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Geoarchaeological analysis of the early mediaeval site of Vetricella (Southern Tuscany, Italy): Site formation processes and circular ditches

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ABSTRACT

Vetricella is a mediaeval archaeological site located within the coastal plain of the river Pecora (southern Tuscany, Italy). The settlement consists of a fortified mound with a raised central rectangular tower-like building surrounded by three concentric ditches. This paper presents the results about geoarchaeological stratigraphy and site formation processes and provides new important information regarding the foundation of the settlement, its occupational phases and its abandonment. Field data and micromorphological observation show that Vetricella was settled on a relict palaeosol characterised by an argillic Bt horizon covering the top of the Upper Pleistocene alluvial fan. The latter was already hanging over the floodplain, thus providing a safe and relatively dry place to overcome the hydraulic hazard. The main occupational phases of the settlement are characterised by continuous operations of raising and levelling, constantly modifying or removing pre-existing surfaces. On the other hand, the geometry and backfilling of the three concentric ditches are the result of a high engineering design and management for the use of spaces, resources and activities of the settlement. The last phase of occupation of the settlement is marked by the spoliation of the central tower-like building and the levelling of the entire surface of the archaeological site. No evidence of natural driven processes responsible for the abandonment has been observed, due to the long-term stability of the alluvial fan surface.

1. Introduction

Vetricella (Scarlino, Grosseto) is a mediaeval archaeological site dating from the 8th to 13th century CE, located in the proximal part of the coastal plain of the river Pecora (southern Tuscany, Italy, Pieruccini et al., 2021). The archaeological site is described in the literature as part of a royal court of Valli, (Bianchi and Collavini, 2018; Bianchi and Hodges, 2020), consisting of a fortified mound with a raised central tower-shaped building surrounded by a system of three concentric ditches (Marasco, 2009). The site has been investigated by an intensive archaeological research and was included in the contexts studied as part of the ERC (European Research Council) advanced nEU-Med project, aiming to analyse the phases and mechanisms of economic growth in this part of the Mediterranean (Bianchi and Hodges, 2018; 2020).

This paper focuses on the site formation process of Vetricella, examining through a geoarchaeological approach the sedimentary record of surface processes within the site and their relationship to human activities, including the use of space, site modifications and engineering choices. These analyses contribute to shed more light in the understanding the reasons for the choice of the site location and allow the definition and description of the processes associated with the abandonment of the site.

2. Site presentation

2.1. Regional setting

Vetricella is located in the proximal portion of the Pecora coastal plain (also known as "Piana di Scarlino", Marasco, 2013), which is part of the distal catchment of the river Pecora (Fig. 1). The coastal plain is relatively flat with an elevation of about 10 m above sea level (asl, henceforth), gently sloping towards the sea for ca. 8 km. It is bordered by rugged hills ranging in height from 200 m to 500 m asl. The south-eastern part of the coastal plain is characterised by a still existing marshy area, which represents the only remains of the Scarlino marshes reclaimed in the first half of the 19th century CE (Pieruccini and Susini, 2020).

The proximal part of the coastal plain is characterised by the

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presence of two generations of alluvial fans belonging to two different depositional phases (Pieruccini et al., 2021, Fig. 1). The older alluvial fan, on which the site of Vetricella is located, was deposited during the Upper Pleistocene, extending from north to south for about 4.5 km. Its surface is terraced up to 6 m above the present-day thalweg, and it is crossed by a palaeodrainage network of shallow channels filled with Holocene sediments (Pieruccini et al., 2021). The younger alluvial fan, entrenched in the older one, was formed during the Holocene, and it extends from north to south for about 4 km, merging with the former marshy environment of the coastal plain (Fig. 1). Its deposition is related to the increased sedimentary input from the inland, which occurred in historical times (9th-13th cent. CE, Pieruccini et al., 2018; 2021).

2.2. *The archaeological site of Vetricella*

Vetricella was first identified during an aerial survey in 2006 (Campana et al., 2006, Fig. 2a). Subsequent field investigation and geophysical surveys of the area (Campana et al., 2009) confirmed the presence of a mound with a concentration of pottery fragments attributed to the early mediaeval period (Marasco, 2009).

Between 2016 and 2018, extensive archaeological campaigns were carried out as part of the nEU-Med project (Bianchi and Hodges, 2018; 2020), uncovering an area of approximately 3000 m^2. The excavations revealed evidence of a central rectangular tower-like building surrounded by three concentric ditches, hypothesised to have served as defensive purposes, at least for the two innermost ditches (Marasco and Briano, 2020, Fig. 2bc). The presence of a cemetery area (Viva, 2020), productive structures and numerous finds also suggest that the site may have been connected to the centre of the Curtis regia of Valli (Bianchi and Hodges, 2020).

Due to the large area occupied by the settlement, only a limited part has been thoroughly investigated. The stratigraphic sequence is summarised in six occupation periods, based on the relationship between the stratigraphic units, the main elements of the material culture and the available radiometric dating (Marasco et al., 2018; Marasco and Briano, 2020, Table 1). However, the overall thickness of the archaeological deposit is relatively thin and highly variable both vertically and laterally. Moreover, modern agricultural works have severely affected the archaeological deposit (Fig. 2d). Conversely, a greater thickness is noted within the backfill of the ditches (Susini and Pieruccini, 2020).

3. Materials and methods

The facies analysis included the description of three sections exposed during the archaeological campaigns and six exploratory trenches opened to intercept the backfills of the three ditches and determine their function over time (Fig. 3). Sediment colours have been taken with the Munsell Soil Colour Chart under dry conditions.

The micromorphological study included 28 thin sections from different areas and archaeological contexts (Table 2). Sampling through Kubiena boxes followed a selective criterion aimed at obtaining as complete an overview of the sedimentary record as possible. Sample preparation was carried out at the 'Servizi per la Geologia' (Piombino, Italy) according to the preparation guidelines.

Thin sections were analysed under a petrographic microscope model ZEISS AXIO Scope A.1 MAT at a magnification between 12.5X and 400X (considering the additional 10X magnification given by the ocular lenses) using plane-polarised light (PPL) and crossed-polarised light (XPL). In addition, the microscope is equipped with a reflected light (RL) source to analyse opaque masses (Ligouis, 2017). Photographic documentation was acquired with a high-resolution digital colour camera Axiocam 105 supplied with the microscope and processed with the associated software ZEN 2.3 Lite.

The micromorphological description followed the main manuals proposed by Bullock et al. (1985) and Stoops (2003), whilst the interpretation of the data obtained mainly refers to the work proposed by Stoops et al. (2010) and Nicosia and Stoops (2017). Only the most important features have been summarised, whereas systematic and analytical descriptions of all thin sections (following Goldberg and Aldeias, 2018) can be found in the supplementary material. The facies listed in the description have been defined according to their macroscopic and microscopic characteristics, which are univocally related due to the abrupt changes occurring among them. Therefore, the classical concepts of microfacies (Courty, 2001; Goldberg and Macphail, 2006; Flügel, 2009) have not been adopted for this work.

4. Site formation processes of Vetricella

Facies and micromorphological analyses identified 18 sedimentary facies, grouped into three main geoarchaeological phases, taking into account only major changes in depositional style and significant unconformities. Thus, the overall stratigraphic setting of the site differs from the archaeological stratigraphy (Marasco et al., 2018; Marasco and Briano., 2020).

4.1. *Pre-settlement phase*

4.1.1. *Alluvial fan (facies Af)*

The deposit referred to as the Upper Pleistocene alluvial fan is the lowermost recognised in the stratigraphic sequence and was not

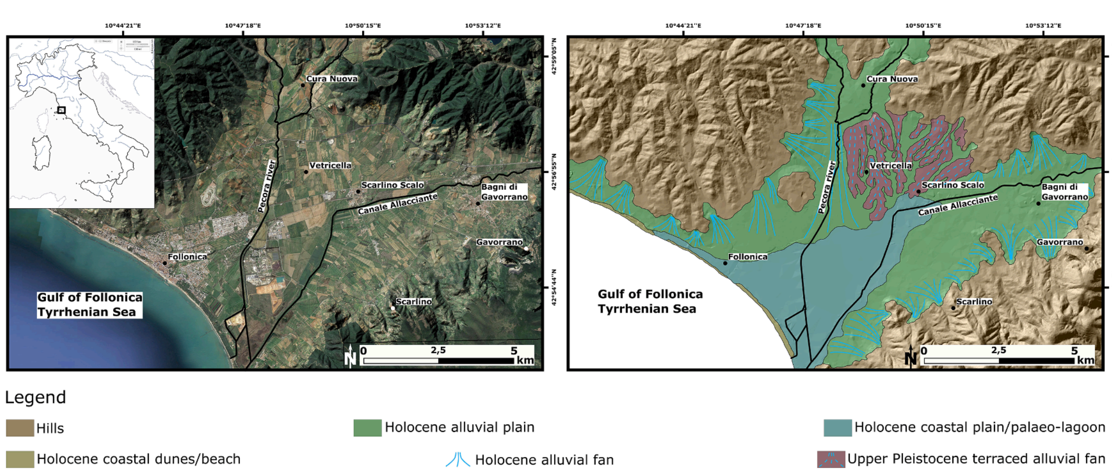

Fig. 1. Left: location of the archaeological site of Vetricella in relation to the Follonica coastal plain. The inset shows the location of Vetricella in Italy; Right: geomorphological map of the area surrounding Vetricella.

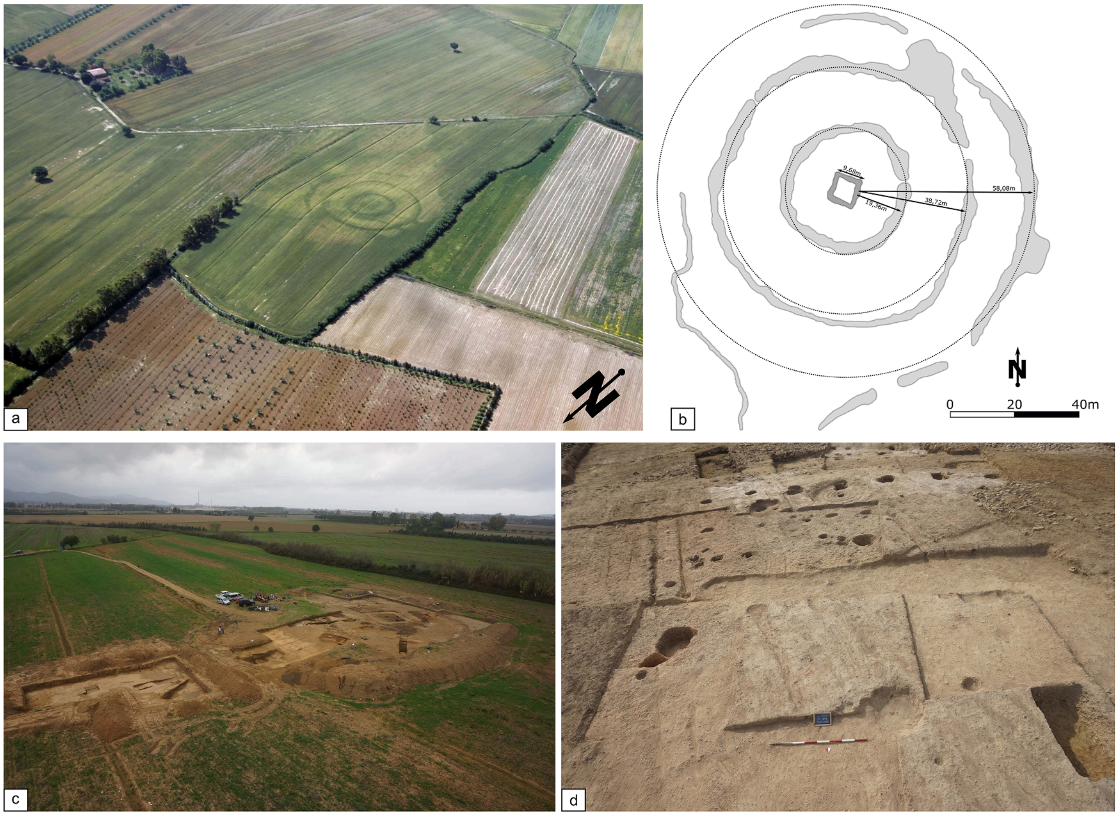

Fig. 2. The archaeological site of Vetricella. a) 2005 aerial survey (Lap&T) with evidenced the anomalies of the concentric ditches and the central building; b) general planimetry of Vetricella according to the identified anomalies and radius of the three ditches (modified from Marasco et al., 2018); c) drone view of Vetricella by the end of the 2016 excavation campaign; d) drone view of the central building with modern ploughing marks on the top and in the background numerous post-holes and one of the two mortar machines.

sampled for micromorphological analysis (Pieruccini et al., 2021, Fig. 4ad). It consists of polygenic, clast-supported subangular to subrounded, fine- to coarse-grained gravels with massive, strongly packed brown-yellowish (10YR 5/6) silty-clayey matrix. Most gravel elements show reddish-brown (5YR 4/4) coatings and patinas of Fe-Mn oxides.

4.1.2. Argillic soil (facies Bt)

The facies refers to a truncated and buried Bt horizon preserved locally above facies Af (Fig. 4bd and Table 2). The horizon has a moderately developed subangular blocky structure (Fig. 5a1), locally prismatic, and consists of moderately packed, matrix-supported, strong brown (7.5YR 5/6) silty-clay matrix with cross-striated and concentric grano-striated b-fabric (Fig. 5a2). Ped walls and voids are generally coated by limpid yellowish-brown (10YR 5/6) microlaminated silts and clays that occasionally pass through complete dense infillings with crescent-type fabric (Fig. 5a3). These coatings are also observed to be fractured and reworked within the groundmass (*papulae*, Bullock and Thompson, 1985, Fig. 5a4). The coarse fraction is sparse and consists of fine- to medium-grained sands and very scarce subangular to subrounded fine- to medium-grained siliciclastic gravels, with partial argillification of the clasts. Carbonate elements characterising the gravels of facies Af are almost completely leached out and can only be observed on the top of the facies as secondary $CaCO^3$ micritic and sparitic coatings (Fig. 5a2).

4.2. Settlement phase

4.2.1. Early occupation surfaces (facies Os1)

The facies refers to the first phases of settlement, which occurred above or by removing the facies Bt (Fig. 4abd and Table 2). The facies is massive and consists of moderately packed, matrix-supported, brownish yellow (10YR 6/6) to strong brown (7.5YR 5/8) silty-clay sediments and frequent fine- to medium-grained subangular to subrounded sands and gravels with weak to moderate planar to subplanar orientation. The rock fragments are polygenic and derived from facies Af, as indicated by the Fe-Mn oxides coatings and the partial argillification of quartz elements (Fig. 5b1). Moreover, the presence of pedorelicts from facies Bt indicates the reworking of the argillic horizon (Fig. 5b2). The facies is also characterised by scarce anthropogenic elements, such as charcoal fragments (Fig. 5b3) and refined metallurgical finds (Angelini et al., 2017, Fig. 5b4), although they might have been reworked over short- or long-distances from the combustion structures found during the excavations.

4.2.2. Main occupation surfaces (facies Os2-1 and Os2-2)

The main occupation surfaces occur on top of facies Os1 and are in turn partially eroded or buried under the abandonment levelling facies (Fig. 4abd and Table 2). These facies consist of several layers with a strong lateral variability due to the continuous raising/ levelling operations throughout the life of the settlement. These two facies are distinguished mainly by their location.

Facies Os2-1 is observed between the central building and the inner ditch (Figs. 3, 4ab), and is made of clast-supported fine- to coarse-grained subangular to subrounded gravels with massive, moderately packed, greyish brown (10YR 5/2) silty-sand matrix.

Facies Os2-2 is observed outside the inner ditch, close to the cemetery area (Figs. 3, 4d), and exhibits similar sedimentary characteristics to facies Os2-1, with a yellowish brown (10YR 5/8) silty-sand matrix. In thin section, both facies are massive (Fig. 5c1d1), with the coarse elements deriving from facies Af showing the same Fe-Mn oxides coatings and partial argillification of the siliciclastic fraction (Fig. 5c2d2).

Table 1
Vetricella, main periodisation of the settlement (modified from Marasco et al., 2018).

Period	Sub-period	Chronology	Main stratigraphic features	Interpretation
Period 1		8th – mid-9th c. CE	Structural postholes; probable kilns and fire-related activities	Settlement associated with specialized activities
Period 2		2nd half 9th c. CE	Fortification system with three concentric ditches and a main central building (tower-like structure); occupation layers	Fortified control site for land and resources management
Period 3		1st half 10th c. CE	Occupation layer and progressive infilling of the ditches	Progressive continuation of the previous context
Period 4	Sub-period 4.1	2nd half 10th c. CE	New construction phase, with a mortar mixer and new floor levels; intentional filling of the ditches and new wooden enclosures; evidence of a cemetery with a small oratory	Renewed and expanded control site
	Sub-period 4.2	1st half 11th c. CE	Levelling and elevation layers; new construction phases with repeated reconstructions and reusing of previous structures; new delimitation of the central area	Progressive continuation of the previous context and subsequent decrease
Period 5		Mid-11th – mid-12th c. CE	Site reoccupation and new storage structures; layers rich in carbonized seeds; new delimitation of the central area	New function as probable part of a manorial property
Period 6		Mid-12th – mid-13th c. CE	Systematic dismantling of the main central building and site re-occupation; new structures and seed storage pits	New settlement connected to agricultural resources management
Period 7		2nd half 20th c. CE	Ploughing and agricultural activities	Contemporary farm

However, the coarser elements from facies Os2-2 exhibit a weak planar to subplanar orientation (Fig. 5d4). Pedorelicts from the argillic horizon are also observed (Fig. 5c3). Conversely, anthropogenic components are relatively scarce and made of charcoal microfragments and partially phosphatised animal bone fragments (Fig. 5c4d3).

4.2.3. Central building (facies Cb1, Cb2 and Cb3)

The stratigraphic sequence of the central building lies directly above the Upper Pleistocene alluvial fan, whilst the top has been disturbed and truncated by modern agricultural work, as shown by the plough marks (Fig. 2d).

Three facies are recognised, from bottom to top. Facies Cb-1 (Fig. 4c) consists of clast-supported fine- to coarse-grained subrounded to subangular gravels and rock fragments with massive, moderately packed, yellowish-brown (10YR 5/6) silty-sand matrix. Facies Cb-2 (Fig. 4c and Table 2) consists of poorly sorted, fine- to coarse-grained subrounded gravels with massive, moderately packed, yellowish-brown (10YR 5/4) silty-sand matrix (Fig. 5e1e2). Coarser elements show a weakly to moderately expressed sub-horizontal linear fabric. In addition, scatters of phosphatised ash are also observed (Fig. 5e3e4). Facies Cb-3 (Fig. 4c and Table 2) is similar to facies Cb-2, consisting of massive, moderately packed, greyish brown (10YR 5/2) silty-sand matrix with fine- to medium-grained, subrounded to subangular gravel. The constituents of the coarse fraction show a moderately expressed linear fabric (Fig. 5f1). Anthropogenic elements, such as microcharcoal fragments and limestone mortar grains, are sporadically present (Fig. 5f2). Locally, fragments of reworked earthen floors are present (Fig. 5f), with a well-expressed laminar microstructure composed of alternating beds of very fine-grained sands and silts (Fig. 5f3f4).

4.2.4. Inner ditch (facies Ind)

The inner ditch has a radius of ca. 19,36 m with a circumference of ca. 122.5 m, with both banks having symmetrical geometry. It was investigated in trench D417, where it has a width of ca. 4 m and a depth of ca. 2 m (Fig. 6). However, a greater depth cannot be ruled out as the top of the backfill is truncated by the modern ploughed horizon. The inner ditch was largely excavated within the gravels of the Upper Pleistocene alluvial fan (facies Af), whilst only its uppermost portion (ca. 30 cm) was excavated within the early occupation surfaces (facies Os1).

Overall, the backfill of the inner ditch is moderately packed and consists of lenses and/or continuous rough layers of sediments and anthropogenic materials with geometries subparallel to the basal surface, suggesting inputs from the inner and outer banks of the ditch. Facies and micromorphological analysis identified five main sedimentary facies.

Facies Ind-1 refers to most of the ditch backfill (Fig. 6 and Table 2). The facies is moderately reworked by the action of edaphic fauna and flora and consists of layers moderately packed, matrix-supported brown (7.5YR 5/2) sands and silts, with poorly sorted fine- to coarse-grained angular to subangular gravels with planar to cross-planar beddings (Figs. 6, 7a1). Pedorelicts of facies Bt are also observed. Anthropogenic elements are overall common both at macro- and micro-scale and chaotically mixed within the sediment (Fig. 7a2a3). Dusty silty-clay coatings on pores and clasts are common, although only observed at the top of the backfill (Fig. 7a4). This suggests that they are associated to slaking processes (Kühn et al., 2010; Darboux et al., 2016) due to modern agricultural workings.

Facies Ind-2 is a lens localised on the inner part of the ditch, sloping and thinning towards the centre (Fig. 6 and Table 2). The lens consists of moderately loose, massive, light brownish grey (10YR 6/2) silty-sands with poorly sorted, fine- to medium-grained, angular to subangular gravels and abundant light grey (10YR 7/1) to white (10YR 8/1) small- to medium-grained mortar and lime fragments that derive from the Calcarous Tufa deposits present in the river Pecora catchment (Pieruccini et al., 2021, Fig. 7b1b2). Anthropogenic materials, especially pottery fragments, are commonly widespread (Fig. 7b3b4).

Facies Ind-3 is the backfilling of three postholes excavated within facies Ind-1 (Fig. 6). The facies consists of massive, moderately packed, matrix-supported brown (7.5YR 5/4) silts and sands with common fine- to medium-grained subrounded to subangular gravels. No micromorphological samples were collected from this facies.

Facies Ind-4 refers to thin discontinuous combustion lenses, dipping from the outer bank towards the centre of the ditch (Fig. 6 and Table 2). At the microscale, these lenses are made of, from bottom to top: a) dark brown to reddish rubified sediments; b) thin blackish layered burnt or partially burnt plant remains with abundant fibrous organic matter associated with micritic ash and impregnations of oxidised vivianite; c) silty grey-whitish ash (Fig. 7c1). The latter is layered, showing two phases of combustion at different temperatures (Fig. 7c2c3). The base consists of abundant calcium oxalate with partial preservation of the original morphology of the plants, most probably indicating that the temperature reached did not exceed 500 °C (Canti and Brochier, 2017, Fig. 7c4). On the other hand, the top is made of a micritic groundmass with saccharoidal appearance, abundant pseudomorphic calcite

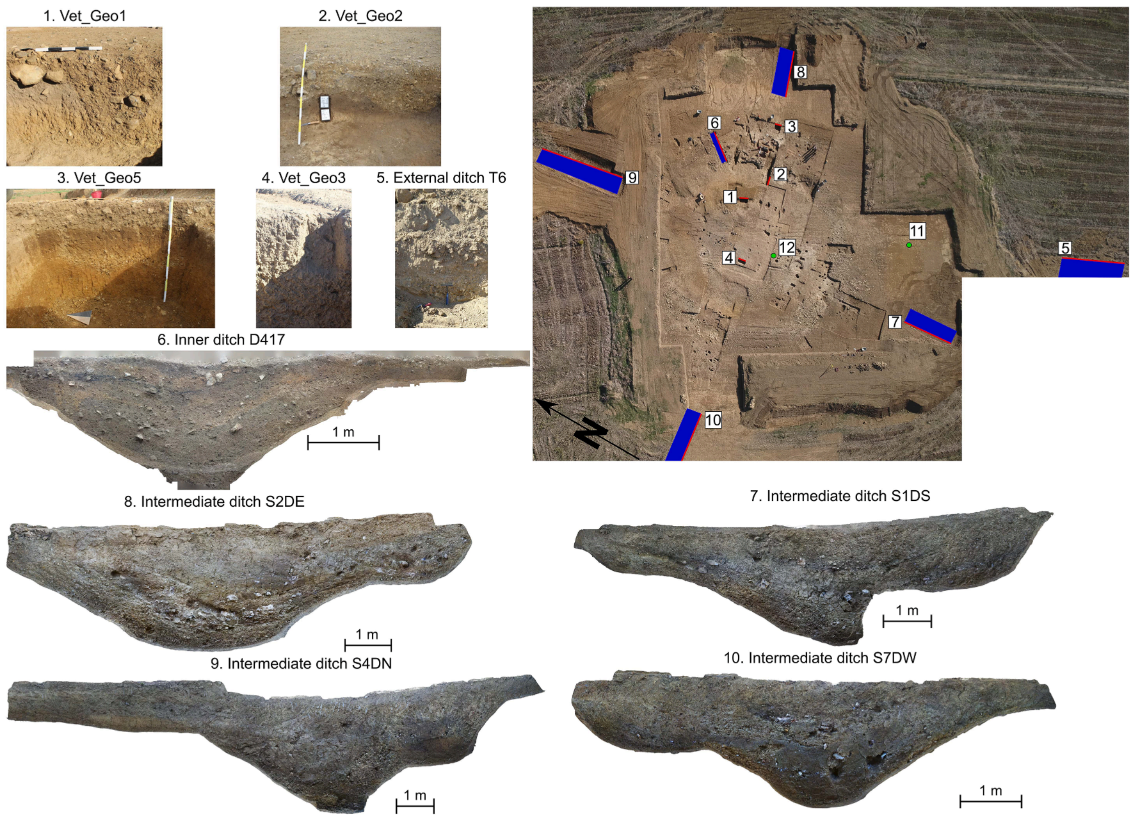

Fig. 3. Vetricella, the stratigraphic sections analysed and their location within the archaeological site (top right). Red lines indicate the aforementioned stratigraphic sections, blue squares indicate the trenches opened, green circles indicate the position of the micromorphological samples collected outside the stratigraphic sections (CSN_SET3H7 and CSN5601). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Vetricella, list of thin sections.

Phase	Facies	Label	Year	Provenance	
				Area	Section
Pre-settlement	Bt	CSN_D81701	2017	Sector East, between Central building and Inner ditch	Vet_Geo2
		CSN_D81707	2017	Sector East, cemetery area, between inner and intermediate ditches	Vet_Geo5
		CSN_SET3H7	2017	Sector South, between inner and intermediate ditches	//
		CSN_S4DN_Bt	2018	Sector North, outside the intermediate ditch	Trench S4DN
Settlement	Os1	CSN_D81702	2017	Sector East, between Central building and Inner ditch	Vet_Geo2
		CSN_D81705	2017	Sector East, cemetery area, between inner and intermediate ditches	Vet_Geo5
		CSN_ECFI02	2016	Sector East, between Central building and Inner ditch	Vet_Geo1
	Os2-1	CSN_ECFI01	2016	Sector East, between Central building and Inner ditch	Vet_Geo1
	Os2-2	CSN_D81704	2017	Sector East, between Central building and Inner ditch	Vet_Geo2
		CSN_D81706	2017	Sector East, cemetery area, between inner and intermediate ditches	Vet_Geo5
	Cb2	CSN_EC01	2016	Central building	Vet_Geo3
	Cb2-3	CSN_EC02	2017	Central building	Vet_Geo3
	Ind-1 and Ind-5	CSN_D41701	2016	Inner ditch Sector East	Trench D417
	Ind-1 and Ind-4	CSN_D41702	2016		Trench D417
	Ind-1	CSN_D41703	2016		Trench D417
	Ind-2	CNS_D41704	2016		Trench D417
	Ind-1	CSN_D41705	2016		Trench D417
	Ind-1	CSN_D41706	2016		Trench D417
	Ind-1 and Ind-4	CSN_D41707	2016		Trench D417
	Ind-1, Ind-4, and Ind-5	CSN_D41708	2016		Trench D417
	Indt-B1	CSN_S1DS2b	2018	Intermediate ditch Sector South	Trench S1DS
	Intd-B2	CSN_S1DS3b	2018		Trench S1DS
	Intd-B2	CSN_S2DE5b	2018	Intermediate ditch Sector East	Trench S2DE
	Indt-B1	CSN_S2DE7	2018		Trench S2DE
	Indt-B1	CSN_S4DN5	2018	Intermediate ditch Sector North	Trench S4DN
	Intd-B2	CSN_S7DW3a	2018	Intermediate ditch Sector West	Trench S7DW
	Intd-B2	CSN_S7DW6	2018		Trench S7DW
Post-settlement	Lv	CSN_ECFI03	2017	Sector East, between Central building and Inner ditch	Vet_Geo1
	Lv	CSN_5601	2017	Sector East	//

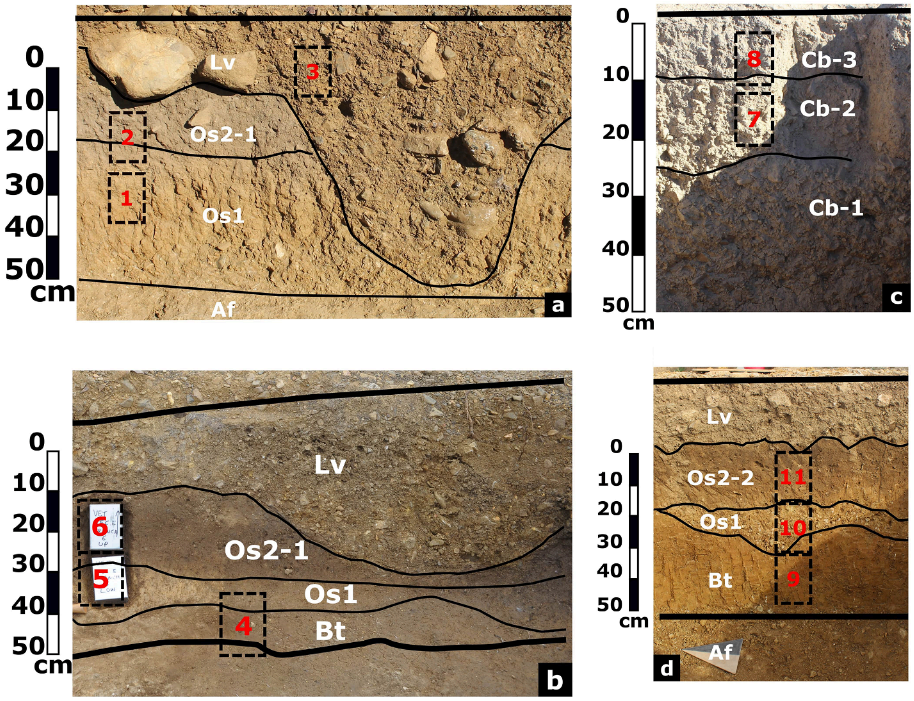

Fig. 4. Vetricella stratigraphic sequence and location of the micromorphological samples. a) section Vet-Geo1; b) section Vet_Geo5; c) section Vet_Geo3; d) section Vet_Geo5. Micromorphological samples: 1 – CSN_ECFI02; 2 – CSN_ECFI01; 3 – CSN_ECFI03; 4 – CSN_D81701; 5 – CSN_D81702; 6 – CSN_D81704; 7 – CSN_EC01; 8 – CSN_EC02; 9 – CSN_D81707; 10 – CSN_D81705; 11 – CSN_D81706.

aggregates and vesicular pores (Fig. 7c4). These features suggest that the second stage of combustion likely exceeded 500 °C and briefly reached temperatures over 650 °C (Shahack-Gross and Ayalon, 2013).

Facies Ind-5 refers to a 5 cm thick lens dipping and thinning from the outer bank towards the centre of the ditch (Fig. 6 and Table 2). It consists of loose, highly porous fibrous structure, with abundant organic and faecal matter associated with frequent fine- to medium-sized charcoal fragments and burnt and fresh bone fragments (Fig. 7d1d2). The latter are also partially or completely phosphatised (Fig. 7d3). Phosphatic features in the form of yellow to blue and green coloured nodules, impregnations, and crusts of hydrated iron phosphates (vivianite, Gaines et al., 1997) are also abundant (Fig. 7d4).

4.2.5. *Intermediate ditch (facies Intd)*

The intermediate ditch was entirely excavated within the Pre-settlement phase (facies Af and Bt) and has an estimated radius of 38,72 m for a circumference of 241 m. In all four trenches, the intermediate ditch has an average width of ca. 8 m and a depth of approximately 2 m, although a greater depth cannot be excluded. The ditch sections show a constant geometry, with a step about 1 m high and 1.5 m wide on the inner bank, that effectively forms a ramp (Susini and Pieruccini, 2020, Fig. 8).

The stratigraphic sequence has already been analysed in Susini and Pieruccini (2020), identifying two distinct sedimentary facies related to anthropic inputs (facies Intd-A) and natural fillings (facies Intd-B). Here, a more in-depth view will be given to the natural fillings, which the micromorphological analysis distinguished into two facies.

Facies Intd-B1 (Fig. 8 and Table 2) consists of massive to weakly laminated, matrix-supported, dark greyish brown (10YR 4/2) clays to silty-clay sediments with scarce sands and pebbles and occasional sandy lenses. The laminations are plane-parallel with a fining-upward transition from sandy, locally with evidence of imbrication, to silty-clayey laminae (Fig. 7e1). Common gastropod shells and freshwater bivalve molluscs (fam. *Unionidae*) in life position are also present (Fig. 7e2). Fe-Mn oxides impregnation and depletion are present, the latter in iron-depleted domains and depletion hypocoatings along channels (Fig. 7e3). Secondary calcium carbonate precipitates are commonly observed, with continuous dense micritic and sparitic coatings and fillings occasionally juxtaposed to impure silty-clay coatings (Fig. 7e4).

Facies Intd-B2 (Fig. 8 and Table 2) show a weakly developed subangular blocky structure and has been partially reworked by biological activity, with vermicular microstructures and loose incomplete infillings (Fig. 7f1). Nonetheless, fining-upward laminations are still locally observed (Fig. 7f2). The facies consists of massive, matrix-supported, brown (7.5YR 4/2) silts with clay sediments with scarce sands and pebbles. Reddish-brown mottles and blackish patinas are commonly observed within the groundmass, which is also locally enriched with humified organic matter (Fig. 7f3) and scattered microcharcoal fragments (Fig. 7f4).

4.2.6. *External ditch (facies Extd)*

The external ditch has a radius of ca. 58,08 m with a circumference of ca. 365 m. It was investigated in trench T6, where it has a width of ca. 2 m and a depth of ca. 50 cm. Due to its shallowness and highly reworking by agricultural activities (facies Ap), no micromorphological samples have been collected, as well as no distinction between facies has been possible. The filling of the ditch is made of clast-supported poorly sorted subangular to subrounded gravels with scarce massive, dark brown (10YR 3/3) silty-sands matrix.

4.3. *Abandonment and post-settlement phase*

4.3.1. *Levelling deposits (facies Lv)*

These sediments cover all the underlying occupation surfaces, filling the topographic irregularities, as well as postholes and rubber pits (Fig. 4abd and Table 2). They are made of poorly layered clast-supported fine- to coarse-grained subangular to subrounded gravels with massive, moderately packed, yellowish-brown (10YR 5/8) silty-sand sediments (Fig. 7g1). Here as well, the coarser fraction derived from facies Af (Fig. 7g2g3). Anthropogenic elements are also very common (Fig. 7g4).

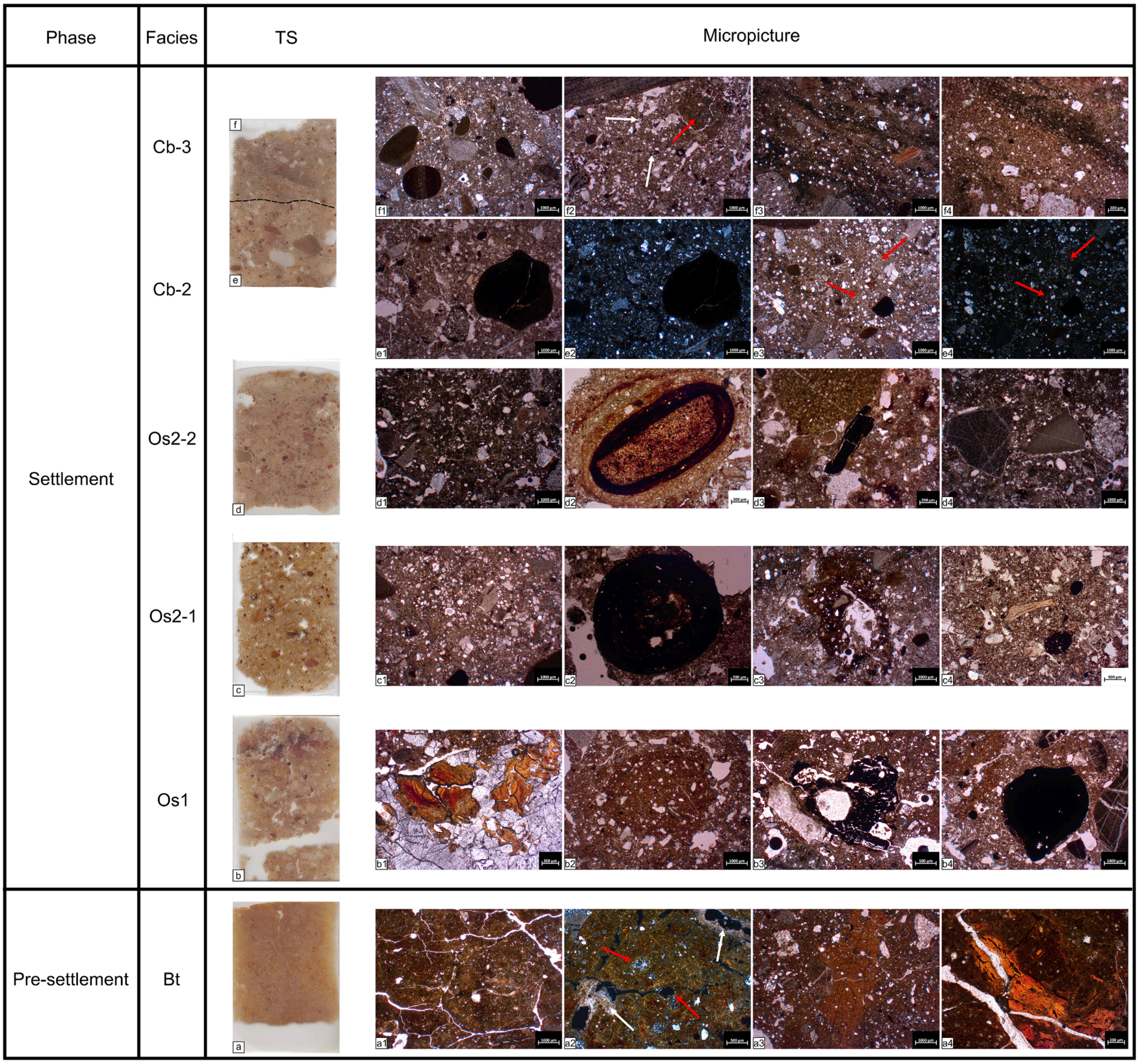

Fig. 5. Vetricella micropictures (I). a) Facies Bt – a1) moderately developed subangular blocky microstructure (scale 1000 μm); a2) secondary $CaCO_3$ precipitation (white arrow) and cross-striated and grano-striated b-fabric (red arrow, scale 500 μm); a3) complete dense clay filling with crescent-type fabric (scale 1000 μm); a4) partially disrupted clay coatings (scale 200 μm). b) Facies Os1 – b1) reworked polycrystalline quartz fragments with partial argillification (scale 200 μm); b2) reworked pedorelict of facies Bt (scale 1000 μm); b3) microcharcoal fragment altered by bioturbation (scale 500 μm); b4) metallurgical fragment, probably the section of a hand-wrought nail (scale 1000 μm). c) Facies Os2-1 – c1) massive microstructure (scale 1000 μm); c2) concentric Fe-Mn nodule (scale 200 μm); c3) reworked pedorelict of facies Bt (scale 1000 μm); c4) bone fragment (scale 500 μm). d) Facies Os2-2 – d1) massive microstructure with higher abundance of the gravelly fraction (scale 1000 μm); d2) reworked subangular clast of facies Af with microstratified Fe-Mn coating, hypo-coating and quasi-coating (scale 200 μm); d3) microcharcoal fragment (scale 200 μm); d4) *iso*-oriented gravels (scale 1000 μm). e) Facies Cb-2 – e1) massive microstructure (scale 1000 μm); e2) same as e1 but in XPL, note the abundance of micritic groundmass (scale 1000 μm); e3) scatters of micritic phosphatised ash (red arrows, scale 1000 μm); e4) same as e3 but in XPL (scale 1000 μm). f) Facies Cb-3 – f1) massive microstructure, note the degree of roundness of the gravelly fraction (scale 1000 μm); f2) anthropic inputs with microcharcoal fragments (white arrows) and mortar fragments (red arrow) (scale 1000 μm); f3) earthen floor fragment with well visible laminar microstructure (scale 1000 μm); f4) particular of f3, note the stone alignments (scale 200 μm). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.3.2. *Ploughed horizon (facies Ap)*

The modern ploughed horizon seals the entire archaeological sequence, and it is made of medium to coarse gravels, moderately packed, with abundant brown (10YR 5/3) sandy-silty matrix, and common fine roots.

5. Discussion

The pedo-sedimentary sequence of Vetricella was reconstructed by integrating the stratigraphic and micromorphological data obtained from the geometries of the deposits, the distribution and juxtaposition of the pedo-sedimentological features of the recognised sedimentary facies and the archaeological context to which they refer (Table 3).

5.1. *Pre-settlement phase*

Regardless the Upper Pleistocene alluvial fan deposits, already discussed in Pieruccini et al. (2021), the truncated and buried Bt horizon belongs to a leached reddish palaeosol (possibly a polycyclic Alfisol, Nettleton et al., 2000; USDA, 2014) which developed on top of the alluvial fan gravels. The main pedogenic processes consist of the complete carbonate leaching and clay illuviation. These processes point to a

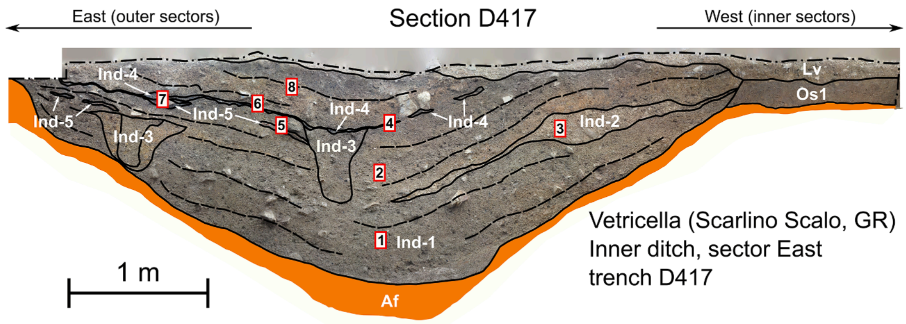

Fig. 6. Vetricella, stratigraphic sequence of the inner ditch, Section D417. Micromorphological samples: 1 – CSN_41706; 2 – CSN_D41705; 3 – CSN_D41704; 4: CSN_D41702; 5 – CSN_D41707; 6 – CSN_D41701; 7 – CSN_D41708; 8 – CSN_D41703.

relative geomorphological stability of the surface and long-lasting wet and warm conditions following the deposition of the alluvial fan at the onset of the Holocene (Pieruccini et al., 2021). The striated and granostriated b-fabric and the presence of papulae suggest shrinking-swelling processes (Kühn et al., 2010), possibly related to seasonal precipitation contrast.

Conversely, figures of secondary calcium carbonate precipitation are only observed within the site of Vetricella, where fresh carbonates on top were added by human activities (e.g. the mortar derived from the Calcareous Tufa deposits). Nevertheless, field analysis clearly shows that the preservation of the Bt horizon only occurred outside Vetricella, whilst it has been completely removed within the site where the occupational surfaces are directly on top of the surface of the alluvial fan (e.g. the central building).

5.2. Settlement phase

The deterioration of stability conditions is evidenced by the settlement facies overlying the Bt horizon. The settlement surfaces are the product of polyphasic anthropic activities over the centuries, mainly through removals and filling/levelling works, with the previous layers constantly altered or completely removed. However, these facies contain residual materials, such as reworked Fe-Mn nodules, clayey pedorelicts and strongly weathered quartz fragments, suggesting continuous reworking of the Bt horizon originally draping the relict surface of the Upper Pleistocene alluvial fan.

Anthropogenic inputs are relatively scarce at the microscopic level, suggesting that the observed samples were collected in areas that may not have been used for living or production activities. On the other hand, the massive microstructures with linear fabric, locally banded, and the *iso*-orientation of the coarse mineral fraction are consistent with compaction as a result of continuous trampling of these surfaces (Rentzel et al., 2017).

The stratigraphy of the central building highlights the presence of three facies. Facies Cb-1, which is archaeologically sterile, probably represents the raising and stabilisation of the topographic surface of the Upper Pleistocene alluvial fan with the removal of the pedogenetic cover. Facies Cb-2 is made of almost uniformly rounded gravels and sorted siliciclastic sands, suggesting that this surface may have been conceived as a substratum, or foundation of inert material, possibly with a stabilising and draining function for the floor of the building. In fact, the uppermost facies Cb-3 shows the presence of reworked fragments of probable earthen floor structures, with homogeneity and very low porosity, indicating a preparation with a mixture of silts and sands with water (Peinetti, 2016; Peinetti et al., 2017).

However, typical constituents associated with trampling surfaces or otherwise related to domestic activities ("active zone", Gé et al., 1993; Macphail and Goldberg, 2017) were not observed. Furthermore, anthropogenic elements are again very scarce. Thus, it is currently not possible to determine whether the material results from in situ remodelling (i.e. reworking of the stratigraphies within the building itself) or from external contributions from other settlement areas. Regardless, they can be interpreted as on-purpose ground layers of the floor levels ("passive zone", Gé et al., 1993; Macphail and Goldberg, 2017). In situ floor remnants have never been found within the central building, although the spoliation and modern ploughing may have played a major role in their destruction (Marasco et al., 2018).

5.2.1. Inner ditch

Stratigraphic and micromorphological analysis of the backfill highlights the only presence of anthropogenic sediments (facies Ind-1) and the lack of any running- or standing-water facies related, indicating that the inner ditch did not serve as a water collector. However, any original function of the ditch, such as defensive purpose as indicated by Marasco and Briano (2020), culminate with an intentional backfilling by 'jetties' from both the inner and outer banks, as suggested by layers and stonelines with a bidirectional dipping. Moreover, the presence of postholes (facies Ind-3) and the mortar layer (facies Ind-2) testify to a sporadic interruption of the backfill and a change in the use of the space.

The uppermost layers (facies Ind-4 and Ind-5) suggest that the surface of the partially filled ditch was used for specific activities such as long-duration high-temperatures firing (facies Ind-4) and as a dump (facies Ind-5, Fig. 7). The poor preservation of the faecal remains prevents the determination of their origin (i.e. herbivorous or omnivorous animals), although the absence of spherulites could suggest a swine origin, as also evidenced by the animal exploitation at Vetricella (Aniceti, 2020). However, the preservation of spherulites might be due to local sediment pH condition and weathering (Brochier, 2002; Karkanas, 2010) or exposure to high temperatures (Brochier, 2002; Shahack-Gross, 2011).

5.2.2. Intermediate ditch

The fine-grained facies Intd-B1 consists of dominant features indicative of running water and water logging processes within the ditch (Fig. 7). Several repeated fining-upward cycles indicate stronger bed currents (thick laminae of fine sands with rare imbricated coarser rock fragments) passing into thin silty-clayey laminae closing up with massive and thicker clays. Therefore, the ditch must have been almost continuously filled or partially filled with water, possibly with seasonal related flooding. This is also suggested by the presence of freshwater bivalves of *Unionidae*, which point to a strong seasonality, as these molluscs can settle on muddy soils and can survive drought periods (Mitchell et al., 2018). Moreover, the presence of these freshwater molluscs might also indicate the presence of fishes, since their parasitic larvae attach to the fish gills as an obligate part of their life cycle (Aldridge, 1999).

Postdepositional modifications observed in facies Intd-B2 are mainly related to hydromorphic and biological features, both of which indicating phases of short-term waterlogging and drying of the ditch (Kühn et al., 2010, Fig. 7). Impure clay coatings are commonly juxtaposed by

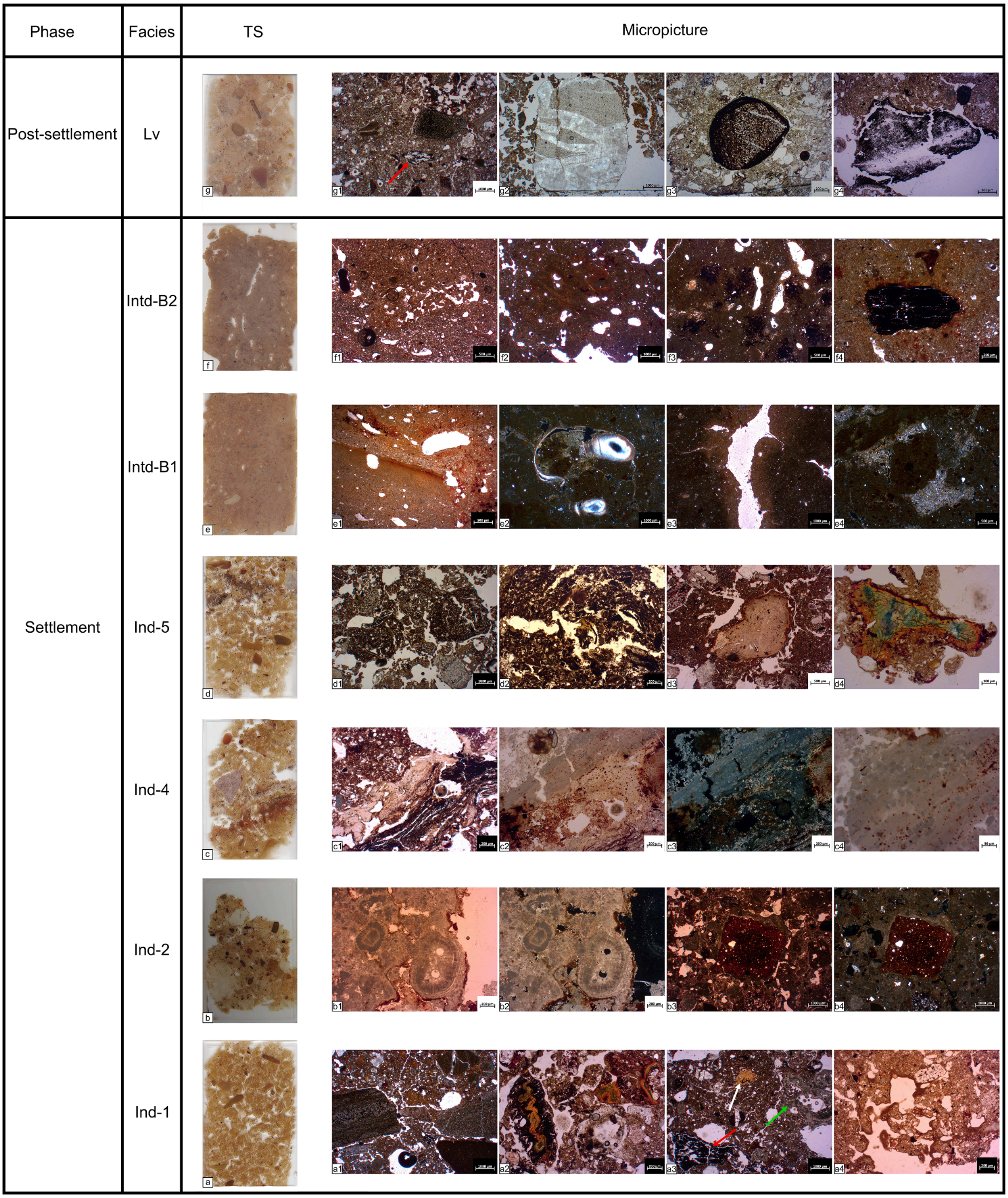

Fig. 7. Vetricella, micropictures (II). a) Facies Ind-1 – a1) *iso*-oriented gravel fragments (scale 1000 μm); a2) concentration of organic matter with vivianite crusts and completely phosphatised herbivorous tooth (scale 200 μm); a3) anthropogenic inputs with charcoal fragments (red arrow) burnt bone fragments (white arrow) and mortar elements (green arrow, scale 1000 μm); a4) dusty silty-clay coating on pores (scale 200 μm). b) Facies Ind-2 – b1) mortar grain coming from calcareous tufa (scale 200 μm); b2) same as b1 but in XPL (scale 200 μm) b3) ceramic fragment embedded in mortar (scale 1000 μm); b4) same as b3 but in XPL (scale 1000 μm). c) Facies Ind-4 – c1) herbivorous faecal remains (scale 1000 μm); c2) particular of c1, note the fibrous structure (scale 200 μm); c3) partially phosphatised bone fragment (scale 500 μm); c4) vivianite crust (scale 100 μm). d) Facies Ind-5 – d1) layered microstructure of the facies Ind-5 with the basal charcoal layer and ash layer on top (scale 200 μm); d2) ash layer, note the stratification of the ashes (scale 200 μm); d3) same as d2 but in XPL, note that at the lower layer of the ashes the calcium oxalate particles are still recognisable (scale 200 μm); d4) particular of d2 with the calcium oxalate particles visible (scale 50 μm). e) Facies Intd-B1 – e1) fining-upward microstructure with vesicles (scale 500 μm); e2) gastropod shells (scale 1000 μm); e3) depletion figures on channel (scale 1000 μm); e4) secondary $CaCO_3$ precipitation on voids (scale 500 μm). f) Facies Intd-B2 – f1) worm faecal pellets (scale 500 μm); f2) fining-upward microstructure reworked by bioturbation (scale 1000 μm); f3) humified organic matter (scale 500 μm); f4) charcoal fragment (scale 200 μm). g) Facies Lv – g1) massive microstructure with occasional charcoal fragments (red arrow) (scale 1000 μm); g2) reworked subrounded polycrystalline quartz fragment of facies Af (scale 1000 μm); g3) reworked round sandstone fragment of facies Af with Fe-Mn coating and impregnation (scale 200 μm); g4) charcoal fragment (scale 500 μm). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

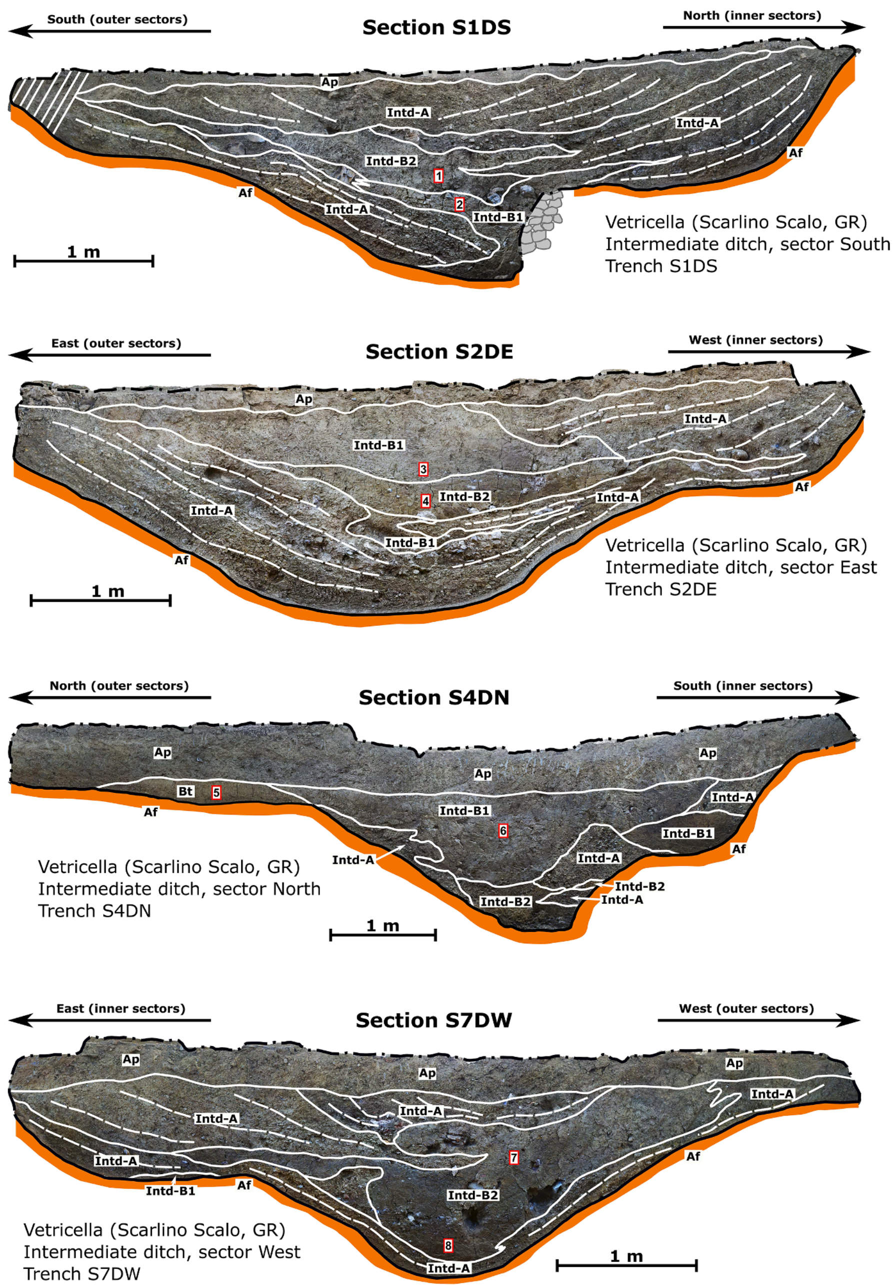

Fig. 8. Vetricella, stratigraphic sequences of the intermediate ditch (modified from Susini and Pieruccini, 2020). Micromorphological samples: 1 – CSN_S1DS3b; 2 – CSN_S1DS2b; 3 – CSN_S2DE7; 4 – CSN_S2DE5b; 5 – CSN_S4DN_Bt; 6 – CSN_S4DN5; 7 – CSN_S7DW3a; 8 – CSN_S7DW6.

micritic coatings suggesting once again the onset of drier conditions, as also evidenced by edaphic fauna activity (Kooistra and Pulleman, 2010).

The main feature of the intermediate ditch is its geometric asymmetry (Susini and Pieruccini, 2020). The step in the inner bank possibly served as a ramp to facilitate the access to the ditch for maintenance work (e.g. cleaning and dredging) or for water supply, as it is estimated that the ditch could hold ca. 581 m^3 of water at its maximum filling (Susini and Pieruccini, 2020). The sediments and the facies highlight a discontinuous water filling of the ditch, which was subject to considerable fluctuations, most likely linked to the seasonal water supply.

5.2.3. *External ditch*

Due to the shallowness of the external ditch and the strong alteration due to modern agricultural activities, the stratigraphic analysis did not reveal sustainable information regarding its function in connection to the settlement of Vetricella. However, as it clearly appears also from the aerial image (Fig. 2), the outermost marks are not closed, but present an opening on the southern part that archaeologist have interpreted as a possible entrance to the settled area (Marasco, 2009).

Remote sensing and field analysis did not reveal the presence of canals or collectors that directed water into the ditch. During the settlement phase of Vetricella, the riverbed of the river Pecora was at a lower elevation than the settlement (Pieruccini et al., 2021). Moreover, the site of Vetricella is located in a slightly elevated area between two channels that acted as a 'natural' drainage system. Feeding the intermediate ditch was therefore mostly depending on seasonal rainfall variations and the amount of water draining from the surrounding landscape. Thus, it is plausible that the external ditch functioned as a regulator for excessive concentrated and diffuse runoff waters, although more data are needed in order to confirm this hypothesis.

Table 3
Vetricella, comparison between the main archaeological periodisation (Marasco et al., 2018) and the geoarchaeological phases.

Phase	Facies	Archaeological period	Chronology	Main geoarchaeological features
Pre-settlement	Af		Upper Pleistocene	Alluvial fan with coarse-grained poorly sorted gravelly layers
	Bt		Early-Middle Holocene	Interglacial natural palaeosoil with reddish leached truncated horizon
Settlement	Os-1	Period 1	8th – mid-9th c. CE	Chaotic poorly sorted and poorly layered gravels and sands. Reworking of the alluvial fan sediments and palaeosoil with first evidence of anthropogenic activities and inputs
	Os-2 Cb	Period 2	2nd half 9th c. CE	Ditches excavations and building of the central tower-like structure with layered floor and occupational layers. High level of engineering competence and remarkable technical knowledge for ditches excavations, productive activities and no evidence for domestic settlement
	Os-2 Cb Ind	Period 3	1st half 10th c. CE	Basal infilling of the intermediate ditch by sedimentary processes and occupation layers: alternating running and standing water within the intermediate ditch, productive activities and no evidence for domestic settlement
	Intd Extd	Period 4	2nd half 10th c. CE	Infilling of the inner ditch with anthropic layers, continuous infilling of the intermediate ditch by sedimentary processes coupled with anthropic layers and occupation layers: inner ditch filled by wasted materials coming both from the inner and outer part of the ditch; evidence of repeated phases of drying-up of the intermediate ditch and important anthropic contribution of gravelly sediments and wasted anthropic materials both from the internal and the external parts; productive activities and no evidence for domestic settlement
			1st half 11th c. CE	Complete infilling of the inner ditch and almost complete infilling of the intermediate ditch; occupation layers: use of the inner ditch as dumping and use of fire; prevailing anthropic inputs of gravelly sediments by the sides of the intermediate ditch; productive activities and no evidence for domestic settlement
	Os-2 Cb	Period 5	Mid-11th – mid-12th c. CE	Complete filling of the ditches and occupation layers, no evidence of domestic settlement
Post-settlement	Lv	Period 6	Mid-12th – mid-13th c. CE	Coarse-grained, poorly sorted gravels and sands levelling layers with poor evidence of anthropic inputs.
	Ap	Period 7	2nd half 20th c. CE	Modern ploughing and disturb of the archaeological layers

5.3. Abandonment phase

From an archaeological point of view, the final phases of Vetricella suggest a distinct place with different functions from the previous periods and perhaps a new role in relation to new political and economic dynamics (Bianchi and Hodges, 2020). These changes are marked by extensive dismantling and spoliation processes, including the levelling of the whole surface and the filling of holes and cuts associated with the wooden elements, as evidenced by facies Lv. The central building was carefully demolished, with the removal of the perimeter wooden and stone elements and the backfilling of the robber trench (Marasco and Briano, 2020). The stratigraphic record is chaotic, discontinuous, and made of mixed sediments coming from all the sources both inside and outside the archaeological site (anthropic material and gravels). The few preserved sediments are strongly disturbed by modern agricultural ploughing works that left peculiar marks. Thus, no natural driven processes can be detected in order to explain the abandonment phase. Indeed, the site and the surrounding alluvial fan surface stratigraphies do not show evidence of geomorphic processes, such as runoff or flooding, that may have forced the settlement to be abandoned.

6. Conclusions

The geoarchaeological investigation of the early mediaeval site of Vetricella allowed a better understanding of the processes that took place during the phases of occupation, frequentation, and abandonment of the settlement. Overall, the extensive archaeological excavations of Vetricella revealed an exceptional amount of material evidence pointing out a highly specialised production (e.g. iron casting) consistent with a royal court in a rural context (Bianchi 2020; Hodges, 2020).

The earliest evidence of occupation indicates that the settlement was located on a relict palaeosol characterised by an argillic Bt horizon covering the top of the Upper Pleistocene alluvial fan. This suggests that the earliest phases of settlement life occurred in a long-lasting stable landscape.

The main bulk of the occupation of the settlement is evident from polyphasic raising and levelling activities that took place over the centuries, and continuously modified or removed the previous surfaces. The investigated area was most likely not used for living or production purposes. For the construction of the central building, a foundation was prepared directly above the Upper Pleistocene alluvial fan, on which the earthen floors were placed. The latter were completely removed or dismantled during the last occupation of the settlement, which was marked by spoliation of the buildings and the levelling of the entire surface of the archaeological site.

The geometry and backfilling of the three concentric ditches built around the central building made it possible to understand their function and management over time. It is likely that the construction of the three ditches is coeval and was integrated into a precise planning to manage the spaces, resources and activities of the settlement. The outer, shallowest ditch probably served to regulate surface waters from concentrated and diffuse runoff. The intermediate ditch shows a construction technique that is the result of a precise functional strategy that required a high engineering design and construction. Its asymmetrical geometry served for maintenance and use as a water reservoir, most probably for productive and domestic activities. The innermost ditch shows symmetrical geometry of the banks and served as a defensive structure during its initial phase. The sedimentary features of the backfill consist exclusively of sediments of anthropogenic origin, resulting from the mobilisation of material from the surrounding area. The stratigraphic analysis revealed subsequent different uses of the inner ditch according to its original purpose, corresponding to the different phases of the frequentation of the archaeological site. The ditch was mainly used as dump for materials of domestic nature (waste, food, etc.) and of productive nature (mortar). In addition, the ditch was used for the construction of wooden structures or as a place for fire activities.

CRediT authorship contribution statement

Davide Susini: Data curation, Investigation, Visualization, Writing – original draft. **Pierluigi Pieruccini:** Supervision, Resources, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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