuradhapura hinterland, Sri Lanka

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A B S T R A C T

We identify and offer new explanations of change in water management infrastructure in the semi-arid urban hinterland of Anuradhapura, Sri Lanka between ca. 400 BC and AD 1800. Field stratigraphies and micromorphological analyses demonstrate that a complex water storage infrastructure was superimposed over time on intermittently occupied and cultivated naturally wetter areas, with some attempts in drier locations. Our chronological framework, based on optically stimulated luminescence (OSL) measurement, indicates that this infrastructure commenced sometime between 400 and 200 BC, continued after Anuradhapura reached its maximum extent, and largely went into disuse between AD 1100 and 1200. While the water management infrastructure was eventually abandoned, it was succeeded by small-scale subsistence cultivation as the primary activity on the landscape. Our findings have broader resonance with current debates on the timing of introduced 'cultural packages' together with their social and environmental impacts, production and symbolism in construction activities, persistent stresses and high magnitude disturbances in 'collapse', and the notion of post 'collapse' landscapes associated with the management of uncertain but essential resources in semi-arid environments.

1. Introduction

Archaeological surveys and excavations at the Anuradhapura UNESCO World Heritage Site and its hinterland are yielding new insights into the transformations of South Asian urban-fringe landscapes. These studies suggest that beginning ca. 400 BC, Anuradhapura emerged as an increasingly populous urban area to become the island's secular capital and Buddhist religious centre, and that hinterland monasteries and a transient worker group ensured the flow of staple resources to the urban population (Coningham et al., 2007). Resilient and expanding throughout the first millennium AD, it is generally recognized from historical sources that Anuradhapura and its hinterland were abandoned and the population dispersed ca. AD 1017 as a result of South Indian invasion, after which the capital ultimately moved southeast to Polonnaruva (de Silva, 2005).

As yet, there is little documentation of the timing and nature of hinterland management transformations required to support the developing urban centre, and no understanding of the process of hinterland abandonment and its aftermath. Because the Anuradhapura region is located in the semi-arid region of Sri Lanka, effective capture and storage of water was, as today, critical to staple rice production (Dharmasena, 1994; Panabokke et al., 2002). Features associated with water management are therefore likely to be among the most sensitive indicators of landscape change. Our survey work has identified a number of such features – a water management infrastructure – in the early Anuradhapura hinterland landscape, including bunds and associated water storage tanks, water transport channels and moat sites. Typically, the bunds are constructed earthen dams that from archaeological survey range from ca. 1.75–4.0 metres (m) in height and from ca. 70–200 m in length, producing water storage areas (reservoirs) several hectares (ha) in extent (Fig. 1); water transport channels are

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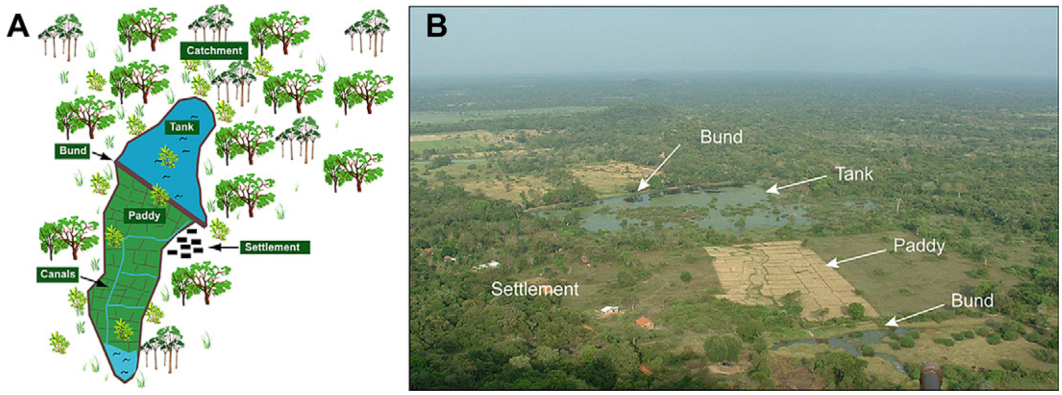

Fig. 1. Water management structures. **A**: Schematic based on Ulluwishewa (1991b, p. 97) demonstrating the relationship between bunds, tanks, paddy, and canals. **B**: Photograph of water management structures in the Nachchaduwa wewa region, Anuradhapura hinterland.

typically ca. 3 m across and now infilled, and moat sites consist of double platforms constructed over surrounding water storage areas up to ca. 1.5 m in depth.

In this paper, our focus is on soils and sediments associated with water management features and 'reading' their stratigraphies to establish the dynamics of urban hinterland landscape change. More precisely, our first objective is to establish land cover conditions prior to the formation of water management features through analysis of underlying palaeosols and sediments, and our second objective is to consider the nature of disuse based on the sediments infilling these features. Our approach in addressing these objectives is to apply soil and sediment micromorphology supported by physical and chemical analyses. Our third objective is to establish these findings within a geo-chronological framework of water management features in the landscape, and in doing so set these features within the context of the origins, development and abandonment of Anuradhapura as an urban centre. To do so, we develop and apply optically stimulated luminescence (OSL) protocols and analyses.

Our findings have a wider resonance beyond establishing the dynamics of landscape change in the Anuradhapura urban hinterland, allowing us to test existing ideas and develop new aspects of regional Buddhist landscape models that endeavour to explain transformations in the development and demise of water management infrastructures. These aspects include testing working hypotheses that the creation of irrigated landscapes with artificial reservoirs in South Asia was initiated and driven by Buddhist introduction (Coningham et al., 2007; Shaw et al., 2007) and at the time of introduction were an entirely new system of land resource management. We consider hypotheses that water management infrastructure development had a role beyond food production, as symbolic construction activities (Mosse, 2005; Scarborough, 2003). We also consider notions of collapse (Brohier, 1935; Crumley, 1994; de Silva, 2005; Diamond, 2005), hypothesizing that that the conjunctures of multiple and interacting environmental and social factors are more likely than single factor explanations of water management infrastructure demise (Buckley et al., 2010; Evans et al., 2007; Kummu, 2009; Leach, 1959; Strickland, 2011). In doing so, we stimulate new ideas on introduced 'cultural packages' together with their social and environmental impacts, production and symbolism in construction activities, persistent stresses and high magnitude disturbances in 'collapse,' and the notion of post 'collapse' landscapes associated with the management of uncertain but essential resources in semi-arid environments.

2. Materials and methods

2.1. Study area and context

Sri Lanka is under the influence of a monsoonal climate regime modified by the effects of mountains in the centre of the island. The Southwest Monsoon (SWM) occurs from the middle of May until September; the Northeast Monsoon (NEM) runs from December to February (Panabokke, 1996). Anuradhapura receives most of its annual precipitation (ca. 1300–1450 mm) during the NEM, which is characterized by unpredictable variations in rainfall, spatially heterogeneous precipitation, and frequent cyclonic storms. The mean annual temperature of the region is 27.3 °C, and evapotranspiration is highest from May to September, exceeding 6 mm/day (Baghirathan and Shaw, 1978; Gunnell et al., 2007; Smithsonian Ecology Project, 1967).

Anuradhapura is located in Sri Lanka's northern lowlands, characterized by low-relief undulating topography varying ca. 50–400 m above sea level, with occasional inselbergs of greater elevation (Gunatilake, 1987). The region's major rivers, the Kala and Malwatu Oyas, are seasonal and drain northwest towards the Gulf of Mannar (Cooray, 1984; Haggerty and Coningham, 1999).

The geology of the Anuradhapura region consists predominantly of quartzites, schists, granites, and gneisses of Precambrian age (Cooray, 1984; Haggerty and Coningham, 1999). The Quaternary geology is dominated by the Red Earth formation formed on weathered bedrock or on bedrock-derived colluvium and is typically clayey sand or loam in texture. Minerals are predominantly rounded quartz grains and minor inclusions of ilmenite, magnetite, spinel and zircon embedded in a matrix of kaolinite clay and fine iron oxide (Cooray, 1984; Panabokke, 1996). Reddish Brown Earths (RBE; Chromic Luvisols, FAO, 1988) comprise the most common soil group occupying higher and mid-slope positions in the landscape, with illuviation the dominant pedogenic process. Low Humic Gleys (LHG; Gleysols, Eutric Gleysols, FAO, 1988) are developed on colluvium deposited from the slopes of low hills or on alluvial sediments along river valleys and channels. Their morphological characteristics include mottling and gleying, documenting continuous or seasonal waterlogging. Nodules of calcium carbonate (*kankar*) are frequently observed within the top few inches of the soil surface, although these can reach depths of more than 1 m (Cooray, 1984; Panabokke, 1996). Alluvial soils (Fluvisols, Eutric Fluvisols, FAO, 1988; Panabokke, 1974) are common in flood plains and river valleys.

Currently, land use in the Anuradhapura region is primarily irrigated rice agriculture (Bandara, 2003; Ulluwishewa, 1991a). Paddy cultivation takes place on lower topographic positions on LHG and alluvial soils, creating concentrations of Fe–Mn oxides and clays (Zhang and Gong, 2003) together with subsoil hardpans with reduced infiltration (IUSS Working Group, 2006; Kawaguchi and Kyuma, 1977; Zhang and Gong, 2003). Swidden cultivation (locally called *chena*) takes place on the higher landscape positions in RBE soils with at least an eight to ten year rotation (Fig. 2; Dharmasena, 1994; Siriweera, 1990). *Chena* soils have high fertility but tend to become compacted, resulting in low infiltration and increased runoff. Erosion rates tend to be high because of compaction, but also due to de-vegetation contributing to landscape degradation, subsequently resulting in siltation and infilling of irrigation works (Dharmasena, 1994).

2.2. Site selection and methods

For this study, the hinterland is defined as the area within a ca. 50 km radius from the Anuradhapura citadel (Coningham et al., 2007; Fig. 2). Beginning in 2005, five seasons of archaeological survey documented hundreds of sites (including ceramic scatters, metalworking, and monastic sites) and water management structures, most of which are currently in use. We limited the present study to relict water management structures: four bunds and the infills from two adjacent tanks, two channels and one moat

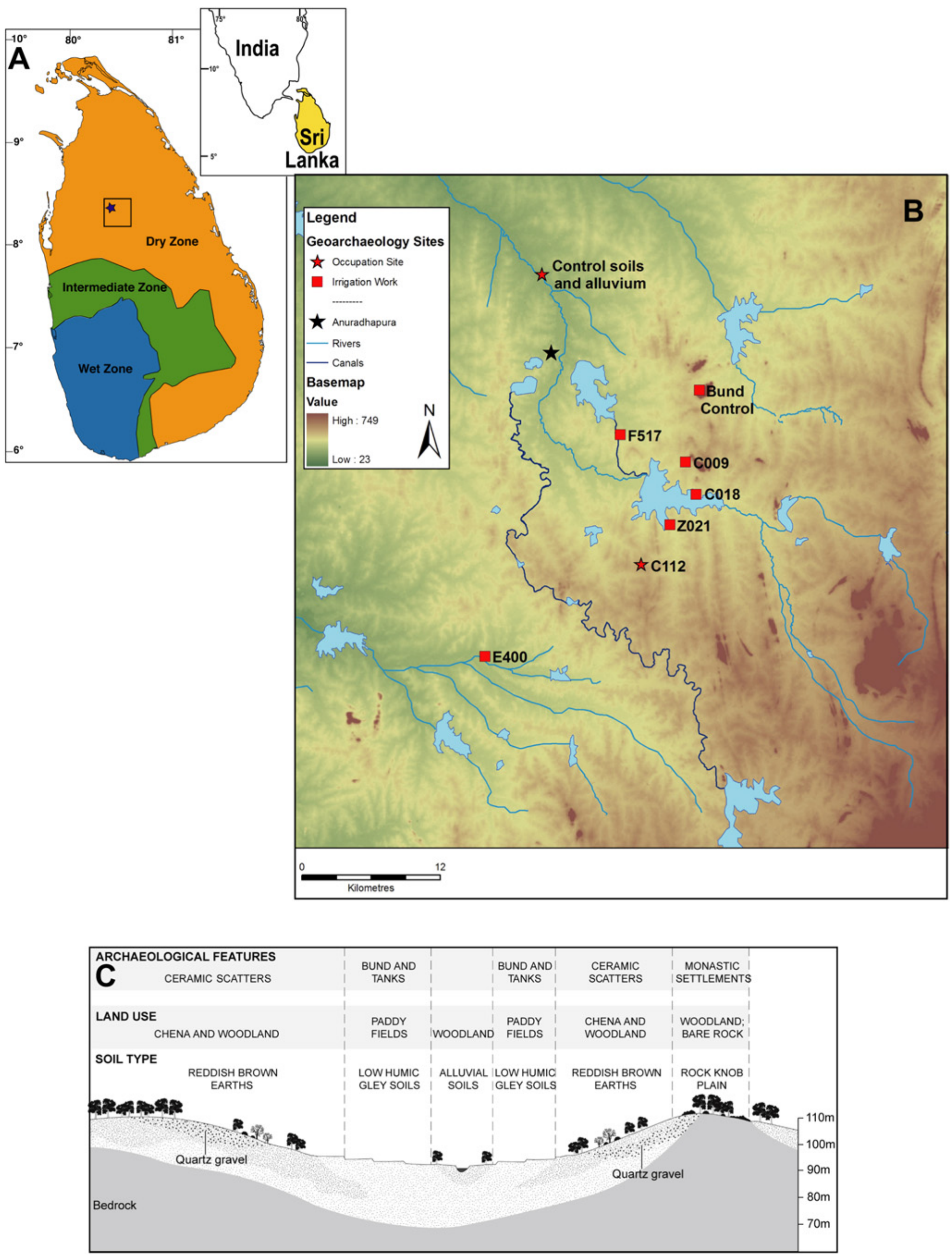

Fig. 2. Study area. **A**: Study area (square) within the Dry Zone of Sri Lanka; Anuradhapura is indicated by the star. Modified from Wijesinghe (1979). **B**: Study sites discussed in this paper; study site notation following Coningham et al. (2007). Map modified from Brohier (1935). **C**: Relationship of archaeological features, land use, and soil type with relation to the topography of the study area. Modified from Panabokke (1996).

Table 1
Control sites, archaeological sites and historical associations.

	Site	Type	Historical association
Controls	Modern bund	Control bund	Local knowledge indicates bund section constructed ca. 50 years ago
	B062: Modern paddy and chena soils	Agricultural soils	Paddy soils actively being cultivated; local knowledge indicates the 3 sampled chena soils were under active cultivation (C3), abandoned <25 years (C1), and abandoned >25 years (C2).
	B062: Alluvial sediment	Alluvial sediment	Unknown age.
Tanks and bunds	C009 (*Ehalagamawewa*)	Tank and bund, isolated/rain-fed	None apparent.
	E400 (*Veheragala*)	Tank and bund, appears unrelated to Nachchaduwa system	Associated with monastic site A155 (*Veheragala*): Black and Red ware, NBPW, diagnostic coarse ware: ca. 360 BC onwards.[a,b,c,e,f]
	Z021 (*Parthigala*)	Tank and bund, appears connected to Nachchaduwa system	Associated with monastic site Z00: Architecture at site mid-8th to 12th centuries AD,[a] although bricks from a stupa suggest a pre-existing monastery dating to ca. 4th–6th centuries AD.[e] Z021 bund is submerged by water in Nachchaduwa tank and assumed to be older.
	Z021a (*Parthigala*)	Bund, appears connected to Nachchaduwa system	Ceramics within bund suggest ca. 3rd century BC to 12th century AD. Z021a is submerged by water in Z021 tank and assumed to be older.[a,b,c]
Infills	C018 (*Ghalwaduwagama*)	Infilled channel	Ceramics suggest affiliations with ASW2 Period F (ca. AD 300–600).[c]
	C112 (*Marathamadra*)	Infilled moat at monastic site	Monastery is dated typologically to between the 8th and 10th centuries AD.[a]
	F517 (*Kirikulama*)	Infilled channel and monastic settlement	Channel stratigraphically below brick and stone pillared hall at site; moonstone at hall suggests construction ca. 6th–7th centuries AD or later.[d]

NBPW = Northern Black Polished Ware; ASW2 = Anuradhapura Salgaha Watta 2.
[a] Coningham et al. (2007).
[b] Coningham (1999, 2006).
[c] Coningham and Batt (1999).
[d] Bandaranayake (1974).
[e] Mark Manuel (pers. comm.).
[f] Prickett-Fernando (2003).

(Table 1). Most of the study sites are located near the Nachchaduwa wewa (tank); historical sources suggest it was constructed sometime between the third to ninth centuries AD (Fig. 2; Brohier, 1935; Gunawardana, 1971).

Hand-dug stratigraphic sections from each of the sites were drawn and described using Munsell colours, texture and inclusions, enabling field-based interpretations that guided sampling. Stratigraphic sections from known contexts, identified during semi-structured ethnographic interviews with local farmers, were sampled as modern controls. These controls consist of a recently constructed bund, recently cultivated paddy and chena soils, and alluvial sediments.

Undisturbed soil samples were taken from key contexts in the stratigraphies using 5 × 8 cm Kubiëna tins, and thin sections were manufactured at the Thin Section Micromorphology Laboratory, University of Stirling following standard procedures (http://www.thin.stir.ac.uk/methods.html). Thin sections were described using plane polarized (PPL), cross-polarized (XPL), and oblique incident light (OIL), using magnifications ranging from 10 to 400×. Semi-quantitative estimation of groundmass components and pedofeatures was based on standard visual aids (Bullock et al., 1985; Courty et al., 1989; Stoops, 2003).

Bulk sediment samples were taken from individual horizons in the immediate area of the thin section sample; analyses was performed on the <2 mm fraction, and included organic content estimated using loss-on-ignition (Heiri et al., 2001), frequency dependent susceptibility measurements (%χ_{fd}) conducted using the Bartington MS2 Magnetic Susceptibility System (Dearing, 1999), and total phosphorous (P), measured using the sodium hydroxide fusion method (Smith and Bain, 1982), followed by colorimetry using the Spectronic Helios Epsilon spectrophotometer (Thermo Electron Corporation) at a wavelength of 880 nm. Analyses were replicated to give errors of less than 5%.

Samples for optically stimulated luminescence (OSL) measurement were collected using copper tubes inserted into the vertical face of the stratigraphy, subsequently extracted, and sealed. Sample locations were enlarged for *in situ* field gamma spectrometry (FGS) measurements, taken using an Ortec DigiBASE spectrometer pack with a 2 × 2″ NaI probe. Sample tubes were then processed and analysed in the Scottish Universities Environmental Research Centre (SUERC) luminescence laboratory under safelight conditions (Burbidge et al., 2008; Cresswell and Sanderson, 2009). Luminescence was measured using the single aliquot regeneration (SAR) sequence (Murray and Wintle, 2000), employing Risø DA-15 automatic readers (Bøtter-Jensen et al., 2000). *In situ* FGS measurements were combined with laboratory measurements of standard high-resolution gamma spectrometry (HRGS) to produce gamma dose rates used in OSL measurement. The SUERC Thick Source Beta Counting (TSBC) system determined beta dose rates (Sanderson, 1988) and cosmic dose rates were determined using Prescott and Stephan (1982) and Prescott and Hutton (1988). Sample preparation and water measurements were performed using standard methods (Burbidge et al., 2008; Cresswell and Sanderson, 2009).

3. Results and discussion

3.1. Stratigraphies

Field stratigraphies and field-based interpretations are given in Figs. 3, 4 and 5. Land surfaces and underlying Quaternary deposits, construction phases, and tank and channel infills are evident, and provide the foundation for micromorphological and geo-chronological investigation.

3.2. Soil and sediment record

Table 2 provides summary descriptions of key features of thin sections from the archaeological stratigraphies. To interpret these descriptions a first characterization of features enabled cultural and environmental definitions (Table 3) and Table 4 summarizes the micromorphological features of the control stratigraphies. These foundations provide the basis for interpretations of the archaeological stratigraphies, and are further supported by bulk soil and sediment chemical data (Table 5). Four key landscape processes are identified: landscape stability associated with pedogenic features, landscape instability associated with sedimentary accumulations that frequently include relict pedogenic features, wetting and

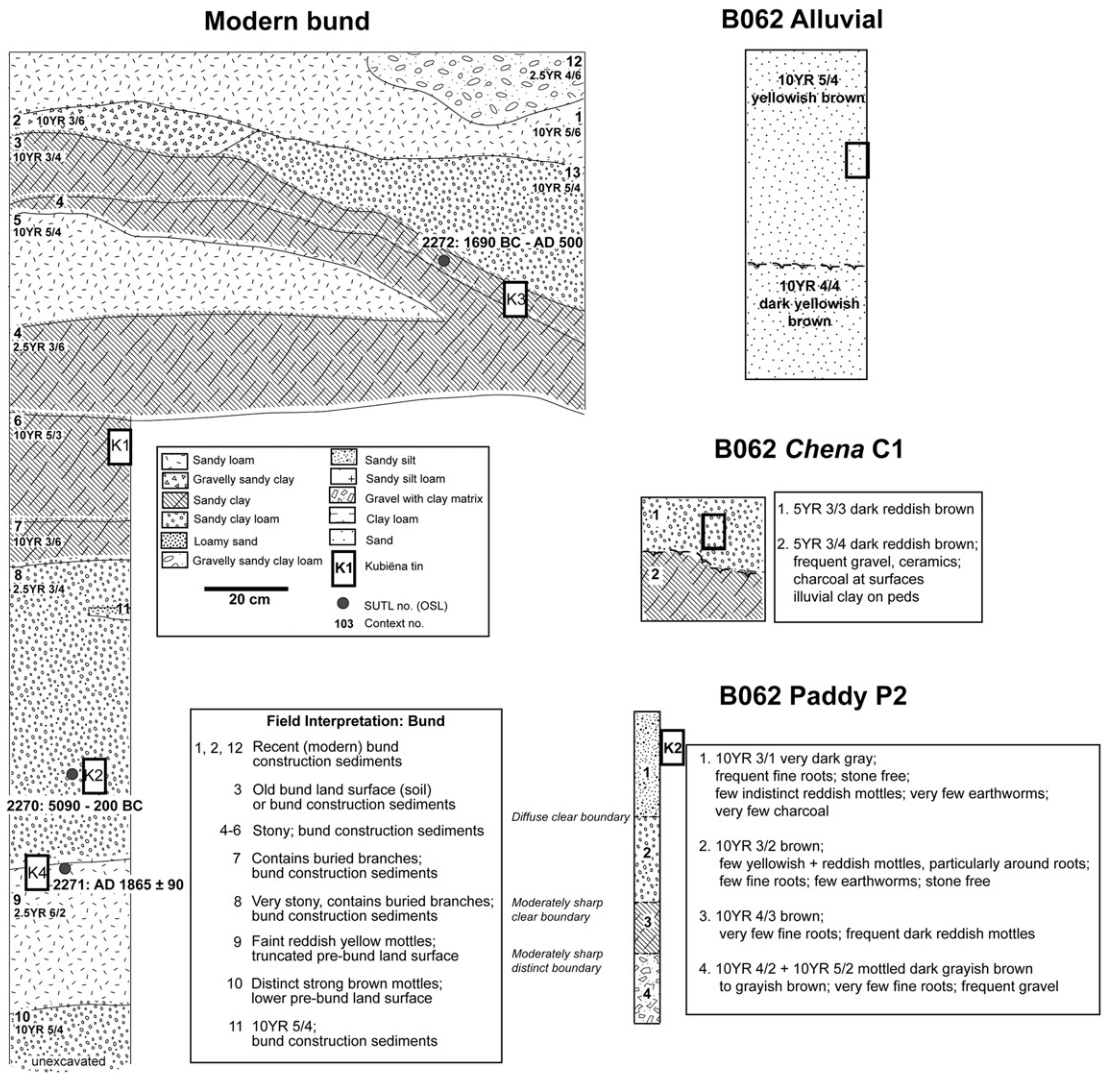

Fig. 3. Stratigraphy, control sites.

drying processes indicating soil moisture environments, and introduced material and disturbances indicating direct cultural activity. Biological activity is commonly observed in all samples.

3.2.1. Land cover conditions prior to the formation of water management features

E400. The micromorphology of the pre-bund/bund interface records sequences of disturbance and stability in moist conditions (indicated by sponge spicules and cuneiform bulliform phytoliths, Bremond et al., 2005; Madella et al., 2005; Bertoldi de Pomar, 1970 in Zucol et al., 2005) on LHG soil. Disturbance is indicated by heterogeneous and multiple discrete juxtaposed sediment lenses, micro-scale sediment deposition, fractured pedofeatures, and silty infills with inclusions of calcitic crystals, organics and phytoliths. Stable conditions are suggested by an intact micromass featuring isotropic material lenses with parallel orientation that may represent illuvial clays or possible calcium iron phosphates. Introduced material is evident from the abundant ceramics with different types of clay coatings, a few of which are truncated or fractured but none of which are superimposed on the surrounding sediments (Fig. 6A). This suggests that the coatings were deposited on the ceramics during pedogenesis following an occupation period, prior to their deposition in the bund. Sediment compaction, groups of mineral grains with V- or U-shaped basic distribution (possible tool marks), and anorthic fragments of clay and iron coatings and lenses together with elevated %LOI, $\%\chi_{fd}$, and total *P* values (Table 5) supports the view that these sediments were introduced as part of an occupation surface. Landscape stability at the time of bund construction is evidenced by abundant phytoliths and the intact illuviated calcitic, clay, and iron pedofeatures, together with an absence of occupation indicators. Relatively abundant charcoal fragments suggest burning of surface vegetation took place on this unoccupied surface prior to bund construction.

C009. Pre-bund and pre-tank sediments evidence sponge spicules indicating moist conditions preceding bund construction. Iron enrichment and depletion features indicate frequent cycles of seasonal saturation and complete or near-complete drying, even within the pre-tank sediments; characteristics of the better-drained RBE soils are thus retained. Illuvial pedofeatures document a relatively stable landscape prior to the onset of bund construction; these include limpid to slightly dusty clay coatings (Fig. 6B). Limited landscape disturbance is demonstrated by low frequency very dusty illuviated clay coatings and distinctly laminated dusty and slightly dusty clay features. A slightly elevated total *P* value for the pre-bund surface sediments and low frequencies of cereal husks, bone, ceramic and vesicular materials suggest

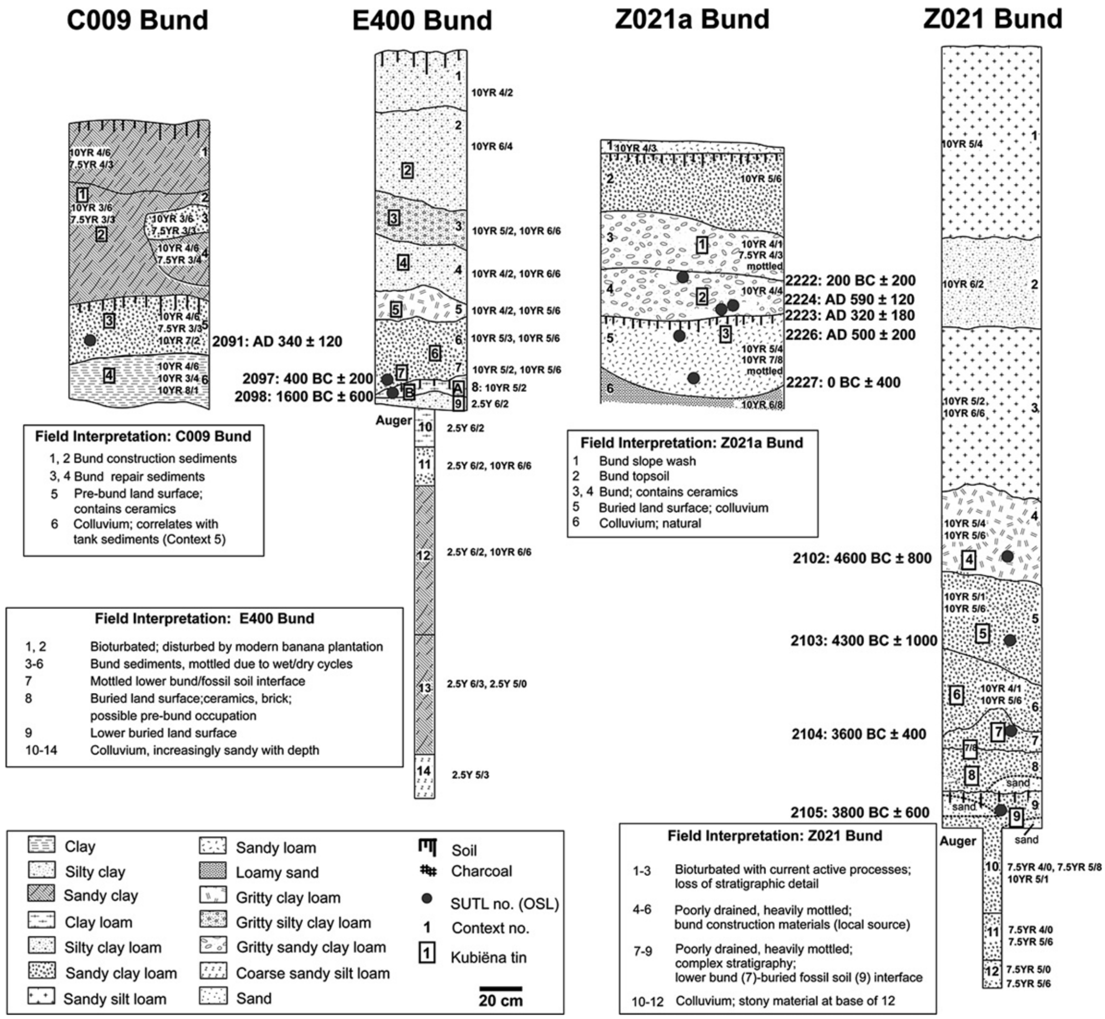

Fig. 4. Stratigraphy, bund and pre-bund surfaces.

activities related to low intensity occupation at the site prior to bund construction.

Z021a. Sponge spicules indicating the presence of water or moist soil conditions (Bertoldi de Pomar, 1970 in Zucol et al., 2005) and cuneiform bulliform phytoliths documenting plant growth under conditions of high evapotranspiration and a submerged substrate (Bremond et al., 2005) are both present within the Z021a bund sediments, suggesting saturation of the area. However, these sediments also demonstrate soil characteristics typical of RBE, indicating dominantly dry conditions, and the site is interpreted as undergoing a seasonally variable moisture regime. The base of thin section Z021a-3 (pre-bund surface, see Fig. 4) features a crumb structure representing spheroidal and ellipsoidal excrements, sediments reworked by colluviation. Fine sandy and silty pedofeatures similar to those seen in the modern bund sediments indicating disturbance are observed only in the lower part of the slide (Table 4; see example, Fig. 6D). The upper part of the same slide is thus interpreted as a surface on which cultural activities took place prior to bund construction, creating the silty pedofeatures observed lower in the section. This interpretation is supported by ceramic fragments, traces of bone and charred material in thin section, and enhanced P levels of the sediments (Table 5). Fragments of *mutti* (cooking or storage jars) are also evident within the bund construction sediments (Units 3, 4; Fig. 4) and were most likely introduced from the surface immediately adjacent the bund, the source of the bund sediments.

Z021. As at bund Z021a, cuneiform bulliform phytoliths in the pre-bund surface/lower bund interface thin section indicate the presence of moist conditions (Fig. 6C). Apart from a trace of charcoal, some compaction features, and anorthic soil lenses, there are almost no direct micromorphological indicators of human activity within the pre-bund/bund interface LHG soils. Despite this, the geometry and height (ca. 50 cm) of the pre-bund surface/lower bund interface (Unit 7; Fig. 4) suggests that during its early phase, the bund may have functioned as a *niyara*, a small bund up to 60 cm high that contains water in paddy fields (Mr. H.B. Premadasa, pers. comm.; Fig. 7). Micromorphological support for this hypothesis is found in thin section Z021-7/8, which documents slight compaction and silty pedofeatures in the upper boundary of Unit 8 (e.g. Fig. 6D). The silty features are consistent with those observed in the paddy and modern bund control samples (Table 4) and at the base of the E400 and Z021a bunds (Table 2), and are interpreted as accumulations related to disturbance during cultivation or bund construction. Thin section Z021-9 at the base of the bund (Fig. 4) also features many dusty brown to black coatings and lenses that may represent accumulations of dust or fine charcoal due to burning of vegetation in the wider landscape, either during cultivation or in preparation for bund construction. The moderate $\%\chi_{fd}$ values support this interpretation, as they suggest a mixture of superparamagnetic (indicating burning or soil formation) and non-superparamagnetic grains (Dearing, 1999).

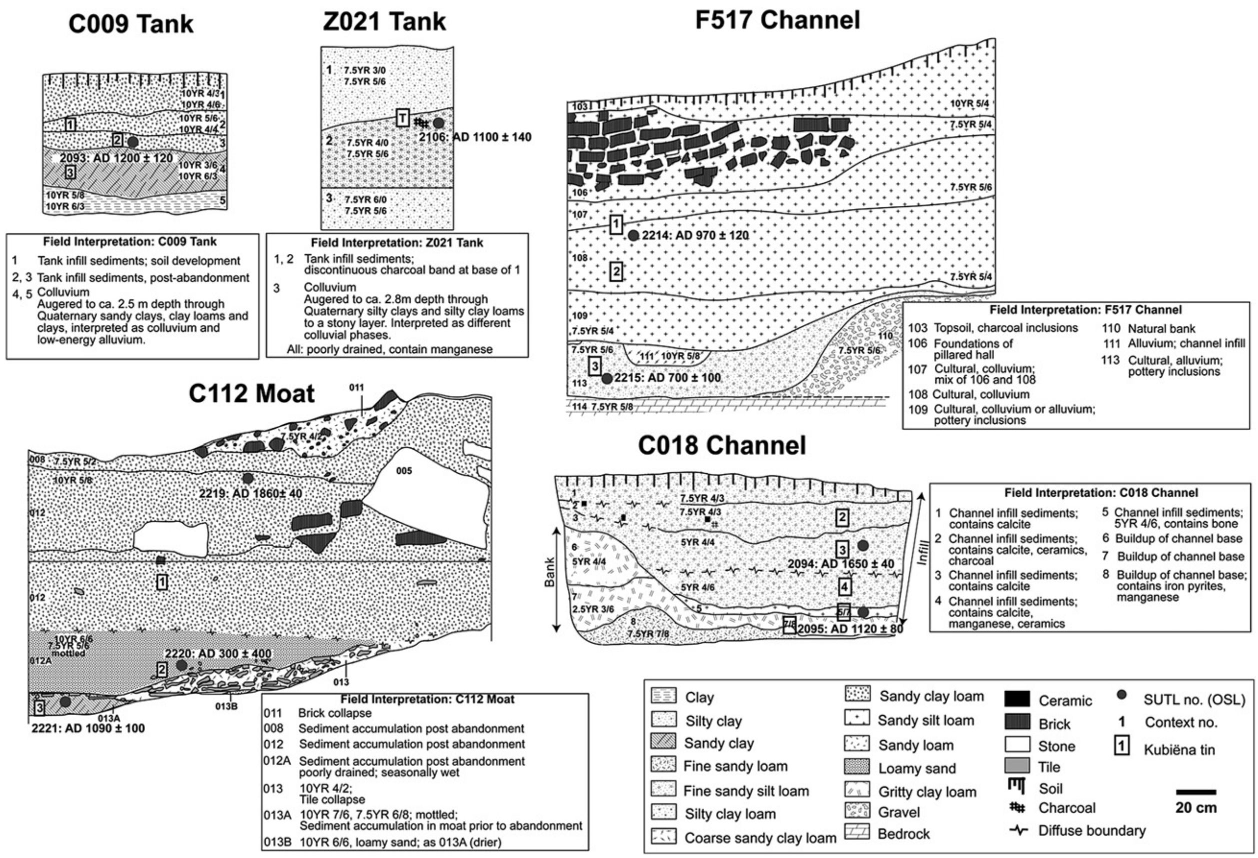

Fig. 5. Stratigraphy, infill sediments.

The sedimentary record from the pre-bund/lower bund sediments demonstrates landscape gradients in occupation intensity and in soil moisture conditions where water management structures were constructed. Two of these works (E400 and C009) are situated on surfaces that were intermittently occupied, with evident earlier phases of cultivation-related disturbance, but not at the time of bund construction. Domestic activity prior to construction is evident at Z021a, and paddy cultivation is suggested by the sediments beneath bund Z021. These observations suggest markedly different early land use contexts, and by implication social contexts, on which individual water infrastructure features were superimposed. Soil moisture conditions range from poorly drained (E400, Z021) to moderately or well-drained (C009, Z021a) locations. While construction in moister locations is an obvious approach when developing water management infrastructures, construction in drier areas opens consideration of attempts to secure additional water resources in periods of drought, even where the landscape is naturally drier. Alternatively, these may be symbolic constructions; the fact that its Sinhalese name (*Ehalagamawewa*) translates to 'dry tank' suggests that the C009 tank did not bring long-term drought relief.

3.2.2. The nature of disuse

C009 and Z021. The C009 tank infill sediments demonstrate anorthic soil fragments and sediment lenses at low frequencies, indicating limited human activity immediately following tank

Table 2

Summary of micromorphological features of sediments beneath bunds, within bunds, and infilling irrigation works. The presence and type of cultural inclusions and silty infills highlight the differences between the landscape context types. See Online supplementary materials for summary of individual thin sections. n = number of thin section samples.

Landscape context	Coarse material					Micromass and structure				Pedofeatures	
	Silica microfossils	Arrangement	Fine organic material	Sorting	Angularity	Micromass	b-Fabric	Structure	Porosity	Compound	Clay
Pre-bund surfaces ($n = 11$)	●	Random +/or preferred	●	P-M	SR-A	Speckled, dotted	Stipple-speckled, striated	Complex	Variable 10–50%	X	X
Bund sediments ($n = 12$)	●	Random +/or preferred	●	P-M	SR-A	Speckled, dotted ± impure	Stipple-speckled, striated	Complex, vughy	5–30%	X	X
Tank infills ($n = 4$)	●	Random	●	P-M	R-A	Speckled, dotted	Stipple-speckled, striated	Complex	Variable 3–20%	X	X
Channel infills ($n = 8$)	●	Random	●	M	SR-SA	Speckled, dotted, impure	Stipple-speckled, striated	Complex, vughy	1–20%	X	X
Moat infill ($n = 3$)	t	Random	●	P	R-A	Speckled, dotted	Stipple-speckled, striated	Vughy, crumb	10–30%		X

● = 1–5%; n = number of thin sections observed; t = trace; X = feature is present in most cases; XX = feature is abundant in most cases (>50%); R = rounded; A = angular; SA = subangular; SR = subrounded; M = moderate; P = poor. Pedofeatures are noted only if they are considered to be *in situ* accumulations.

disuse. Well-oriented clays and compound iron/clay pedofeatures in C009 Unit 3 (lower infill sediments; Fig. 5) support the inference of pedogenesis and stability of the surrounding landscape. The increased %χ_{fd} values for C009 Unit 2 (infill sediments; Fig. 5, Table 5) are interpreted as a depositional hiatus with subsequent soil formation; this hiatus was followed by later sediment deposition indicating renewed erosion of the landscape. The Z021 tank infill is dominated by recent organic material and indicators of soil fauna activity. The trace of charcoal fragments in the sample is interpreted as re-deposited from the surrounding landscape; other indicators of cultural activity are absent.

C112. The most striking micromorphological features in the lower part of this stratigraphy from an infilled monastic moat site are angular and well-rounded fragments of well-oriented limpid clay pedofeatures, present in relatively high abundances (Fig. 8A). These are pedogenic features that form on stable landscapes, and their presence in the moat as fragments suggests landscape disturbance and erosion after their formation. These features increase in abundance higher in the profile, and may represent new *chena* cultivation in the immediate area surrounding the site following monastery abandonment. Particulate organic coatings on planar voids near the upper boundary of Unit 012A (lower infill sediments; Fig. 5) indicate deposition in a near-surface environment and may also be related to cultivation. Subsequent increased sorting, a higher c/f ratio, and a chitonic c/f related distribution indicates more rapid sediment deposition, and likely records a re-deposited former lag deposit or eroded surface. This scenario suggests erosion of the catchment area prior to and during deposition of Unit 012A (Fig. 5). Rounded wood charcoal fragments and a silica skeleton of a cereal grain, likely *Oryza* (Rosen, 2001; Alison Weisskopf, pers. comm., Fig. 8B) are also evident and reflect a previous episode of cultivation that could be related to the disturbance features in the moat or to the formation of the organic coatings. Unit 012 (infill sediments) is distinguished by a higher proportion of angular clasts (>40% of the coarse fraction), and more than 50% of the coarse mineral fraction is very coarse sand or gravel-sized. The angularity and size of the clasts suggest rapid, high-energy deposition. Given the low abundance of associated cultural indicators in this part of the infill, this deposition was likely due to landscape erosion, possibly during a local flood event or a minor colluvial episode following a period of drought.

F517. The channel at F517 is now infilled, documenting disuse of the channel for water transport, but recording cultural activity at the site throughout the main period of infill following channel disuse. Micromorphological analysis demonstrates similar abundances of phytoliths, humified organics, charcoal fragments, and anthropogenic indicators throughout the sampled profile, suggesting that pedogenic surface horizons were the primary sedimentary sources during channel infill. A truncated compacted and striated feature in Unit 113 (lower infill sediments; Fig. 5) is consistent with tool mark features evident in control sites; this with elevated P measurements (Table 5) for the unit indicate cultivation directly within the mid- to lower channel infill sediments. Unit 111 (Fig. 5) is well-sorted reworked alluvial sediment infilling a shallow channel cut into Unit 113 sediments, and the absence of artefacts and organic material within the unit suggests its accumulation resulted from a change in management that drew water away from the site. The dominantly subangular and angular mineral grains in Unit 108 (infill sediments; Fig. 5) suggest a local sediment source deposited primarily through colluvial and anthropogenic processes. Cultural inclusions within the infill sediments consist of anorthic soil fragments, ceramics, bone fragments, vesicular isotropic material (Fig. 8C), and charcoal, including charred cereal husks. Double- and/or single-peaked glume phytoliths were also observed. Together with the cuneiform bulliform phytoliths in the sample, the double-peaked glume phytoliths provide a strong case for the presence of *Oryza* at the site (Pearsall et al., 1995; Piperno, 2006; Zhao et al., 1998). Possible taphonomic factors acting on double-peaked phytoliths confound the positive identification of single-peaked glume phytoliths in thin section; however, if present, they indicate *Setaria italica* (foxtail millet; Pearsall et al., 1995), a rapidly growing, drought tolerant plant (FAO, 2011). Ethnographic interviews in the Anuradhapura hinterland document foxtail millet and finger millet (*Eleusine coracana*; 'tana', Siriweera, 1990) as two of the primary *chena* crops sown at the beginning of the rainy season. The absence of tool marks or other strong micromorphological indicators of cultivation in the mid- to upper infill sediments, combined with the presence of bone, ceramics, and vesicular isotropic material, suggests the primary activity at the site following deposition of Unit 109 was habitation-based. Well-oriented laminated clay coatings are present in thin sections from Units 113 and 108, but feature very few clay layers, indicating short episodes of illuviation and relatively constant rates of sediment accumulation within the channel. Although there is substantial evidence for human activity in and around the channel sediments throughout the history of the site, the limpid to slightly dusty clay pedofeatures record illuviation during stable landscape episodes and may have been associated with temporary abandonment. Thin section F517-1 (Fig. 5) documents the boundary between Units 108 and 107, which is compacted and striated with U-shaped features interpreted as tool marks. This suggests a former land surface immediately predating the construction of the image house.

Pedofeatures				Cultural							
Fe	Ca	Organic	Silty infills	Inherited pedofeatures	Charred grains	Charcoal	Tool marks, compaction	Anorthic lenses	Vesicular isotropic material	Ceramics	Bone
XX	X	X	X		X	X	X	X	X	X	X
XX	X	X	X	X		X	X	X		X	X
XX		X				X		X	X		
X	X	X			X	X	X	X	X	X	X
X		X				X		X		X	

C018. Micromorphological sample C018-7/8 (channel base; Fig. 5) is divided into three sections, the lower two of which record channel construction. The massive microstructure at the base of this sample indicates compaction and layering of re-deposited sediments with undifferentiated and striated b-fabric and an increased abundance of incorporated organic material. These characteristics are consistent with those of the cultivated control soils, and the sediments are interpreted as relict *chena* soils that were re-deposited or disturbed during channel construction; the elevated total *P* values for Unit 8 support this interpretation (Table 5). The middle of the sample (C018-7/8B) is primarily composed of gravel-sized quartz aggregates that are not abundant in any other sediment sampled within the entire study area, and were likely imported into the site specifically to line the channel. This layer probably functioned to protect the channel from erosion during transportation of water and is consistent with the protective stone linings on the bund of a large tank observed by Myrdal (1990) in her work in the Sigiriya region, ca. 50 miles to the southeast. Efforts to compact the channel base thus reducing infiltration are also evident; our double ring field infiltration experiments suggest a mean channel infiltration rate of 2.43 cm/cm^2/day, against 5.93 cm/cm^2/day for the surrounding RBE. The characteristics of the upper section of this sample (C018-7/8A) are consistent with the rest of the infill sediments (i.e., C018-5/7, 4-2; Fig. 5). Most anorthic sediment lenses and soil fragments in the C018 infill thin sections have similar lithologies and frequently incorporate organic material, phytoliths, charcoal, and charred material, suggesting they are fragments of surface soil horizons that underwent cultivation prior to disturbance and deposition in the channel.

Micromorphological samples C018-3 and 2 (infill sediments; Fig. 5) demonstrate an intensification of cultivation activities around the channel and within the infill sediments themselves. This evidence includes fragments of charred material resembling burnt husks of cereal grains (probably rice, see Reedy, 2008), elevated frequencies of integrated anorthic soil fragments containing increased abundances of coarse charred and fine organic

Table 3
Micromorphological indicators for anthropogenic and environmental processes, Anuradhapura hinterland.

Micromorphological indicator	Type	Process
• Charcoal, charred material	Landscape disturbance, cultivation	Anthropogenic
• Anorthic sediment fragments[a]	Bund construction	
• Angular anorthic clay fragments[a]		
• Brown to strong brown (OIL) micromass + frequently masked or undifferentiated b-fabric		
• Possible tool marks, compaction		
• Very dusty to impure clay pedofeatures[b]		
• Silty pedofeatures[b]		
• Double- and/or single-peaked glume phytoliths[k]		
• Well-sorted layered sediments in tanks	Irrigation	
• Cuneiform bulliform phytoliths[c]		
• Bone fragments	Occupation	
• Ceramics		
• Limpid isotropic vesicular material[d]		
• Compaction		
• Illuviation of limpid to dusty clays, Fe	Landscape stability, pedogenesis	Environmental
• Increased organic content		
• Increased phytolith abundances[d]		
• Fe enrichment/depletion[e]	Wet/dry cycles	
• Fe coatings		
• $CaCO_3$ pedofeatures[f]		
• Cuneiform bulliform phytoliths[c]		
• Sponge spicules[g]	Saturated conditions, abundant water, moist environment	
• Globular echinate phytoliths (Arecaceae)[d]		
• Cuneiform bulliform phytoliths[c]		
• Gley colours[e]		
• Striated b-fabric[h]	Shrink/swell of micromass clays	
• Disorthic or fractured coatings		
• Excrements	Bioturbation	
• Microstructure: highly vughy, crumb, channel		
• Disorthic or fractured coatings		
• Biological channel infills		
• Crescentic b-fabric[i]		
• Compaction, striation		
• Intact and/or fresh roots		
• Gibbsite, goethite, runiquartz	Relict characteristics[j]	
• Sediments with red opaque groundmass and faint or undifferentiated b-fabric, few pedofeatures		

[a] Macphail and Goldberg (2010).
[b] Kühn et al. (2010).
[c] Bremond et al. (2005), Piperno (2006), Sangster and Parry (1969), Parry and Smithson (1964).
[d] Piperno (2006).
[e] Lindbo et al. (2010).
[f] Durand et al. (2010), Panabokke (1996).
[g] Bertoldi de Pomar (1970) in Zucol et al. (2005).
[h] Courty et al. (1989).
[i] Stoops (2003).
[j] Bronger and Bruhn (1989), Marcelino et al. (2010), Stoops (1989), Stoops and Marcelino (2010).
[k] Pearsall et al. (1995), Piperno (2006), Zhao et al. (1998).

Table 4
Micromorphological characteristics of control samples. n = number of thin section samples.

Site type	Structure, porosity, sorting	Groundmass	Pedofeatures
Pre-bund surface ($n = 1$)	Vughy, channel microstructure; 3% porosity, moderate to poor sorting	Relatively homogeneous <15% phytoliths Roots, tissues, charcoal/charred material Fine organic material Impure clay micromass	Dusty/impure clay coatings Organic, Fe coatings Compound illuviated features Silty clay/fine sandy infills Possible Ca–Fe–P features
Bund sediments ($n = 3$)	Complex, heterogeneous microstructure; Variable porosity ≤50%, dominantly poor sorting	Heterogeneous, disturbed Anorthic soil lenses Minerals with preferred orientation <5% phytoliths Roots, tissues, charcoal/charred material Impure/speckled/dotted micromass	Pedofeatures dominantly inherited Minor amounts of illuviated organic, Ca, dusty clay pedofeatures U- or V-shaped features (tool marks) Excremental pedofeatures
Paddy ($n = 3$)	Vughy, blocky microstructure; ≤5% porosity, moderate sorting	Rounded to subangular minerals <5% phytoliths Roots, tissues, charred cereal grains Rounded impure/dusty clay lenses Impure clay micromass	Particulate lenses, coatings of clays ± Fe Fe pedofeatures Silty infills Possible phosphatic features Calcitic pedofeatures
Chena ($n = 3$)	Vughy, highly vughy, blocky microstructure; 7–20% porosity, moderate sorting	Rounded to angular minerals <15% phytoliths Roots/tissues, charcoal/charred material Rounded/angular anorthic soil fragments Anorthic limpid clay fragments Impure/speckled/dotted micromass	Dusty clay, iron, organic pedofeatures Excremental pedofeatures Possible phosphatic features Illuviated limpid clay coatings in abandoned chena
Alluvial ($n = 1$)	Single grain microstructure; 10% porosity, well sorted	Randomly arranged coarse fraction <1% phytoliths, sponge spicules Roots, plant tissues Fine organic material absent	Dusty black isotropic coatings Excrements near surface

material (Fig. 8D), and U-shaped or parallel-oriented compaction features, interpreted as tool marks; these observations are supported by elevated total P levels (Table 5). Thin section C018-2 demonstrates elevated abundances of cultural indicators relative to C018-3 and undifferentiated b-fabric consistent with the *chena* control soils, suggesting channel cultivation intensified following deposition of Unit 2. Cuneiform bulliform (Madella et al., 2005) phytoliths were observed throughout most of the channel infill sediments, and indicate shallow surface water conditions in the vicinity of the channel during most of the post-abandonment period (Bremond et al., 2005). However, the absence of bulliform phytoliths and reduced abundance of redoximorphic pedofeatures

Table 5
Bulk sediment analyses.

	Site	% LOI	% Xfd	Total P mg/100 g		Site	% LOI	% Xfd	Total P mg/100 g
Bund	C009 Bund-1	2.4	5.6	55.2	Channel infill	C018-1	3.8		72.4
	C009 Bund-2	2.1	5.2	32.1		C018-2	3.2	4.4	73.9
	C009 Bund-3	2.1	6.1	6.1		C018-3	3.3	4.0	70.4
	C009 Bund-4	2.4	6.7	6.7		C018-4	3.7	3.9	58.3
	C009 Bund-5	2.5	4.4	26.4		C018-5	3.5	3.7	65.3
	C009 Bund-6	2.4	6.4	17.1		C018-6	3.8		52.5
Bund	E400 Bund-1	4.1	5.5	49.8		C018-7	2.8		65.1
	E400 Bund-2	1.7	1.6	15.5		C018-8	3.6	0.8	59.7
	E400 Bund-3	2.5	2.6	17.8	Moat infill	C112-008	4.0	6.2	79.1
	E400 Bund-4	2.2	0.9	15.6		C112-012	2.6	4.5	53.6
	E400 Bund-5	2.5	3.1	17.1		C112-012A	1.4	5.0	45.4
	E400 Bund-6	2.3	3.0	15.7		C112-013A	2.6	4.0	29.8
	E400 Bund-7	2.0	2.5	16.4	Channel infill	F517-107	2.3	3.4	44.9
	E400 Bund-8	2.5	8.5	31.7		F517-108	1.9	3.3	42.0
	E400 Bund-9	2.3	4.2	21.9		F517-109	2.1	3.7	43.7
	E400 Bund-11	1.9	2.7	13.7		F517-111	1.1	3.0	37.8
	E400 Bund-13	1.9	3.0	14.8		F517-113	2.6	2.6	51.3
	E400 Bund-14	2.1	3.0	12.7	Tank	C009 Tank-1	2.2	5.2	44.7
Bund	Z021 Bund-1	2.6	4.7	19.4		C009 Tank-2	2.3	9.1	36.7
	Z021 Bund-2	3.1	4.7	18.6		C009 Tank-3	2.2	5.6	27.9
	Z021 Bund-3	1.8	5.1	19.0		C009 Tank-4	3.2	3.2	22.9
	Z021 Bund-4	1.9	5.2	15.4		C009 Tank-5	2.6	6.6	21.3
	Z021 Bund-5	2.0	6.6	15.8	Tank	E400 Tank-1	8.6	2.4	52.9
	Z021 Bund-6	2.3	6.3	9.8		E400 Tank-2	2.3	3.3	24.5
	Z021 Bund-7	2.4	5.9	13.9		E400 Tank-3	3.3	4.7	52.0
	Z021 Bund-8	2.3	4.8	10.1		E400 Tank-4	2.5	2.3	37.9
	Z021 Bund-9	2.1	4.8	14.8		E400 Tank-5	2.2	3.6	36.7
	Z021 Bund-10	1.7	6.3	13.3		E400 Tank-6	1.8	3.1	31.3
	Z021 Bund-11	3.1				E400 Tank-7	3.2	1.5	51.9
	Z021 Bund-12	2.6	4.4	18.1		E400 Tank-8	1.4		79.5

(*continued on next page*)

Table 5 (*continued*)

	Site	% LOI	% Xfd	Total P mg/100 g		Site	% LOI	% Xfd	Total P mg/100 g
Bund	Z021a-1	4.6	0.8	45.0	Tank	Z021 Tank-1	8.8	0.7	
	Z021a-2	2.9	0.6	40.0		Z021 Tank-2	3.5	4.7	15.9
	Z021a-3	3.3	0.9	42.6		Z021 Tank-3	4.3	3.9	11.2
	Z021a-4	2.9	2.0	34.3		Z021 Tank-4	2.3	5.1	25.3
	Z021a-5	2.7	0.9	48.7	Controls	B062-P1 5–15 cm	4.3	2.3	71.2
	Z021a-6	1.6	0.4	38.7		B062-P1 42–50 cm	3.1	4.1	59.0
Controls	Modern Bund-3	4.0	6.6	54.2		B062-P1 54–60 cm	4.1	2.8	66.9
	Modern Bund-6	4.8	5.4	54.5		B062-P2 5–15 cm	5.0	3.5	68.8
	Modern Bund-8	4.2	5.1	58.3		B062-P2 29–39 cm	3.1	5.4	68.1
	Modern Bund-9	2.7	5.8	65.3		B062-P2 50–55 cm	4.0	5.5	54.1
	B062-C1-1	3.8	1.9	74.3		B062-P2 65–75 cm	3.3	4.5	55.4
	B062-C1-2	3.9	2.2	90.7		B062-P3 5–10 cm	5.1	4.6	72.6
	B062-C2-1	6.1	3.3	113.6		B062-P3 13–20 cm	4.4	3.4	65.0
	B062-C2-2	6.1	3.5	82.5		B062-P3 25–35 cm	2.7	5.9	73.2
	B062-C3-1	5.0	1.3	88.0		B062-P3 45–55 cm	3.5	7.0	51.7
	B062-C3-2	4.9	2.7	66.5		B062-P3 60–70 cm	3.6	2.9	47.8
						B062 Alluvium	0.6	3.1	47.2

in thin section C018-2 demonstrates evidence that surface water conditions ceased or diminished after deposition of Unit 3 (Fig. 5).

Our key findings inferred from infill sediment characteristics are that, following the disuse of large-scale tanks, cultural activities immediately surrounding these locations largely ceased and the landscape become stable. Conversely, habitation and small-scale cultivation continued around the smaller-scale works (the moat and channels) after they began to infill. These smaller-scale sites document gradually reducing surface moisture conditions and a shift towards *chena*-based subsistence agriculture during and after the abandonment of the hinterland's water management infrastructure.

3.3. Geo-chronological framework

3.3.1. Control bund construction

The truncated former surface beneath the modern control bund (SUTL 2271) produced an age of 150 ± 40 years (construction ca. AD, 1865 ± 90; Table 6), consistent with local information indicating bund construction during the early twentieth century. This measurement suggests that pre-bund land surfaces have enough sunlight exposure for the OSL signal of the sediments to be reset prior to bund construction. In contrast, the modern bund construction sediments (SUTL 2270, 2272) demonstrate heterogeneous equivalent dose (D_E) distributions, and their average

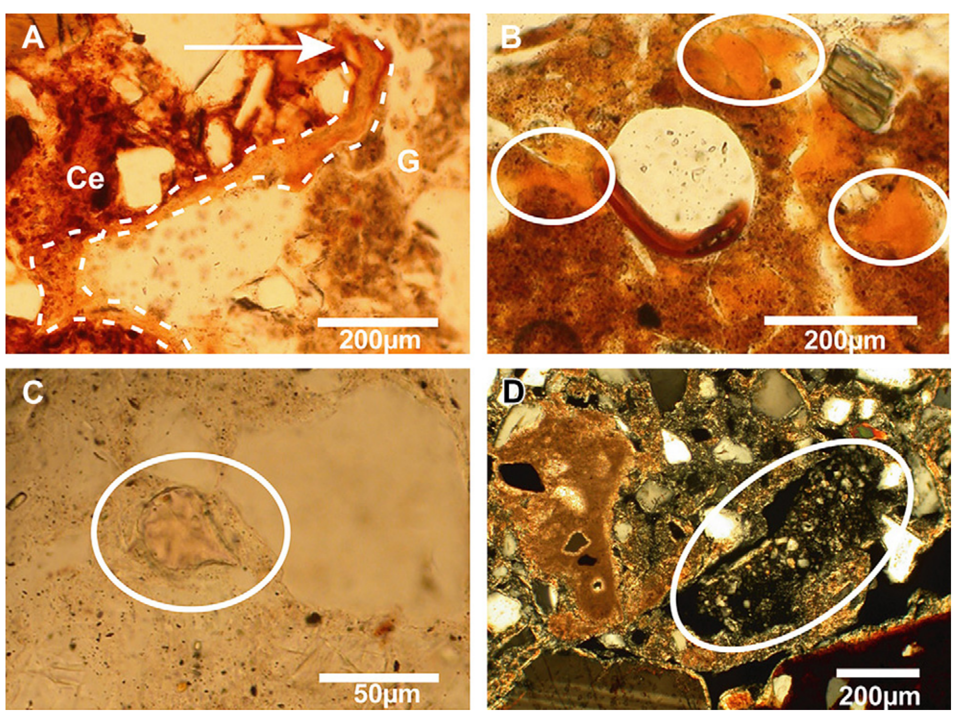

Fig. 6. Micromorphological features from pre-bund surfaces or surface/bund interfaces. **A**: Truncated (arrow) slightly dusty clay coating (outlined in dashed line) on ceramic (Ce) fragment, E00-8A, PPL. G = the dominant groundmass. The ceramic likely originated on a former occupation surface that underwent pedogenesis prior to bund construction. **B**: Limpid clay coatings, C009 2-3, PPL. Indicates landscape stability and pedogenesis prior to bund construction. **C**: Cuneiform bulliform phytolith (Madella et al., 2005), Z021-8C, PPL. Indicates a submerged substrate, high evapotranspiration, and probable irrigated rice cultivation (Bremond et al., 2005; Piperno, 2006). **D**: Silty pedofeature, Z021-4B, XPL. This is an example of silty pedofeatures that are commonly observed at surface/bund interfaces and are interpreted as disturbance due to early pre-bund land use activities such as paddy cultivation or during the early stages of bund building, such as use of low bunds as *niyara* (e.g. Z021 bund, Fig. 7). They are also occasionally observed within bund sediments (as in this example), where they are interpreted as indicating a brief hiatus in bund-building activities (i.e., during the rainy season; Myrdal-Runebjer, 1996).

Fig. 7. Modern *niyara* (arrows) and lower Z021 stratigraphy (circled).

apparent ages are much older than the underlying truncated land surface. This demonstrates that bund materials consist of mixed sediments of different ages and that there is inadequate exposure during bund construction to reset the OSL signal.

3.3.2. Chronology of the Anuradhapura hinterland water management infrastructure

Both the pre-bund surface and lower bund/buried surface interface samples from bund E400 produced asymmetrical D_E

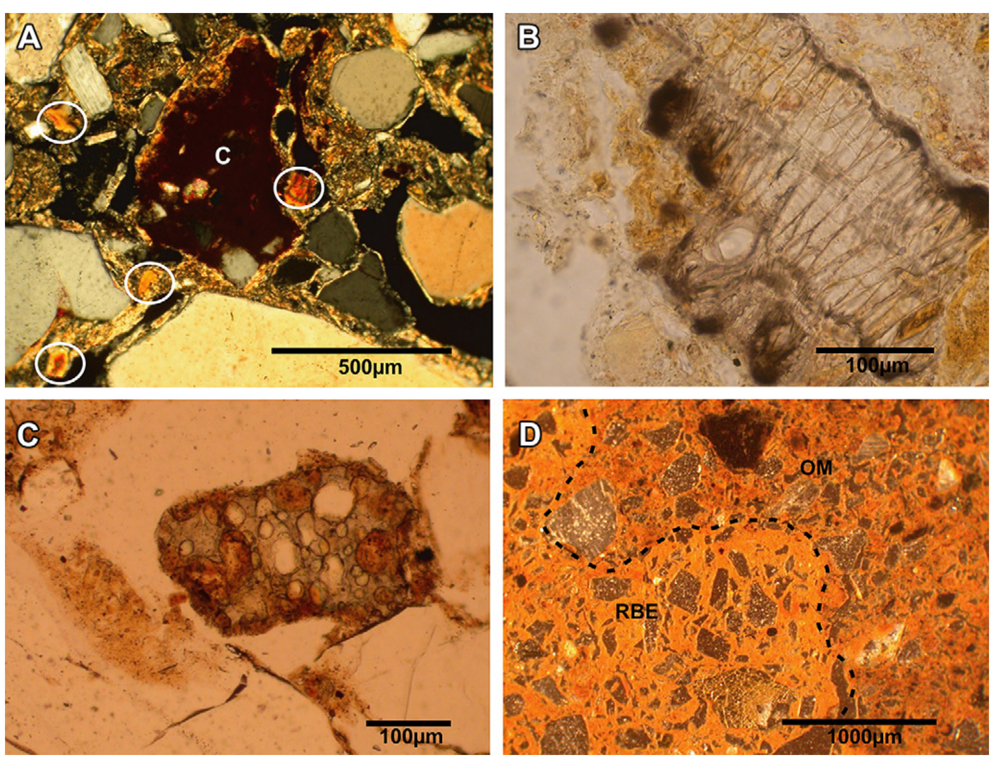

Fig. 8. Micromorphological features of infill sediments. **A**: Angular anorthic limpid clay coating fragments (circled), lower infill C112-3, XPL. C = ceramic fragment. Coating fragments are interpreted as indicating disturbance (possibly related to cultivation or erosion after a severe drought) of a formerly stable land surface prior to deposition in the moat. **B**: Silica skeleton, possibly from a rice husk (Rosen, 2001; pp. 195; Alison Weisskopf, pers. comm.), infill C112-2, PPL. Indicates that the area surrounding C112 may have been undergoing rice cultivation and was possibly related to the disturbance documented in 8A prior to its deposition in the moat. **C**: Vesicular isotropic material, probably melted phytoliths, infill F517-2, PPL. These indicate burning at relatively high temperatures (Canti, 2003; Drees et al., 1989), are absent in the *chena* control soils, and are interpreted as indicating occupation involving metalworking or ceramic production. **D**: Sharp contact (dashed line) between organic-rich sediment (OM) and reddish brown earth soils (RBE), upper infill C018-2, OIL. Interpreted as indicating intensified cultivation of the upper part of the channel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 6
Optically stimulated luminescence dose rates, equivalent doses, ages and calendar dates.

Sample		Total dose rate (mGy/a)	Equivalent dose (Gy)[a]	Apparent Age (ka)[b]	Error (%)	Calendar date (2σ)[c,d]	Sedimentary context* and interpretation of date
SUTL no.	Site						
2091	C009 B-5	2.29 ± 0.06	3.81 ± 0.09	1.66 ± 0.06	4	**AD 340 ± 120★**	Pre-bund surface; maximum age for bund construction
2093	C009 T-4	2.95 ± 0.20	2.37 ± 0.06	0.80 ± 0.06	7	**AD 1200 ± 120●**	Basal tank infill sediments; onset of sedimentation and tank disuse
2094	C018 C-3	3.56 ± 0.12	1.26 ± 0.06	0.35 ± 0.02	6	*AD 1650 ± 40*●	Mid/upper channel infill; end of infill cultivation, onset of drier conditions
2095	C018 C-5	3.13 ± 0.10	2.76 ± 0.10	0.88 ± 0.04	5	*AD 1120 ± 80*●	Basal channel infill sediments; onset of sedimentation and channel disuse
2097	E400 B-7	2.44 ± 0.09	5.92 ± 0.21	2.43 ± 0.12	5	**400 BC ± 200●**	Lower bund/pre-bund surface interface; maximum age for bund construction
2098	E400 B-8	2.11 ± 0.16	7.66 ± 0.18	3.62 ± 0.28	8	**1600 BC ± 600●**	Pre-bund surface/occupation surface; occupation date or possible residual age
2102	Z021 B-4	1.86 ± 0.03	12.18 ± 0.68	6.56 ± 0.38	6	4600 BC ± 800■	Bund construction sediments; residual age
2103	Z021 B-5	1.43 ± 0.08	9.05 ± 0.60	6.32 ± 0.55	9	4300 BC ± 1000■	Bund construction sediments; residual age
2104	Z021 B-7	1.93 ± 0.05	10.84 ± 0.39	5.60 ± 0.25	4	**3600 BC ± 400★**	Bund construction sediments; residual age
2105	Z021 B-9	1.77 ± 0.07	10.23 ± 0.36	5.78 ± 0.29	5	**3800 BC ± 600★**	Bund construction sediments; residual age
2106	Z021 T-2	1.07 ± 0.05	0.98 ± 0.07	0.92 ± 0.07	8	*AD 1100 ± 140*●	Lower tank infill sediments; onset of sedimentation and tank disuse
2214	F517 C-108	3.46 ± 0.21	3.59 ± 0.05	1.04 ± 0.06	6	**AD 970 ± 120●**	Upper channel infill sediments; maximum age of overlying building
2215	F517 C-113	2.89 ± 0.09	3.78 ± 0.10	1.31 ± 0.05	4	*AD 700 ± 100*●	Basal channel infill sediments; onset of sedimentation and channel disuse
2219	C112 M-012	2.07 ± 0.07	0.29 ± 0.04	0.14 ± 0.02	12	AD 1860 ± 40■	Upper moat infill; near-end of sediment accumulation in moat
2220	C112 M-012A	1.74 ± 0.12	3.04 ± 0.20	1.75 ± 0.17	10	AD 300 ± 400■	Lower moat infill consisting of mixed sediments; residual age
2221	C112 M-013A	2.08 ± 0.09	1.91 ± 0.07	0.92 ± 0.05	6	**AD 1090 ± 100★**	Basal moat infill; onset of sedimentation, moat disuse; monastery abandonment
2222	Z021a B-4	3.31 ± 0.12	7.29 ± 0.30	2.20 ± 0.12	6	**200 BC ± 200■**	Bund construction sediments; residual age
2223	Z021a B-4	3.44 ± 0.10	5.80 ± 0.24	1.68 ± 0.09	5	*AD 320 ± 180*●	Bund construction sediments; residual age
2224	Z021a B-4	3.57 ± 0.12	5.05 ± 0.15	141 ± 0.06	5	**AD 590 ± 120★**	Bund construction sediments; maximum age for bund construction
2226	Z021a B-5	3.32 ± 0.21	4.89 ± 0.26	1.47 ± 0.12	8	*AD 500 ± 200*●	Upper pre-bund land surface; maximum age for bund construction
2227	Z021a B-5	2.85 ± 0.19	5.82 ± 0.36	2.04 ± 0.19	9	**0 BC ± 400■**	Lower buried land surface; approximate age of colluvium underlying bund
2270	Modern bund-8	2.83 ± 0.12	5–20	1.8–7.1			Bund construction sediments; residual age
2271	Modern bund-9	2.99 ± 0.13	0.43 ± 0.13	0.15 ± 0.04	30.3	AD 1865 ± 90	Truncated pre-bund land surface; maximum age for bund construction
2272	Modern bund-3	2.69 ± 0.10	4–10	1.5–3.7			Bund construction sediments; residual age

B = bund; T = tank; C = channel; M = Moat. * = based on interpretations of field characteristics and micromorphological analyses, see Table 2 and text.
★ Symmetrical distribution with low to moderate scatter of sample D_E values, and identical values for the arithmetic and robust means of D_E.
■ Roughly symmetrical distribution with high levels of scatter and identical values for the arithmetic and robust means of D_E. Likely represents a mixture of sediments with different OSL ages.
● Asymmetrical distribution with single main grouping and scatter to higher values indicating a small portion of grains with residual OSL ages. Robust mean estimates are lower than arithmetic mean estimates, but the modal value of the D_E data lies at the lower limit of the range of uncertainties; therefore, the actual calendar date of the sample may lie on to the more recent end of the error estimate.
[a] H15 Robust Mean (Royal Society of Chemistry, 2001).
[b] Ages calculated as equivalent dose divided by total dose rate and presented in ka before AD 2007. Reported at 1 sigma.
[c] Errors rounded to 1 significant figure, values rounded accordingly.
[d] Bold or italics indicates that the equivalent dose/dose rate appears to be representative or an overestimate (respectively) of the actual dose.

distributions, and their true ages are interpreted as being on the younger end of the error range (Table 6). The lower bund/buried land interface sediments (SUTL 2097) date to ca. 400–200 BC, making bund E400 the earliest of the study bunds. The pre-bund surface (SUTL 2098) dates to ca. 1600–1000 BC, which is earlier than expected; this surface is associated with land management activity (see Section 3.2.1). The pre-bund surface at C009 (SUTL 2091) produced a date for bund construction at ca. AD 220–460. Sample SUTL 2224 from bund Z021a dates bund construction at ca. AD 470–710; the D_E distributions from other samples within the bund demonstrate that some grains have retained a residual OSL signature.

All of the dates produced from the Z021 samples were older than expected. The bund's putative pre-bund surface and pre-bund surface/lower bund interface both had dates of 3800 BC ± 400 (SUTL 2105) and 3600 BC ± 600 (SUTL 2104), respectively. However, micromorphological analysis (see Section 3.2.1) suggests that the samples are composed of re-deposited sediments, and the dates are therefore interpreted as residual OSL signals. The D_E distributions for the overlying bund construction sediments (SUTL 2103 and 2102) indicate that the majority of the grains in these samples also retained a residual OSL signal, as observed in the control bund sediments.

The basal infill sample at channel F517 (SUTL 2215) has an asymmetrical D_E distribution, and the date is interpreted as documenting channel infill beginning ca. AD 700–800. The sampled infill near the top of the stratigraphic sequence (SUTL 2214) also demonstrates an asymmetrical D_E distribution and suggests a surface dating to ca. AD 970–1090, prior to the construction of the overlying image house. Sampled sediments at the base of moat C112 (SUTL 2221) produced a date of ca. AD 990–1190 for the onset of infill. Most of the other sampled basal infills in the hinterland (the Z021 and C009 tanks and the C018 channel) produced OSL dates with asymmetrical D_E distributions, and the younger portion of the error ranges are likely more representative of the true date.

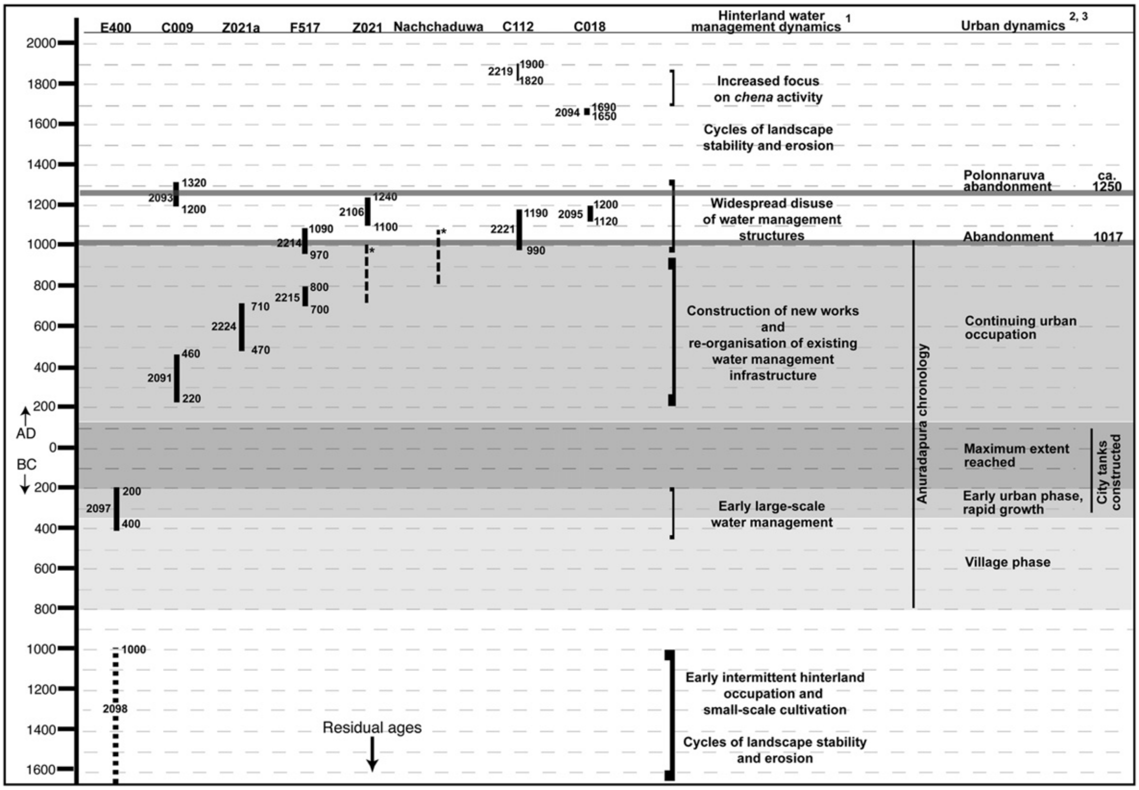

Fig. 9. Integration of early water management infrastructure dynamics in the Anuradhapura hinterland. 1. This study. 2. Coningham (1999). 3. de Silva (2005). Dashed lines marked with an * indicate that the dates for construction of these tanks are inferred using relative dating (see text). The dotted line for the date at E400 indicates that this date is earlier than expected and may represent a residual OSL signal.

All of these basal dates are indistinguishable and indicate that most of the large-scale irrigation works and water features in this study went into disuse over the same 100-year period, ca. AD 1100–1200. Dates from the sampled upper infill sediments at channel C018 (SUTL 2094; AD 1650–1690) and moat C112 (SUTL 2219, AD 1820–1900) indicate that erosion of the landscape continued during the period following disuse of large-scale works. The stratigraphically inconsistent date produced by sample SUTL 2220 at C112 is interpreted as representing a mixture of sediments from different contexts (the former land surface below the adjacent monastery, grains from degraded tiles), as the large scatter of D_E values for the sample indicates the presence of grains with residual OSL signals.

Our OSL chronology demonstrates previously unknown hinterland landscape dynamics and confirms the close chronological relationship between large-scale irrigation and Anuradhapura's urban occupation. Large-scale irrigation was initiated ca. 400–200 BC, beginning with bund E400. The early date for this bund suggests that it was constructed during Anuradhapura's early urban period, before the city reached its maximum extent (Coningham, 1999; Coningham and Batt, 1999), and possibly pre-dating the recognized arrival of monastic Buddhism on the island (ca. 246 BC, Geiger, 1912). Construction of large-scale tanks continued throughout the urban occupation period after the maximum extend of the city was reached, as demonstrated by bunds C009 (AD 220–460), and Z021a (AD 470–710). Using relative dating, the fact that the Z021 tank submerges the Z021a bund indicates that Z021 postdates Z021a. The architectural style of the nearby Z00 monastery (Table 1; ca. 8th-12th centuries AD, Coningham et al., 2007) also supports this interpretation. The Nachchaduwa tank submerges the Z021 bund and therefore dates to the late Anuradhapura period, supporting a 9th century AD date for its construction (Brohier, 1935).

Dates for the basal and upper infills of channel F517, when considered with dates from other water infrastructure features, indicates a period of re-organization of hinterland water management from ca. AD 700; the F517 basal infill documents disuse of the channel for water transport at around the same period as the construction of bund Z021a. Furthermore, the shallow channel cut into the lower infill sediments (Unit 111, Fig. 5) documents two additional subsequent episodes (cut and fill) of hydrological reorganization prior to ca. AD 970–1090; the Z021 and Nachchaduwa tanks were likely constructed during this period, and may explain these hydrological changes. OSL measurements dating time of sediment accumulation for the other basal infills indicate that accumulation commenced during the Polonnaruva period, suggesting that disuse occurred approximately 100–200 years after the historically documented abandonment of Anuradhapura.

4. Conclusions

Integrating 'reading' of the sedimentary record and geochronological framework yields a model of landscape change in the Anuradhapura hinterland confirming that onset and disuse of large-scale water management dates almost precisely to the urban occupation period (Fig. 9). Our findings also offer new insight on general models of landscape change in South Asia and in particular the transformations associated with the development and demise of water infrastructures in the landscape.

The pre-bund surface date of 400 BC ± 200 from E400 coincides with the transformation from village to early urban phase at Anuradhapura (Coningham, 1999; Coningham and Batt, 1999) and during a period of relatively stable climate conditions that would have been expressed as severe and lengthy droughts during the SWM with corresponding NEM storminess and relatively abundant precipitation during winter months (Gunnell et al., 2007; Jung et al., 2004). Water shortages would have been a concern, but the low frequency of climate fluctuations would have aided effective water management. This contextualization highlights the need for water management, driven by and enabling urban development and hinterland expansion. Our evidence from this early period of water infrastructure development does however call into question wider application of the hypothesis that large-scale irrigation was part of a 'cultural package' accompanying the spread of urbanism and monastic Buddhism, as found at Sanchi, central India (Shaw et al., 2007). We open the possibility that the beginnings of large-scale water management, with urbanization, preceded the arrival of monastic Buddhism in Sri Lanka and that early urbanization with a relatively stable climate may itself have been sufficient to stimulate the emergence of large-scale irrigation infrastructures.

Land cover prior to and immediately before early major water infrastructure development is a neglected aspect of landscape change in South and Southeast Asia (Stark, 2006), yet is critical for understanding transitions to managed hydraulic landscapes; our evidence allows consideration of two aspects of this issue. First, we suggest that early tanks and bunds were located on moist (but not waterlogged) soils, indicating that reservoir storage created in this semi-arid environment was entirely artificial and further emphasizing the extent of landscape transformation. Second, we also demonstrate that the land on which tanks and bunds were located was already occupied prior to the initial development of the irrigation infrastructure, with evidence of intermittent swidden agriculture.

Environmental changes associated with shifts from swidden to water-based agriculture and relationships between swidden agriculturalists and water-based agriculturalist in the early Anuradhapura hinterland remain speculative, but ethnographic analyses do give indication of the nature of these relationships. Working with Lua' people of northern Thailand, Kunstadter (1988) indicates higher yield per unit area and increased soil fertility but reduced biological diversity and increases in grazing pressures with change from swidden to irrigation-based land management. With these changes, there is loss of traditional land allocations as legal and registration systems become more prevalent, leading to greater centralized authority. More generally in Southeast Asia, land allocations for alternative use, development of market-based economies and the attraction of urban labour markets have a led to the transitioning of swiddening (Fox et al., 2009). This ethnographic evidence has parallels with the emergence of the early Anuradhapura hinterland and suggests that as water infrastructure was introduced, swiddening activity in the landscape would have been reduced as new resource management relationships developed.

With the proximity of tanks and bunds to monastic settlement, notably at Z021 and E400, our findings recognize that the tank-bund systems became intrinsically linked to Buddhist communities during the Early Historic and Medieval periods, indicating exchange between monastery and laity, with monastic oversight (Coningham et al., 2007; Gunawardana, 1971, 1979). We also demonstrate that later bunds and tanks (C009, Z021a) were being constructed and superimposed on earlier areas of swidden and domestic activity in the hinterland after Anuradhapura reached its maximum extent ca. AD 130 (Coningham and Batt, 1999). Furthermore the landscape continued to undergo new water structure initiatives and reorganization superimposed on earlier areas of paddy cultivation, after ca. 7th century AD (Z021, Nachchaduwa wewa, the evidence for changes in hydrology at channel F517), even after the city's boundaries stopped expanding (Coningham and Batt, 1999; de Silva, 2005). Our work calls into question the assumption (Brohier, 1934, 1935) that large-scale irrigation expanded to meet the increasing water demands of Anuradhapura's urban population. Instead, we build on Mosse's (2005) ethnographic work in drought-prone areas of Tamil Nadu, and suggest that new works may also have been commissioned, without necessarily increasing water supply, as a response to environmentally induced resource stress or to political strife, both of which are well-documented in the island's documentary records (i.e., the *Mahavamsa* and *Culavamsa*; Geiger, 1912, 1929; Gunawardana, 1971). In particular, recurring drought and famine are documented between ca. AD 187 and 406 (when the C009 bund was constructed), despite the efforts of secular rulers to alleviate these problems through expanding the water management infrastructure.

Remarkably, all water management infrastructure features considered in this study began to infill ca. AD 1100–1200; we consider this to be clear evidence of final disuse and water management infrastructure collapse. Since the error ranges for the date of most of the infills in this study (ca. AD 990–1320) extend well into the Polonnaruva period (AD 1250; de Silva, 2005, Fig. 9), we consider that disuse of irrigation works in the Anuradhapura hinterland may be associated with gradual attrition of the dry zone population, rather than complete and sudden abandonment linked to South Indian invasion. Evidence of small-scale cultivation within and around smaller-scale works, consistent with increase in *chena* activity at Sigiriya (in the dry zone southeast of Anuradhapura) during the 17th century AD (Myrdal-Runebjer, 1996) supports this view. Disuse of the hinterland's irrigation works therefore did not result in complete depopulation of the dry zone; rather, people remained on the landscape and continued small-scale management of water resources and soil fertility.

Demise of the water management infrastructure does however demand explanation. The *Mahavamsa* and *Culavamsa* document numerous and varied stresses that persistently acted on the dry zone's landscape throughout the occupations of both Anuradhapura and Polonnaruva (Geiger, 1912, 1929). These included repeated invasions, internal disputes for power, cycles of drought and famine due to the inherently unpredictable and spatially chaotic nature of the region's available water resources, and loss of trade as Anuradhapura's port, Mantai, declined in favour of ports in the southern part of the island (Gunnell et al., 2007; Gunawardana, 2003). These stresses were normally dealt with within resilience boundaries of the hinterland's landscape, but over the long-term would have resulted in a diminished capacity for coping with disturbances resulting in high-magnitude impacts (Holling et al., 2002; Winterhalder, 1994), giving early warning of the potential for 'collapse.' We suggest that two high-magnitude events, both dating to ca. AD 1000, exceeded the abilities of the already-stressed dry zone landscape to cope, and resulted in changes in water management, disuse of large-scale irrigation, and ultimately in landscape transformation. The first of these events was the sacking of Anuradhapura ca. AD 1017, which, according to the *Culavamsa* (LV, v. 15–22, Geiger, 1929; pp. 187–188) was devastating to the urban secular and monastic populations. The second event was a sudden, high-amplitude increase in the strength of the SWM, ca. AD 1100 (Jung et al., 2004), which was likely expressed as a severe and historically unprecedented drought throughout Sri Lanka's dry zone, with a corresponding increase in the violence of cyclonic storms during the NEM. This relatively brief climate episode was followed by weakened monsoon conditions, which would have provided less reliable and decreased NEM precipitation (Gunnell et al., 2007) and may have been sufficient to destabilize the dry zone and further decrease landscape resilience to long-term stresses and infrequent high-magnitude disturbances. Our work demonstrates that multiple and interacting variables, rather than single factors, acted on the dry zone landscape to bring on the demise of the large-scale water management infrastructure that had operated for over 1600 years, highlighting early water management infrastructures and their soil and sedimentary stratigraphies as sensitive indicators of complex landscape changes.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2012.09.034.

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